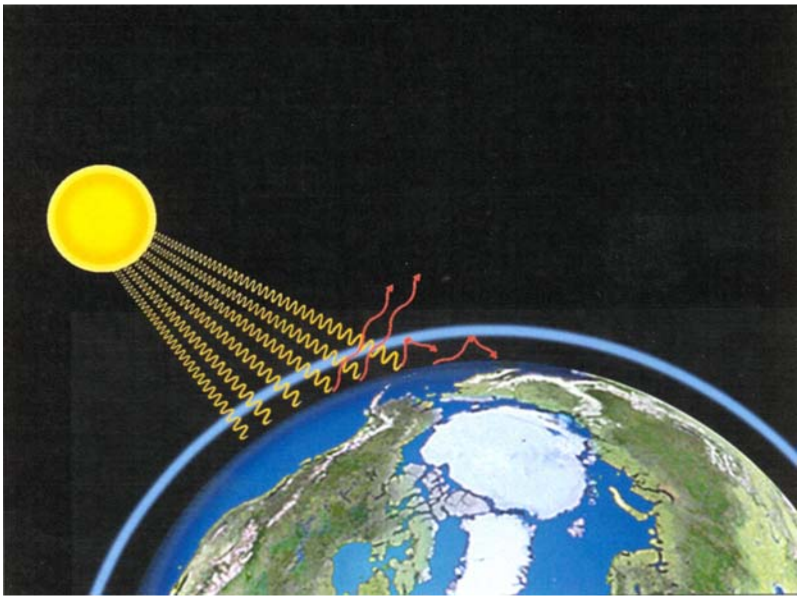
A brief summary of the science of global warming and climate change



Report prepared for an objections hearing in the Land Court of Queensland regarding the proposed Wandoan Coal Mine

Mining tenement numbers ML 50229, ML 50230 and ML 50231 and draft environmental authority (mining lease) number MIN100550607

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3 August 2011

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INTRODUCTION

1. I have been asked by the Friends of the Earth – Brisbane Co-Op Ltd to provide an expert report explaining what are global warming and climate change, how serious these problems are, and how does the mining, transport and use of coal contribute to these processes. I have also been asked to consider whether the predicted total emission from this mine is likely to contribute to climate change. Climate change and ocean acidification are inter-related but another expert, Professor Ove Hoegh-Guldberg has been asked to address the latter and I will, therefore, not address it in this report.

2. The science of global warming and climate change is very complex but there is now a broad scientific consensus about much of it. I have, therefore, deliberately chosen to keep the explanations of the concepts as simple as possible in this report and not over-burden the text with copious citations and complex diagrams or graphs. I also note that other eminent experts, including Dr Malte Meinshausen and Professor Ove Hoegh-Guldberg, are addressing several specific issues such as the resilience of the climate system and the likely impacts of global warming on the Great Barrier Reef Area. It is, therefore, not necessary for me to go into great detail on the topics they are addressing or about the likely severe impacts of global warming and climate change on the environment.

3. This report has been prepared in response to that request for use in an objection hearing in the Land Court concerning a large open-cut coal mine. The mine is the Wandoan Coal Mine, an open-cut coal mine proposed to operate for 30 years west of the township of Wandoan, approximately 350 km northwest of Brisbane and 60 km south of Taroom in the Surat Basin, Queensland (the mine).

4. The thermal coal deposits for the mine are estimated to be in excess of 1.2 billion tonnes, and are located within three Mining Lease Applications (MLAs 50229, 50230 and 50231), which comprise approximately 32,000 hectares. The coal from the mine is proposed to be crushed, processed and blended on site before being transported by rail to port for export or, possibly, for domestic use. The thermal coal produced by the mine is intended to be sold to other companies to be burnt in coal-fired power stations to generate electricity.

5. The Wandoan Coal Project environmental impact statement and an accompanying technical report on greenhouse gas emissions calculated that the emissions from the mining and use of the coal from the mine would be over 41 million tonnes of carbon dioxide equivalents annually and 1.3 billion tonnes of carbon dioxide equivalents over the life of the mine.[1]

6. As a final introductory matter, I note that I understand my duty as an expert witness before the Court based on rule 426 of the Uniform Civil Procedure Rules is to assist the Court. While I appear pro bono to assist the Court in these proceedings, I note also that my duty to assist the Court would override any

[1] Xstrata Coal (2008), Wandoan Coal Project Environmental Impact Statement , Parsons Brinckerhoff Australia Pty, Brisbane, Vol 1, Book 2, Ch 14 (Greenhouse gases and climate change); and Clarke S (2008), Technical Report – Wandoan Coal Project greenhouse gas assessment, URS, Brisbane.

obligation I may have to any party to the proceeding or to any person who is liable for my fees or expenses.

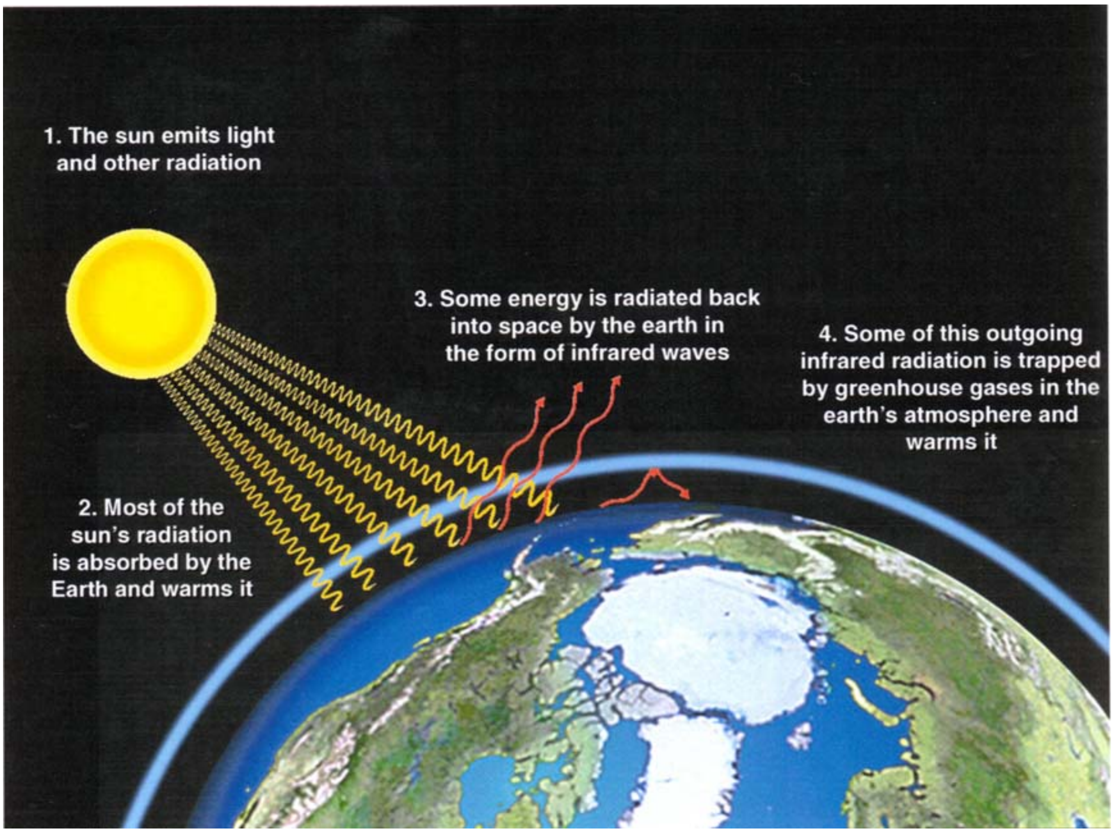
RELEVANT EXPERTISE

7. My brief biography is Appendix 1 to this report. In summary, I am emeritus professor of science, technology and society at Griffith University and adjunct professor at University of the Sunshine Coast and Flinders University. I am a recognised expert on the environmental aspects of energy supply and use. As well as having chaired the relevant committee of the national energy research body from 1983 to 1989, I have acted as a referee for the Inter-governmental Panel on Climate Change and three other global scientific reports on environmental issues. I wrote the first popular paperback book on the subject published in Australia, *Living in the Greenhouse* (1989), and published a follow-up book, *Living in the Hothouse* (2005). I was a member of The Australian Climate Group, which produced in 2004 the report *Climate Change Solutions for Australia*. I was a member of the National Greenhouse Advisory Panel for its entire duration, am deputy chair of the Queensland Sustainable Energy Advisory Council and a member of the Queensland Premier's Climate Change Council.

WHAT IS GLOBAL WARMING AND CLIMATE CHANGE?

8. We have known since the late nineteenth century that the Earth is kept warmer than it would otherwise be by the presence of trace gases in the atmosphere which trap heat. The "**greenhouse effect**" was given its name by the Swedish scientist Arrhenius in the 1890s because he recognised that it worked in the same way as the glass in a greenhouse, admitting the sunlight which warms the interior and blocking the infra-red radiation that would carry the heat away. The natural greenhouse effect is a great benefit and is the fundamental reason why the average Earth temperature, of 15^0C, is about 33°C higher than the temperature on our Moon (which does not have an atmosphere). The following diagram provides a simple pictorial explanation of the greenhouse effect.

Figure 1: Diagram of the greenhouse effect[2]



9. Most people are familiar with one example of the greenhouse effect: the difference in temperature between a cloudy or clear night. After a hot day, a cloudless night is usually considerably cooler than a cloudy night – the difference being that the water vapour in the clouds traps the Earth's heat in and prevents it being radiated to Space. Water vapour is the major greenhouse gas in the atmosphere. This provides a simple example of the greenhouse effect that is a matter of common experience rather than complex science.

[2] Adapted from Gore A (2006), *An Inconvenient Truth*, Bloomsbury, London.

10. There are three key terms that require brief definition and explanation to clarify the concepts associated with the enhanced greenhouse effect:[3]

(a) **Greenhouse gases** are gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere. Moreover there are a number of entirely human-made greenhouse gases in the atmosphere, such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

(b) **Climate change** refers to a significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. The *United Nations Framework Convention on Climate Change* (UNFCCC), in Article 1, defines climate change as, "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thus makes a distinction between "climate change", attributable to human activities altering the atmospheric composition, and "natural climate variability", attributable to natural causes.

(c) **Global warming** is the common term for climate change due to anthropogenic emissions of greenhouse gases leading to increased global temperatures and other climatic effects such as changes in rainfall patterns and the frequency of severe storms.

11. Since the Industrial Revolution, humans have been burning **fossil fuels** – coal, oil and gas – that were stored over the geological time of the Earth's history. Burning these fuels essentially combines the carbon within them with oxygen from the air to produce CO_2. This process has now produced a dramatic increase in the amount of CO_2 in the air. Measurements from laboratories over the last fifty years have been supplemented by assessments of polar ice cores dating back 650,000 years.[4] These studies show that the natural variation of CO_2 levels has been from about 180 to 280 parts per million (ppm) and that global mean temperatures are directly and closely linked to the amount of CO_2 in the atmosphere. The present level of

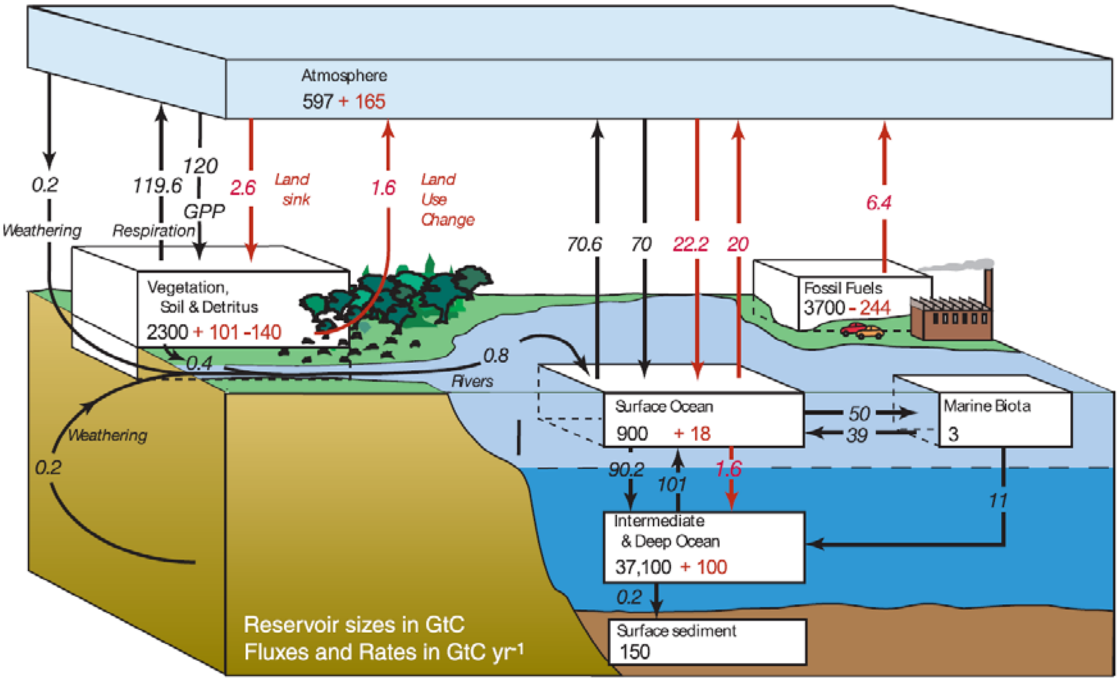
[3] I have referred to my own publications and the Australian Bureau of Meteorology (2003), *The Greenhouse Effect and Climate Change*, BOM, Canberra, for these definitions.

[4] See in particular, Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chappellaz J, Davis M, Dalaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Péplin L, Ritz C, Saltzman E, and Stievenard M, (1999) "Climate and atmosphere history of the past 420,000 years from the Vostok ice core, Antarctica" *Nature* 399: 429-436; and Siegenthaler U, Stocker TF, Monnin E, Lüthi D, Schwander J, Stauffer DR, Barnola JM, Fisher H, Masson-Delmotte V, and Jouzel J, (2005) "Stable Carbon Cycle – Climate Relationship During the Late Pleistocene" *Science* 210: 1313-1317.

CO_2 in the atmosphere is about 390 ppm and increasing steadily by a further 2 ppm each year.[5]

12. Once carbon dioxide is emitted from the burning of fossil fuels such as coal, it enters the global carbon cycle in which the carbon moves in different forms through the atmosphere, oceans and land biota over centuries to millennia (Figure 2).

Figure 2: The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr^{-1}: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red.[6]



13. This is a simple explanation of the main concepts and processes relevant to the issues facing the Court. The Earth's climate and the science of global warming and climate change is far more complex than this but, unless I am requested to by the Court to assist its understanding, I will not go into more detail about these matters, except to add that there is a growing concern in the climate science literature about the risk of exceeding a critical threshold and precipitating rapid and essentially irreversible changes to the climate, as discussed further in paragraph 20.[7]

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[5] Tans P and Keeling R, U.S. Department of Commerce - National Oceanic & Atmospheric Administration – Earth System Research Laboratory – Trends in Atmospheric Carbon Dioxide at http://www.esrl.noaa.gov/gmd/ccgg/trends/ (viewed 13 April 2011).

[6] Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, p 515.

[7] A further, reasonably simple, explanation of the science of the greenhouse effect and climate change is Australian Bureau of Meteorology (2003), *The Greenhouse Effect and Climate Change*, available at http://www.bom.gov.au/info/GreenhouseEffectAndClimateChange.pdf.

HOW SERIOUS A PROBLEM IS GLOBAL WARMING AND CLIMATE CHANGE?

14. The average temperature of the Earth is now warmer than at any time since human records began and it is clear that much of this increase is due to human activities releasing greenhouse gases to the atmosphere.

15. The Intergovernmental Panel on Climate Change (IPCC), the leading international body on climate change science, concluded in its Fourth Assessment Report (AR4) in 2007 that mean global temperatures increased by 0.74°C between 1906 and 2005 and most of the observed increase over the 20th century is very likely (i.e. >90%) due to anthropogenic emissions of greenhouse gases from the combustion of fossil fuels, agriculture, and land-use changes.[8] This finding is based on an extensive body of science. The main reports of the AR4 are nearly 3,000 pages long and published in three volumes. To assist the Court in understanding the full context of the causes and impacts of climate change I have attached the body of the, much shorter, Synthesis Report produced by the IPCC as Appendix 2 to this report.[9]

16. The IPCC projected likely future temperature changes using different scenarios of emissions set out in its *Special Report on Emissions Scenarios* (SRES), with projected concentration of CO_2 in the year 2100 from 540 to 970 ppm, compared to about 280 ppm in the pre-industrial era and about 368 ppm in the year 2000. Further calculations summarised in Section 5.4 of the attached Synthesis Report give the IPCC conclusion that mean global temperatures will increase from 1990 levels by between about 1°C for a low-emissions scenario and about 5°C for a projection of present trends, the future which will eventuate if current proposals for new fossil-fuel production are approved.

17. The levels of reduction in anthropogenic greenhouse gas emissions that are required to stabilise global temperatures at less than a mean 2-3°C rise are uncertain. It will probably require stabilisation of equivalent greenhouse gas concentration of 450 ppm or lower, with further reductions after 2100.[10] The recent summary by the Australian Academy of Science concluded *"To have a better than even chance of preventing the global average temperature from eventually rising more than 2^0C above pre-industrial temperatures, the world would need to be emitting less than half the amount of CO_2 by 2050 than it did in*

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[8] Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.
[9] IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
[10] See generally, Houghton J (2004), *Global Warming: The Complete Briefing*, 3rd ed, Cambridge University Press, Cambridge, pp 257-261; and Pittock AB (2005), *Climate Change: Turning Up the Heat*, CSIRO Publishing, Melbourne, pp 152-155.

2000. To do this on a smooth pathway, global emissions (which are still rising) would need to peak within the next ten years and then decline rapidly."[11]

18. Australia has warmed by 0.9°C since 1910, rather more than the increase in global average temperature. Globally, the period since 1990 has seen all of the ten hottest years since reliable instrumental records began (about 140 years ago). The last decade is the warmest ever recorded and the last year is the warmest year ever recorded. A range of studies collated by the IPCC all agree that the current temperatures are the highest for at least 2000 years. While there is some indirect evidence that there may have been warm periods for small regions in the northern hemisphere in the Middle Ages, all reliable studies show that the recent global and northern hemisphere average temperatures are higher than at any time in at least 2000 years.

19. For Australia, the consequences of anthropogenic global warming and climate change have been: an increase in average temperature of 0.9°C since 1910; an increase in the frequency of very hot days; a decrease in the frequency of very cold nights; more frequent, persistent and intense droughts; more frequent heavy rainfall events; decreased winter rainfall, especially in southern Australia; sea levels increasing about 2 cm per decade; and increasingly frequent extreme events such as category five tropical cyclones, severe east coast low pressure systems and intense bushfires. To assist the Court in understanding the impacts of climate change on Australia, I have attached as Appendix 3 to this report the executive summary of a technical report on climate change in Australia published by the CSIRO.[12]

20. When I wrote *Living in the Greenhouse* in 1989, it was clear that human activity was changing the composition of the atmosphere and clear that the climate was changing, but most scientists felt it was not provable that the climate change was being caused by the enhanced greenhouse effect. Since then, there has been an immense scientific effort to analyse climate change and develop sophisticated computer models which test theories about the link between greenhouse gas levels and climate. The IPCC has now released four assessments in 1990, 1996, 2001 and 2007, with the Fifth Assessment Report due to be released 2014. The IPCC is made up of hundreds of the world's most distinguished atmospheric chemists, physicists and climatologists. Its work is overseen by the United Nations and the World Meteorological Organisation. The assessments show the steady strengthening of scientific confidence that we are seeing real changes in the Earth's climate driven by human activity, principally the release of carbon dioxide and other greenhouse gases (especially methane) as a consequence of energy use.

21. As the attached CSIRO report shows, climate change is already imposing significant economic, social and environmental costs on Australia and the rest of the world. In the specific case of Australia, the most obvious economic costs are the impact of reduced agricultural production, the increased cost of water supply and the increasing costs of severe weather events.

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[11] The report by the Australian Academy of Science, *The Science of Climate Change*, is available at www.science.org.au/policy/climatechange2010.html

[12] CSIRO (2007) *Climate Change in Australia – Technical Report 2007*, CSIRO, Melbourne.

22. In terms of primary production, Treasury estimates that the 2002-03 drought reduced farm output by 24 per cent, cut agricultural income by 46 per cent, reduced employment by about 100,000 jobs and decreased overall national GDP by almost 1 per cent[13].

23. The more recent prolonged drought had a greater impact.[14] All mainland State capitals were forced to implement water restrictions as a result of reduced rainfall and run-off to reservoirs. Since 1977, inflows to water supply systems of Adelaide and Melbourne have been two-thirds of the previous average, while Sydney, Brisbane and Perth figures have been less than half the previous average, WA spent $140 million on a desalination plant to augment its reduced water supply and is now commissioning a second, but there are still concerns about the reliability of its water supply in the dry period that is still continuing as this report is written. Several other States, including Queensland, are committed to desalination technology to augment water supplies.

24. In terms of natural disasters, only one of the twenty largest causes of insured losses (the Newcastle earthquake) has not been weather-related; the world's second-largest re-insurer, Swiss Re, has warned that the global cost of natural disasters could double in the next ten years, as small changes in such climate variables as temperature lead to disproportionate increases in storm intensity, drought severity, probability of flooding or risk of severe bushfires.[15]

25. In social terms, intensified summer heatwaves will cause more deaths from heat stress, as happened in Europe in August 2003. While it understandably attracted much less attention than the catastrophic "Black Saturday" bushfires, the February 2009 heatwave is estimated by the Victorian Department of Health to have caused about twice as many deaths as the fires.[16] Rates of food poisoning and diarrhoeal disease usually increase in hotter conditions (especially in poorer rural communities), while a 2005 report supported by the Australian Medical Association and the Australian Conservation Foundation concluded that vector-borne diseases like dengue fever and Ross River virus will spread as the changing climate increases the areas suitable for the mosquitoes that carry these contagions.[17] This was confirmed by a 2009 outbreak of dengue fever in the Cairns area, with more than 350 cases reported.

26. Finally, climate change is already having a significant impact on Australia's unique natural systems, decreasing the extent of mountain rainforests, causing coral bleaching, moving snow-lines higher with impacts for alpine species, being

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[13] L.Lu & D.Hedley, The impact of the 2002-03 drought on the economy and agricultural employment, Economic Roundup Autumn 2004, Treasury, Canberra
http://www.treasury.gov.au/documents/817/HTML/docshell.asp?URL=03_article_2.asp

[14] See, for example, Dept of Climate Change and energy Efficiency, Water Resources, Canberra 2011, http://www.climatechange.gov.au/climate-change/impacts/water-resources.aspx

[15] Swiss Re (2004) Global Climate Change: Swiss Re's Perspective
http://chge.med.harvard.edu/programs/policy/briefings/documents/simon.pdf

[16] Victorian Government, January 2009 Heatwave in Victoria: an Assessment of Health Impacts.
http://www.health.vic.gov.au/chiefhealthofficer/downloads/heat_impact_rpt.pdf

[17] R Woodruff et al (2005) *Climate Change Health Impacts in Australia*, http://ama.com.au/node/2120

associated with the increased frequency of severe fire events and being linked with “thickening” of woody vegetation in savannas and bushland.[18]

27. There is also the risk that climate change could exceed a critical threshold and cause abrupt changes. As an example of the sort of change which could occur, the average rainfall in the Perth area has reduced by about 20 per cent, but the warmer and drier conditions mean the average annual run-off into the water supply reservoirs since 1997 is only **one-third** of the figure before 1975.[19] Evidence is emerging that the changes to the atmosphere can alter the working of such important global systems as ocean circulation patterns and the stability of polar ice sheets. The deep ocean circulation of the north Atlantic appears to be slowing now; if this were to accelerate, as some fear, it could affect both the regional climate of western Europe and the capacity of the oceans to support life. The increasing level of carbon dioxide in the air is causing more of the gas to dissolve in the oceans and measurably changing the average acidity, with potentially serious implications for shellfish and corals. There is concern that the large ice sheets of Greenland and West Antarctica could be destabilised, leading to sea level increases of several metres. The scale of these potential risks underlines the need for caution in the way we change the natural systems of the Earth.

28. For Queensland a recent report by the State Government[20] states that:
    - by 2050, projected temperature increases are 1 to 1.4^{o}C for the low emissions scenario and 1.7 to 2.2^{o}C for the high emissions future (approving new large coal mines would be consistent with the high emissions future);[21]
    - the best estimates (of both high and low emission scenarios for 2050) are for decreasing stable rainfall,[22] but more severe rainfall events;[23]
    - sea levels have been projected to rise by 0.8 metres by 2100, but indications are that the rise could be significantly more;[24]
    - increasing number of very hot days, e.g. by 2050 Longreach is projected to have 156 days over 35 degrees compared with 112 days now;[25]
    - frequency of severe tropical cyclones increasing by as much as 56 per cent by 2050;[26] and

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[18] See, for example, M Howden, L Hughes, M Dunlop, I Zethoven, D Hilbert & C Chilcott [eds], Climate cgange impacts on biodiversity, CSIRO Canberra 2003, available at http://www.environment.gov.au/biodiversity/publications/greenhouse/pubs/greenhouse.pdf

[19] Figure 4.1 in WA Department of Premier and Cabinet (2006) *Options for bringing water to Perth from the Kimberley, An Independent Review* http://www.water.wa.gov.au/PublicationStore/first/64772.pdf,.

[20] State of Queensland (Department of Environment and Resource Management) (2010), *Climate Change in Queensland - What the Science is Telling Us*, available at http://www.climatechange.qld.gov.au/pdf/climate-change-in-queensland-2010.pdf

[21] Ibid at page 27.

[22] Ibid at page 27.

[23] Ibid at page 30.

[24] Ibid at pages 3 and 42. Also note that recent science has indicated that, at the current rate of acceleration in ice sheet loss, the contribution of ice sheets alone would result in an additional 56 cm of sea level rise by 2100: see Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. Lenaerts, Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.* 38, L05503, doi:10.1029/2011GL046583 .

[25] Ibid at page 29.

[26] Ibid at page 30.

- *"Queensland can expect to experience: increases in increases in heat-related illnesses, difficulty in supplying urban and agricultural water needs due to decreasing rainfall, and increasing temperature and evaporation. Greater numbers of severe tropical cyclones, combined with storm surges, will increase erosion and coastal flooding and cause more damage".*[27]

29. In terms of specific impacts, the report sets out useful "Key messages" boxes on pages 38, 44, 48, 54, 60 and 71.

30. The Stern report in the UK[28] and the report of the Australian Business Leaders Roundtable on Climate Change[29] both concluded that climate change is already having significant economic impacts and that these will worsen dramatically if the problem is not controlled. The IPCC estimates that global release of carbon dioxide needs to be reduced by at least 60 per cent to stabilise the atmospheric concentrations and thus stop the enhancement of the natural greenhouse effect. As noted above, in paragraph 15 and footnote 8, the more recent science has caused these targets to be reviewed downward. Both the Garnaut Report and the more recent summary by the Australian Academy of Science demand more urgent action, with the AAS report leading to the conclusion that global emissions must peak before 2020 and then decline rapidly to have a better-than-even chance of avoiding alarming consequences.

HOW WOULD THE MINING, TRANSPORT AND USE OF COAL FROM THE MINE CONTRIBUTE TO GLOBAL WARMING AND CLIMATE CHANGE?

31. The Wandoan Coal Project environmental impact statement and an accompanying technical report on greenhouse gas emissions calculated that the emissions from the mining and use of the coal from the mine would be 1.3 billion tonnes of carbon dioxide equivalents.[30]

32. An initial point to understand in assessing the contribution that these emissions will make to climate change and global warming is that greenhouse gas emissions are additive, i.e. any emissions add to the amount of greenhouse gases already in the atmosphere.[31] While different greenhouse gases persist in the atmosphere for

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[27] Ibid at page 27.
[28] Stern N (2006), *Stern Review on the Economics of Climate Change*, HM Treasury, London, available at http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.
[29] Australian Business Leaders Roundtable on Climate Change (2006), *The Business Case for Early Action*, available at http://www.businessroundtable.com.au/.
[30] Note that "carbon dioxide equivalents" (CO_2-e), is a standard for measuring the effect of different greenhouse gases. One CO_2-e is equal to the amount of greenhouse gas that has the effect of 1 kilogram CO_2 emitted. The emission of 1 kilogram of N_2O equals 310 CO_2-e and the emission of 1 kilogram of CH_4 equals 21 CO_2-e. The major greenhouse gas emitted from the use of coal is CO_2 itself, which is equal to CO_2-e by definition but the standard term is used here because mining coal also releases other greenhouse gases, especially methane.
[31] In the past 200 years, more than 2.3 trillion tons of CO_2 have been released into the atmosphere due to human activities relating to fossil fuel consumption and land-use changes: Baumert KA, Herzog T,

different lengths of time, CO_2 affects the atmosphere for very long periods. While it has been accepted that significant amounts will still be affecting the atmosphere after 200 years, the most recent science finds that as much as 35 per cent could still be affecting the atmosphere for thousands of years.[32] As a consequence of this, we have to accept that CO_2 emitted into the atmosphere from the mine could influence the atmospheric concentrations of CO_2 for centuries or even longer. It is not possible to link these emissions to any particular impact on a specific part of the environment in Queensland, Australia or globally, other than to contribute to greenhouse gases in the atmosphere and thereby contribute to global warming and climate change. The impacts of greenhouse gas emissions from this mine should, therefore, be understood as contributing to the cumulative impacts of global warming and climate change.

33. In assessing the contribution of the emissions from the proposed mine, it is important to understand that geological structures now trap the carbon contained in the coal, so that the carbon is completely isolated from the atmosphere and will not contribute to global warming or climate change in its current form. It would, therefore, be wrong to say that "the mining of this coal will not make any difference to global warming because if this mine does not proceed the coal will just come from another mine somewhere in the World". It is true that there is a large amount of coal in the World and that the coal could be supplied from another mine.[33] However, that reasoning ignores the fact that coal is a finite resource, so the mining and use of the coal from this mine will release to the atmosphere fossil carbon that would otherwise be trapped in the ground. Such reasoning also ignores the growing recognition that reasonable and practicable measures should be required to avoid, reduce or offset the greenhouse gas emissions from all human activities, including the proposed mine. Global warming and climate change are massive problems for society that, ultimately, need to be addressed through action at the level of individual projects such as this proposed mine.

34. As the emissions of greenhouse gases from the mine will add to the amount of greenhouse gases already in the atmosphere, they need to be considered in the context of national and global emissions. The most recent available data on Australia's national direct greenhouse gas emissions are set out by the Commonwealth Department of Climate Change and Energy Efficiency in the

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and Pershing J (2005), *Navigating the Numbers: Greenhouse Gas Data and International Climate Policy*, World Resources Institute, available at http://www.wri.org/climate/pubs_description.cfm?pid=4093, p 4.

[32] Archer D (2005), "Fate of Fossil Fuel in Geologic Time" 110 Journal of Geophysical Research C09S05, doi: 10.1029/2004/2004JC002625; Archer D and Brovkin V (2008), "The millennial atmospheric lifetime of anthropogenic CO2" Climatic Change 90:283-297 DOI 10.1007/s10584-008-9413-1; Solomon et al (2009), "Irreversible climate change due to carbon dioxide emissions" PNAS 116 (6) 1704-1709, doi: 10.1073/pnas.0812721106: Archer D, et al, Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, Ann.Rev.Earth & Planetary Sciences 37, 117134 (2009), doi: 10.1146/annurev.earth.031208.100206.

[33] Globally, coal reserves are significantly larger than other fuels. At current prices and consumption rates, present reserves of coal will not be depleted until the year 2168. Total global coal consumption, production, and reserves in 2004 are 2,778, 2,732, and 448,464 million tons of oil equivalent, respectively: Baumert, Herzog, and Pershing, n 31, pp 43 and 44.

National Greenhouse Gas Inventory.[34] The *National Greenhouse Gas Inventory* reports Australia's direct greenhouse gas emissions in 2009 as follows:

Sector	**Emissions ($Mt\ CO_2$-e)**
Energy	417.4
Fuel Combustion	377.7
Fugitive Emissions	39.7
Industrial Processes	29.6
Agriculture	84.7
Land Use, Land Use Change and Forestry	18.7
Waste	14.1
Australia's Net Emissions	564.5

35. Global greenhouse gas emissions in 2000 (excluding emissions from land use, land use change and forestry) were estimated to have been about 34 Gigatonnes of CO_2 equivalents (Gt CO_2-e), but the IPCC Fourth Assessment Report gave the 2004 figure as 49 Gt, so the current figure is likely to be even higher still.[35]

36. To put the potential release of CO_2 from the proposed mine extension into context:

    (a) the annual average emissions from the proposed mine (41.7 million tonnes) extension would be about 7.4 per cent of the national figure for a year or about 0.085 per cent of the current annual global release of greenhouse gases.

    (b) The average annual emissions from the proposed mine would be greater than the annual emissions of New Zealand (approximately 32.6 million tonnes in 2007) and, at peak production, greater than the annual emissions of Ireland (approximately 44.3 million tonnes in 2007).[36]

    (c) the lifetime emissions from the proposed mine would be equivalent to 2 years and 4 months of national emissions, or about 2.7 per cent of the current annual global release of greenhouse gases.

37. The IPCC data show that about 40 per cent of the carbon from fossil fuels released each year comes from coal, about 40 per cent from oil and about 20 per cent from gas. Since some of the oil is used to transport coal, the IPCC figure of about

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[34] National Greenhouse Gas Inventory – Kyoto Protocol Accounting Framework at www.ageis.greenhouse.gov.au/.

[35] World Resources Institute, Climate Analysis Indicators Tool (CAIT) Version 4.0. http://www.wri.org/climate/. 1 Gt equals 1,000 Mt.

[36] United Nations Statistics Division, Millennium Development Goals indicators: Carbon dioxide emissions (CO2), thousand metric tonnes of CO2 (collected by CDIAC) available at http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=749&crid=.

10,000 Mt, or 10 Gt, of CO_2 released each year from the burning of coal should be seen as a conservative estimate that does not include the associated transport emissions. Because coal contains more carbon and less hydrogen than oil or gas, it produces proportionately more CO_2 per unit energy. In round figures, gas produces about 60 per cent of the CO_2 per unit energy of coal, while petroleum fuels produce about 80 per cent. Burning coal to generate electricity is extremely inefficient, so that coal-fired electricity releases about five times as much CO_2 per unit energy as directly burning gas.

38. The global problem of climate change stems from compounding of all the local decisions to burn fossil fuels and release carbon dioxide. Australia, like other OECD countries, agreed at the Kyoto conference to curb our greenhouse gas emissions. The consensus at Kyoto was that the global problem requires a global solution, to which all countries must contribute. Apart from the USA and China, every country accounts for a small fraction of the global greenhouse pollution, but all will have to play a role in reducing the burden on the atmosphere. The more recent Copenhagen Accord, negotiated at COP15 in 2009, and the 2010 Cancun Agreement are directed toward a legally binding global agreement to curb greenhouse gas emissions.

39. The Stern report in the UK and the report of the Australian Business Leaders Roundtable on Climate Change both concluded that the most effective way to slow down the release of greenhouse gases is to build a clear price signal into our economic system. The present political debate about a proposal to introduce a very modest carbon tax shows how difficult this will be to implement. So the most obvious solution is to apply stringent conditions to any large project that would release significant amounts of carbon dioxide or methane, making the project greenhouse-neutral. Even then, since the basic purpose of mining steaming coal is to allow it to be burned and therefore release carbon dioxide in vast quantities, a responsible approach would be defer any such proposal until there exists a proven technology for capturing and storing the resulting emissions.

CLEAN COAL AND GEO-SEQUESTRATION

40. There is a strong emphasis at the present time in the Australian and Queensland Governments and the coal industry on "clean coal" and geo-sequestration (basically, capturing and pumping greenhouse gas emissions underground rather than emitting them to the atmosphere).[37] The Xstrata group of companies, of which the main proponent of the mine is part, is the world's largest exporter of thermal coal. In 2004, it noted on its website that:[38]

> Xstrata Coal recognises that coal is also a carbon liability and that climate change is a real international and community issue. Furthermore, the company believes that emission reductions resulting from the use of coal are required and achievable within a sustainable development framework.

[37] See generally, Metz, B., O.Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds) (2005) *IPCC special report on Carbon Dioxide Capture and Storage*, prepared by working group III of the IPCC, Cambridge University Press, Cambridge. Available at www.ipcc.ch.
[38] http://www.xstrata.com/reports/doc/x_hsec_climate_change_2004.pdf.

Through its approach to climate change, Xstrata Coal:

- acknowledges that any action taken to address climate change has a delay, so planning for the future is needed now;
- is committed to playing a part in identifying and implementing solutions to the challenge of climate change;
- recognises that the future will be a "carbon-constrained world";
- is working together with governments, researchers and industry in Australia through the COAL21 programme to develop a portfolio of options for reducing greenhouse gas emissions from the use of coal in electricity generation;
- collaborates in research and development programmes and provides both technical and financial support to dedicated Cooperative Research Centres focused on near zero emission technologies;
- supports additional research into CO_2 capture and storage;
- assesses its products for utilisation in new, near-zero emission future technologies, such as gasification;
- has developed a close working relationship with the power generation industry to help expand the implementation of higher efficiency, low emission power plants;
- strives continually for the more efficient use of energy and reduction of greenhouse gas emissions at its operations;
- looks to collaborate with its customers, both domestic and international, towards the sustainable use of coal through new power generation technologies;
- seeks to enter into joint ventures with power generation companies in capturing and using methane to generate electricity, thereby preventing further greenhouse gas emissions from its operations; and
- monitors and explores opportunities for the use of emission reduction mechanisms proposed in the Kyoto Protocol.

Xstrata Coal plans to spend in excess of US$9 million over the next five years on research into clean coal technology, methane utilisation, and carbon sequestration.

41. More recently, Xstrata Coal put the following comment on its web site:[39]

> The projected growth in demand for fossil fuels underpins Xstrata's strategy to continue to grow our thermal coal business. However, it also highlights the urgent need to find ways to reduce the CO2 emissions that result from using coal as an energy source.
>
> Xstrata mines about 1.5% of the world's annual thermal coal production, and is the largest exporter of the fuel. There are three main sources of greenhouse gas emissions associated with our coal products. The most significant is the use of coal as an energy source by our customers. Greenhouse gas emissions are also generated from the extraction and production of coal. A third source of greenhouse gas emissions is the transportation of coal to our customers.
>
> In 2009, combustion of the coal we produced by our customers accounted for approximately 227 million tonnes of CO2e, or approximately 10 times the Scope 1 and Scope 2 emissions generated by our operations. The transportation of coal from our ports to our customers accounted for approximately 11.6 million tonnes of CO2e.

42. There are many ways in which the use of coal can be made more efficient, thereby reducing overall emissions, but the potential for commercial, industrial-scale CO_2

[39] http://www.xstrata.com/sustainability/environment/climatechange/reducingemissionsfromcoal/

storage underground (carbon or geo-sequestration) is currently a matter of speculation. While CO_2 has been injected into declining oil fields for more than 30 years to increase oil recovery and the technology for capturing of CO_2 is already commercially available for large CO_2 emitters, such as power stations, storage of CO_2, is a relatively untried concept. At this time, no power station anywhere in the world operates with a full carbon capture and storage system.

43. The research that is currently being conducted on geo-sequestration is not expected to produce viable, commercial applications for at least 15 years. Even on the most optimistic view, there would then be major economic and practical issues of retro-fitting existing power stations and other coal burning facilities to capture CO_2 emissions and pump them underground. The potential for geo-sequestration also depends upon locating suitable geological formations into which the gas or liquid form of the emissions can be injected with complete confidence that the carbon would not escape. This is certainly problematic, and very probably costly.

44. Based on currently available technology it can be assumed that none of the CO_2 emissions from the use of the coal from this mine will be captured and stored underground. Consequently, it should be assumed for the purposes of assessing the potential impacts of the mine that all of the greenhouse gas emissions from the mining, transport and use of the coal will be emitted to the atmosphere and contribute to global warming and climate change.

ALTERNATIVES

45. It is sometimes asserted that there is no realistic alternative to fossil fuels for electricity generation. A 1992 report by the national energy research body[40] found we could get all our electricity from a mix of renewables by 2030, with storage to allow for periods of little wind and no sunlight. More recently, the 2010 report by Beyond Zero Emissions and the Institute of Energy at the University of Melbourne[41] showed that we could move to supply Australia’s power needs completely from a mix of renewables by 2020: roughly 50 per cent wind power, 40 per cent solar with storage and 10 per cent hydroelectricity. The 1992 report concluded, on the basis of the technology available nearly twenty years ago, that moving completely to renewables would increase power prices by about 50 per cent. The BZE report found that the overall cost of providing electricity from now to 2050 would not be significantly more if Australia adopted their approach, because the extra capital investment in the next ten to twenty years would be offset by the dramatic reduction in replacement of fossil-fuel capacity and the total elimination of fuel costs. Adopting this approach would require a significant investment in the next decade or two, but it is a practical scheme for meeting our needs without releasing carbon dioxide into the atmosphere by burning fossil fuels.

[40] M.Stevens, Renewable Electricity for Australia, NERDDC Discussion Paper no. 2, Department of Resources and Energy, Canberra 1992

[41] Beyond Zero Emissions, Zero Carbon Australia, BZE/University of Melbourne 2010

SUMMARY OF CONCLUSIONS

46. The burning of fossil fuels – coal, oil and gas – has dramatically increased the amount of carbon dioxide in the air and strengthened the natural “greenhouse effect”.

47. The average temperature of Australia has increased by about 0.9 degrees in the last hundred years, more than the global average.

48. The Australian Academy of Science recently concluded that global emissions need to peak before 2020 and then decline rapidly to give a better-than-even chance of keeping the further increase in average temperatures to 1 degree. Present trends of increasing fossil fuel use could see average temperatures rise by as much as five degrees this century.

49. The climate changes of the last hundred years are already imposing serious economic, social and environmental costs on Australia and the rest of the world.

50. This project, if approved, would add about 1.3 billion tonnes of CO2 equivalent to the atmosphere. Its annual emissions would be greater than the total figure for New Zealand and about 7.4 per cent of Australia’s national total.

51. Based on currently available technology, it must be assumed that none of the carbon dioxide emissions would be captured and stored; all of that carbon dioxide would affect the global atmosphere for centuries.

52. There are realistic alternatives to the burning of increasing quantities of coal.

DECLARATION

53. In accordance with rule 428 of the *Uniform Civil Procedure Rules* 1999 (Qld), I confirm that:

(a) the factual matters stated in this report are, as far as I know, true; and

(b) I have made all enquiries considered appropriate; and

(c) there are no readily ascertainable additional facts that would assist me in reaching more reliable conclusions; and

(d) the opinions stated in this report are genuinely held by me; and

(e) this report contains reference to all matters I consider significant; and

(f) I understand that my duty is to assist the Court and that it overrides any obligation I may have to any party to the proceeding or to any person who is liable for my fees or expenses; and

(g) I have complied with my duty to assist the Court.

Signed:

Professor Ian Lowe

Date: **...........5 August 2011.......................**

Address: **5/2 Tamarindus Street, Marcoola 4564**

APPENDIX 1

BRIEF BIOGRAPHY: PROFESSOR IAN LOWE AO FTSE FQA

Professor Ian Lowe is an emeritus professor at Griffith University, where he was previously Head of the School of Science. He holds a Bachelor of Science with Honours in physics from the University of New South Wales, a D.Phil. from the University of York (UK) and was recently awarded a D.Univ. by Griffith University.

Professor Lowe is an internationally recognised expert on environmental issues, energy, science, technology and futures. He has held senior advisory roles for all three levels of government and consulted extensively for companies and peak organisations in the private sector. He is President of the Australian Conservation Foundation and a Fellow of the Australian Academy of Technological Sciences and Engineering.

Professor Lowe was made an Officer of the Order of Australia in 2001 for services to science and technology, especially in the area of environmental studies. In 2002, he was awarded a Centenary Medal for contributions to environmental science and won the Eureka Prize for promotion of science. He has also received the Prime Minister's Environment Award for Outstanding Individual Achievement and the Queensland Premier's Millennium Award for Excellence in Science. Professor Lowe is a member of the Environmental Health Council, the Radiation Health and Safety Advisory Council and the National Enabling Technologies Stakeholder Advisory Council. He is a past member of many senior advisory bodies, including the National Commission for UNESCO. He chaired the Queensland Government task force implementing the reform of science education and the Brisbane City Council task force on climate change and energy. He is deputy chair of the Queensland Sustainable Energy Innovation Group, which advises the state government on energy innovations, and a member of the Queensland Premier's Climate Change Council. He chaired the advisory council that produced in 1996 the first national report on the state of the environment. He was a member of the National Energy Research, Development and Demonstration Council from 1983 to 1989, chairing its standing committee on economic, social and environmental issues, and directed the Commission for the Future in 1988.

Professor Lowe has been a referee for the Inter-governmental Panel on Climate Change, the scientific body set up by the United Nations to advise on climate change. He attended the Geneva, Kyoto and Copenhagen conferences of the parties to the Framework Convention on Climate Change, and was a member of the Australian delegation to the 1999 UNESCO World Conference on Science. He was on the steering group for the UNEP project Global Environmental Outlook and an invited participant in the 2000 and 2003 workshops on Sustainability Science. He acted as a referee for both the International Geosphere-Biosphere Program's 2004 report, "Global Change and the Earth System", and the UN's Millennium Assessment Report, released in 2005.

Professor Lowe has made countless contributions to newspapers, radio, television and periodicals and gave the ABC's Boyer lectures in 1991.

APPENDIX 2 – IPCC SYNTHESIS REPORT

Extracted from: IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp

[this extract does not includes only the main body of the Synthesis Report and excludes the glossary and index].

Synthesis Report

An Assessment of the Intergovernmental Panel on Climate Change

This underlying report, adopted section by section at IPCC Plenary XXVII (Valencia, Spain, 12-17 November 2007), represents the formally agreed statement of the IPCC concerning key findings and uncertainties contained in the Working Group contributions to the Fourth Assessment Report.

Based on a draft prepared by:

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Lenny Bernstein, Peter Bosch, Osvaldo Canziani, Zhenlin Chen, Renate Christ, Ogunlade Davidson, William Hare, Saleemul Huq, David Karoly, Vladimir Kattsov, Zbigniew Kundzewicz, Jian Liu, Ulrike Lohmann, Martin Manning, Taroh Matsuno, Bettina Menne, Bert Metz, Monirul Mirza, Neville Nicholls, Leonard Nurse, Rajendra Pachauri, Jean Palutikof, Martin Parry, Dahe Qin, Nijavalli Ravindranath, Andy Reisinger, Jiawen Ren, Keywan Riahi, Cynthia Rosenzweig, Matilde Rusticucci, Stephen Schneider, Youba Sokona, Susan Solomon, Peter Stott, Ronald Stouffer, Taishi Sugiyama, Rob Swart, Dennis Tirpak, Coleen Vogel, Gary Yohe

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Introduction

Introduction

This Synthesis Report is based on the assessment carried out by the three Working Groups (WGs) of the Intergovernmental Panel on Climate Change (IPCC). It provides an integrated view of climate change as the final part of the IPCC's Fourth Assessment Report (AR4).

Topic 1 summarises observed changes in climate and their effects on natural and human systems, regardless of their causes, while Topic 2 assesses the causes of the observed changes. Topic 3 presents projections of future climate change and related impacts under different scenarios.

Topic 4 discusses adaptation and mitigation options over the next few decades and their interactions with sustainable development. Topic 5 assesses the relationship between adaptation and mitigation on a more conceptual basis and takes a longer-term perspective. Topic 6 summarises the major robust findings and remaining key uncertainties in this assessment.

A schematic framework representing anthropogenic drivers, impacts of and responses to climate change, and their linkages, is shown in Figure I.1. At the time of the Third Assessment Report (TAR) in 2001, information was mainly available to describe the linkages clockwise, i.e. to derive climatic changes and impacts from socio-economic information and emissions. With increased understanding of these linkages, it is now possible to assess the linkages also counterclockwise, i.e. to evaluate possible development pathways and global emissions constraints that would reduce the risk of future impacts that society may wish to avoid.

Schematic framework of anthropogenic climate change drivers, impacts and responses

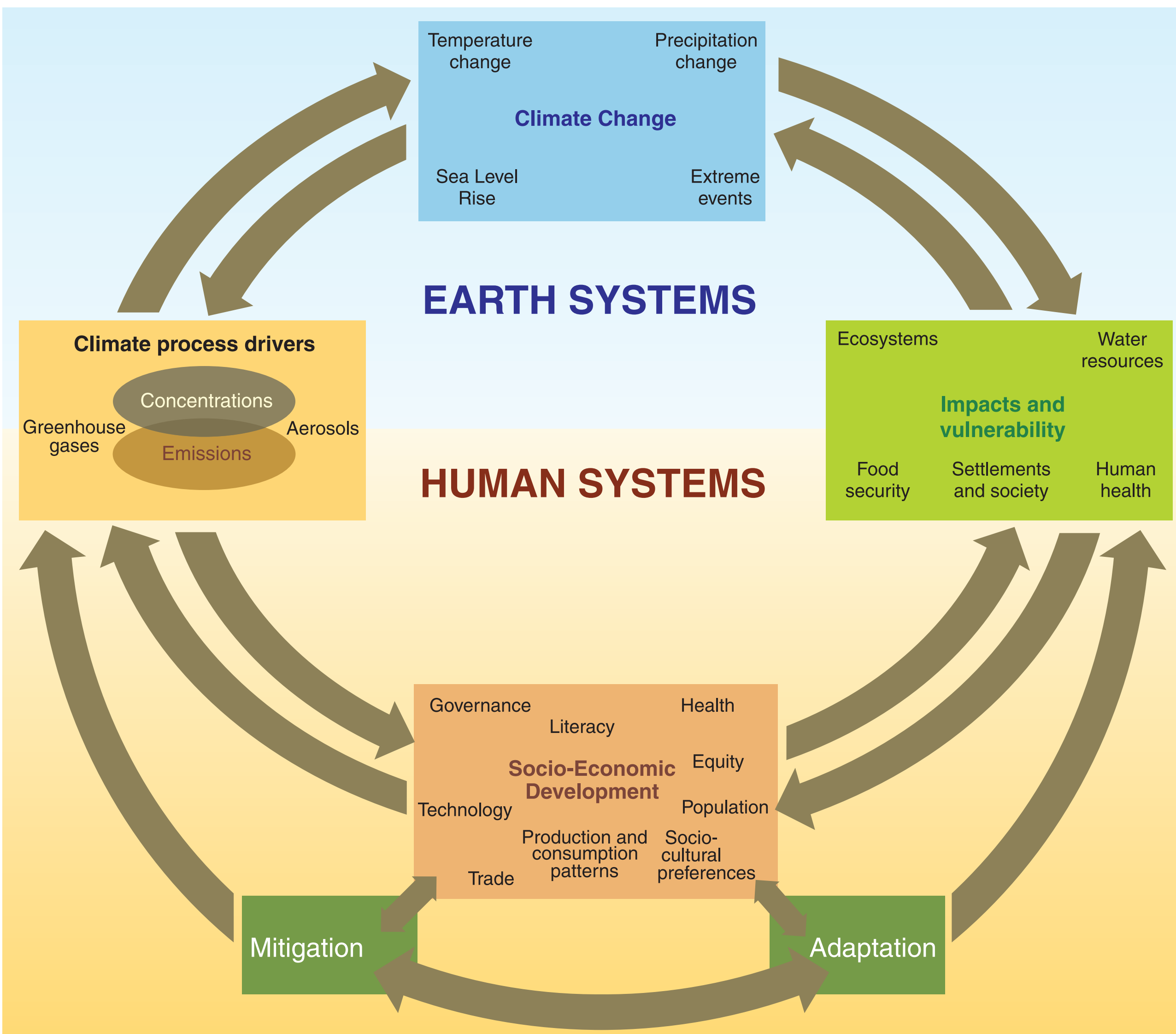

Figure I.1. *Schematic framework representing anthropogenic drivers, impacts of and responses to climate change, and their linkages.*

Treatment of uncertainty

The IPCC uncertainty guidance note[1] defines a framework for the treatment of uncertainties across all WGs and in this Synthesis Report. This framework is broad because the WGs assess material from different disciplines and cover a diversity of approaches to the treatment of uncertainty drawn from the literature. The nature of data, indicators and analyses used in the natural sciences is generally different from that used in assessing technology development or the social sciences. WG I focuses on the former, WG III on the latter, and WG II covers aspects of both.

Three different approaches are used to describe uncertainties each with a distinct form of language. Choices among and within these three approaches depend on both the nature of the information available and the authors' expert judgment of the correctness and completeness of current scientific understanding.

Where uncertainty is assessed qualitatively, it is characterised by providing a relative sense of the amount and quality of evidence (that is, information from theory, observations or models indicating whether a belief or proposition is true or valid) and the degree of agreement (that is, the level of concurrence in the literature on a particular finding). This approach is used by WG III through a series of self-explanatory terms such as: *high agreement, much evidence; high agreement, medium evidence; medium agreement, medium evidence; etc*.

Where uncertainty is assessed more quantitatively using expert judgement of the correctness of underlying data, models or analyses, then the following scale of confidence levels is used to express the assessed chance of a finding being correct: v*ery high confidence* at least 9 out of 10; *high confidence* about 8 out of 10; *medium confidence* about 5 out of 10; *low confidence* about 2 out of 10; and *very low confidence* less than 1 out of 10.

Where uncertainty in specific outcomes is assessed using expert judgment and statistical analysis of a body of evidence (e.g. observations or model results), then the following likelihood ranges are used to express the assessed probability of occurrence: *virtually certain* >99%; *extremely likely* >95%; *very likely* >90%; *likely* >66%; *more likely than not* > 50%; *about as likely as not* 33% to 66%; *unlikely* <33%; *very unlikely* <10%; *extremely unlikely* <5%; *exceptionally unlikely* <1%.

WG II has used a combination of confidence and likelihood assessments and WG I has predominantly used likelihood assessments.

This Synthesis Report follows the uncertainty assessment of the underlying WGs. Where synthesised findings are based on information from more than one WG, the description of uncertainty used is consistent with that for the components drawn from the respective WG reports.

Unless otherwise stated, numerical ranges given in square brackets in this report indicate 90% uncertainty intervals (i.e. there is an estimated 5% likelihood that the value could be above the range given in square brackets and 5% likelihood that the value could be below that range). Uncertainty intervals are not necessarily symmetric around the best estimate.

[1] See http://www.ipcc.ch/meetings/ar4-workshops-express-meetings/uncertainty-guidance-note.pdf

1

Observed changes in climate and their effects

1.1 Observations of climate change

Since the TAR, progress in understanding how climate is changing in space and time has been gained through improvements and extensions of numerous datasets and data analyses, broader geographical coverage, better understanding of uncertainties and a wider variety of measurements. *{WGI SPM}*

Definitions of climate change

Climate change in IPCC usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level (Figure 1.1). ***{WGI 3.2, 4.8, 5.2, 5.5, SPM}***

Eleven of the last twelve years (1995-2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850). The 100-year linear trend (1906-2005) of 0.74 [0.56 to 0.92]°C is larger than the corresponding trend of 0.6 [0.4 to 0.8]°C (1901-2000) given in the TAR (Figure 1.1). The linear warming trend over the 50 years from 1956 to 2005 (0.13 [0.10 to 0.16]°C per decade) is nearly twice that for the 100 years from 1906 to 2005. *{WGI 3.2, SPM}*

The temperature increase is widespread over the globe and is greater at higher northern latitudes (Figure 1.2). Average Arctic temperatures have increased at almost twice the global average rate in the past 100 years. Land regions have warmed faster than the oceans (Figures 1.2 and 2.5). Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000m and that the ocean has been taking up over 80% of the heat being added to the climate system. New analyses of balloon-borne and satellite measurements of lower- and mid-tropospheric temperature show warming rates similar to those observed in surface temperature. *{WGI 3.2, 3.4, 5.2, SPM}*

Increases in sea level are consistent with warming (Figure 1.1). Global average sea level rose at an average rate of 1.8 [1.3 to 2.3]mm per year over 1961 to 2003 and at an average rate of about 3.1 [2.4 to 3.8]mm per year from 1993 to 2003. Whether this faster rate for 1993 to 2003 reflects decadal variation or an increase in the longer-term trend is unclear. Since 1993 thermal expansion of the oceans has contributed about 57% of the sum of the estimated individual contributions to the sea level rise, with decreases in glaciers and ice caps contributing about 28% and losses from the polar ice sheets contributing the remainder. From 1993 to 2003 the sum of these climate contributions is consistent within uncertainties with the total sea level rise that is directly observed. *{WGI 4.6, 4.8, 5.5, SPM, Table SPM.1}*

Observed decreases in snow and ice extent are also consistent with warming (Figure 1.1). Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7 [2.1 to 3.3]% per decade, with larger decreases in summer of 7.4 [5.0 to 9.8]% per decade. Mountain glaciers and snow cover on average have declined in both hemispheres. The maximum areal extent of seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with decreases in spring of up to 15%. Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic by up to 3°C. *{WGI 3.2, 4.5, 4.6, 4.7, 4.8, 5.5, SPM}*

At continental, regional and ocean basin scales, numerous long-term changes in other aspects of climate have also been observed. Trends from 1900 to 2005 have been observed in precipitation amount in many large regions. Over this period, precipitation increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia whereas precipitation declined in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Globally, the area affected by drought has *likely*[2] increased since the 1970s. *{WGI 3.3, 3.9, SPM}*

Some extreme weather events have changed in frequency and/or intensity over the last 50 years:

- It is *very likely* that cold days, cold nights and frosts have become less frequent over most land areas, while hot days and hot nights have become more frequent. *{WGI 3.8, SPM}*
- It is *likely* that heat waves have become more frequent over most land areas. *{WGI 3.8, SPM}*
- It is *likely* that the frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas. *{WGI 3.8, 3.9, SPM}*
- It is *likely* that the incidence of extreme high sea level[3] has increased at a broad range of sites worldwide since 1975. *{WGI 5.5, SPM}*

There is observational evidence of an increase in intense tropical cyclone activity in the North Atlantic since about 1970, and suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. *{WGI 3.8, SPM}*

Average Northern Hemisphere temperatures during the second half of the 20th century were *very likely* higher than during any other 50-year period in the last 500 years and *likely* the highest in at least the past 1300 years. *{WGI 6.6, SPM}*

[2] Likelihood and confidence statements in italics represent calibrated expressions of uncertainty and confidence. See Box 'Treatment of uncertainty' in the Introduction for an explanation of these terms.

[3] Excluding tsunamis, which are not due to climate change. Extreme high sea level depends on average sea level and on regional weather systems. It is defined here as the highest 1% of hourly values of observed sea level at a station for a given reference period.

Changes in temperature, sea level and Northern Hemisphere snow cover

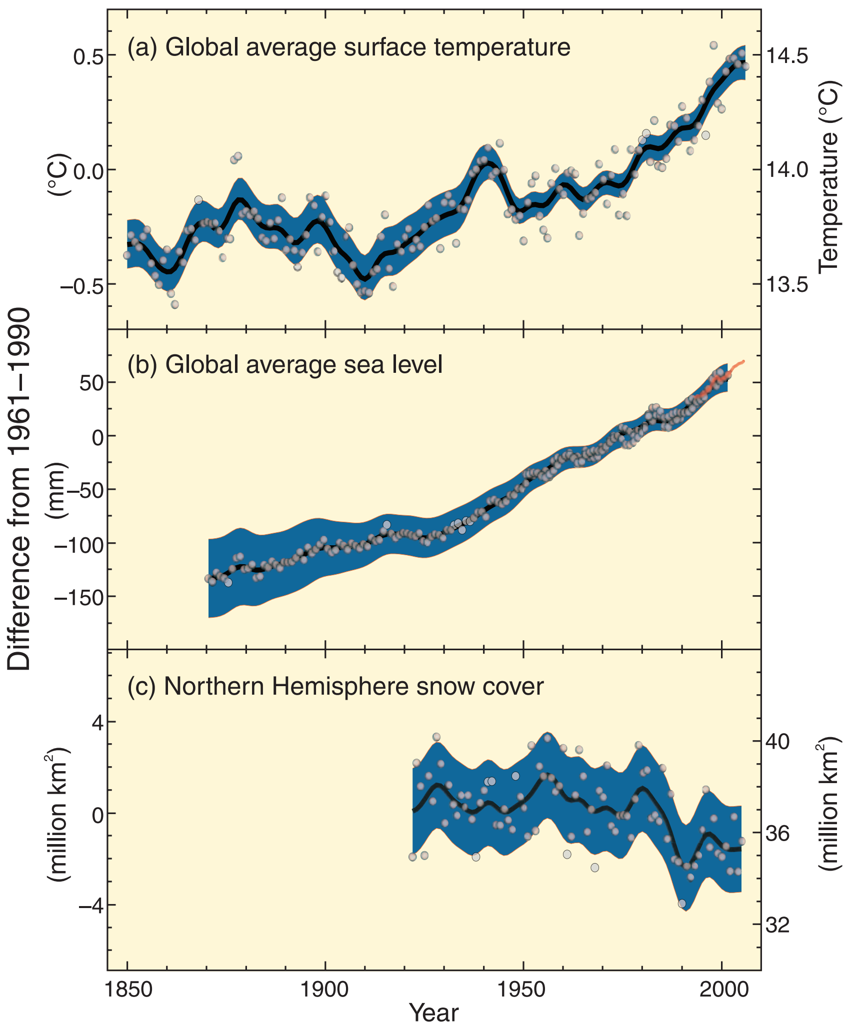

__Figure 1.1.__ Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data; and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). {WGI FAQ 3.1 Figure 1, Figure 4.2, Figure 5.13, Figure SPM.3}

1.2 Observed effects of climate changes

The statements presented here are based largely on data sets that cover the period since 1970. The number of studies of observed trends in the physical and biological environment and their relationship to regional climate changes has increased greatly since the TAR. The quality of the data sets has also improved. There is a notable lack of geographic balance in data and literature on observed changes, with marked scarcity in developing countries. *{WGII SPM}*

These studies have allowed a broader and more confident assessment of the relationship between observed warming and impacts than was made in the TAR. That assessment concluded that "there is *high confidence*[2] that recent regional changes in temperature have had discernible impacts on physical and biological systems". *{WGII SPM}*

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. ***{WGII SPM}***

There is *high confidence* that natural systems related to snow, ice and frozen ground (including permafrost) are affected. Examples are:

- enlargement and increased numbers of glacial lakes *{WGII 1.3, SPM}*
- increasing ground instability in permafrost regions and rock avalanches in mountain regions *{WGII 1.3, SPM}*
- changes in some Arctic and Antarctic ecosystems, including those in sea-ice biomes, and predators at high levels of the food web. *{WGII 1.3, 4.4, 15.4, SPM}*

Based on growing evidence, there is *high confidence* that the following effects on hydrological systems are occurring: increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers, and warming of lakes and rivers in many regions, with effects on thermal structure and water quality. *{WGII 1.3, 15.2, SPM}*

Changes in physical and biological systems and surface temperature 1970-2004

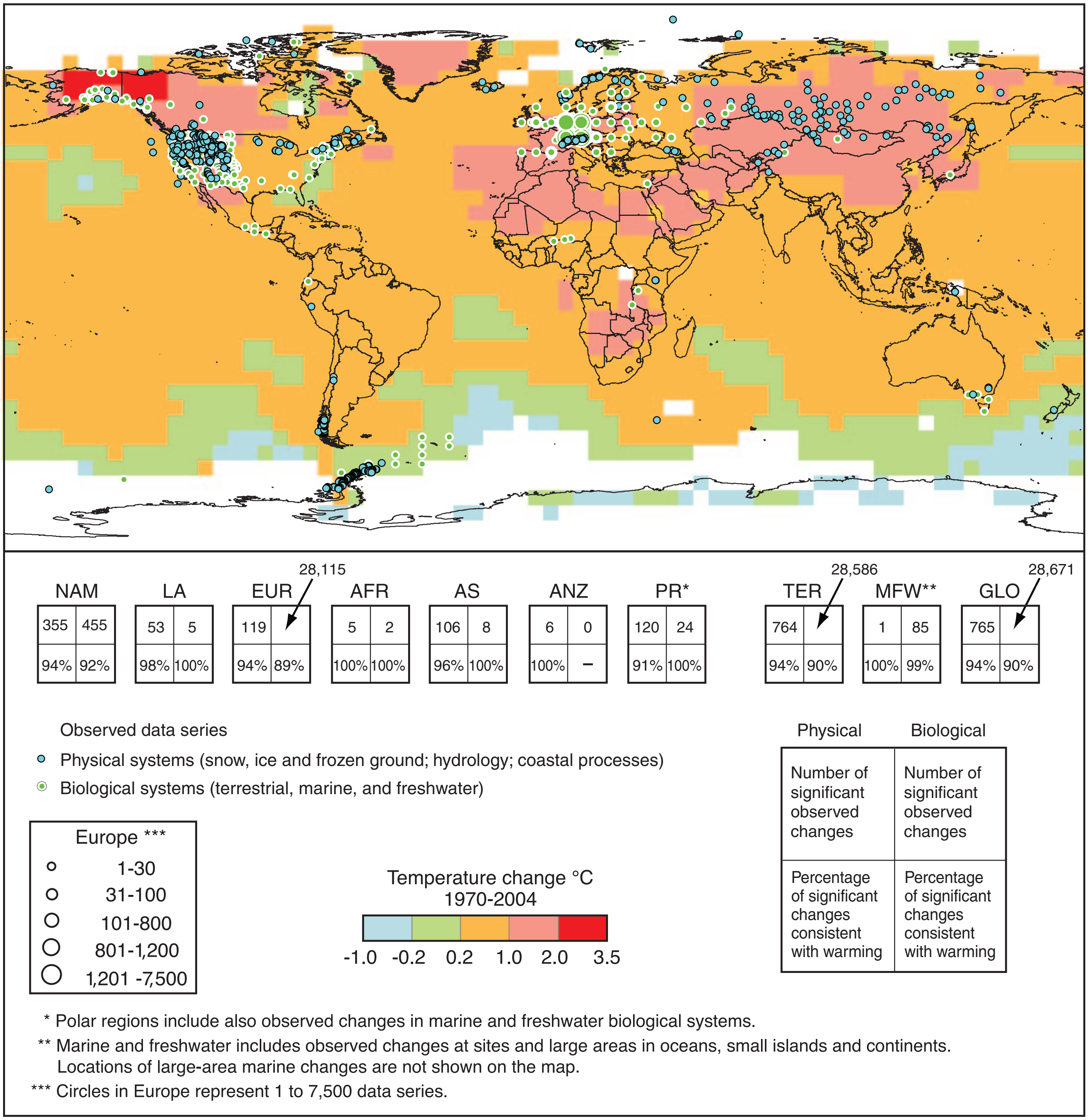

Figure 1.2. *Locations of significant changes in data series of physical systems (snow, ice and frozen ground; hydrology; and coastal processes) and biological systems (terrestrial, marine, and freshwater biological systems), are shown together with surface air temperature changes over the period 1970-2004. A subset of about 29,000 data series was selected from about 80,000 data series from 577 studies. These met the following criteria: (1) ending in 1990 or later; (2) spanning a period of at least 20 years; and (3) showing a significant change in either direction, as assessed in individual studies. These data series are from about 75 studies (of which about 70 are new since the TAR) and contain about 29,000 data series, of which about 28,000 are from European studies. White areas do not contain sufficient observational climate data to estimate a temperature trend. The 2 x 2 boxes show the total number of data series with significant changes (top row) and the percentage of those consistent with warming (bottom row) for (i) continental regions: North America (NAM), Latin America (LA), Europe (EUR), Africa (AFR), Asia (AS), Australia and New Zealand (ANZ), and Polar Regions (PR) and (ii) global-scale: Terrestrial (TER), Marine and Freshwater (MFW), and Global (GLO). The numbers of studies from the seven regional boxes (NAM, …, PR) do not add up to the global (GLO) totals because numbers from regions except Polar do not include the numbers related to Marine and Freshwater (MFW) systems. Locations of large-area marine changes are not shown on the map. {WGII Figure SPM.1, Figure 1.8, Figure 1.9; WGI Figure 3.9b}*

There is *very high confidence*, based on more evidence from a wider range of species, that recent warming is strongly affecting terrestrial biological systems**,** including such changes as earlier timing of spring events, such as leaf-unfolding, bird migration and egg-laying; and poleward and upward shifts in ranges in plant and animal species. Based on satellite observations since the early 1980s, there is *high confidence* that there has been a trend in many regions towards earlier 'greening' of vegetation in the spring linked to longer thermal growing seasons due to recent warming. *{WGII 1.3, 8.2, 14.2, SPM}*

There is *high confidence*, based on substantial new evidence, that observed changes in marine and freshwater biological systems are associated with rising water temperatures, as well as related changes in ice cover, salinity, oxygen levels and circulation. These include: shifts in ranges and changes in algal, plankton and fish abundance in high-latitude oceans; increases in algal and zooplankton abundance in high-latitude and high-altitude lakes; and range changes and earlier fish migrations in rivers. While there is increasing evidence of climate change impacts on coral reefs, separating the impacts of climate-related stresses from other stresses (e.g. overfishing and pollution) is difficult. *{WGII 1.3, SPM}*

Other effects of regional climate changes on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers. ***{WGII SPM}***

Effects of temperature increases have been documented with *medium confidence* in the following managed and human systems:

- agricultural and forestry management at Northern Hemisphere higher latitudes, such as earlier spring planting of crops, and alterations in disturbances of forests due to fires and pests *{WGII 1.3, SPM}*
- some aspects of human health, such as excess heat-related mortality in Europe, changes in infectious disease vectors in parts of Europe, and earlier onset of and increases in seasonal production of allergenic pollen in Northern Hemisphere high and mid-latitudes *{WGII 1.3, 8.2, 8.ES, SPM}*
- some human activities in the Arctic (e.g. hunting and shorter travel seasons over snow and ice) and in lower-elevation alpine areas (such as limitations in mountain sports). *{WGII 1.3, SPM}*

Sea level rise and human development are together contributing to losses of coastal wetlands and mangroves and increasing damage from coastal flooding in many areas. However, based on the published literature, the impacts have not yet become established trends. *{WGII 1.3, 1.ES, SPM}*

1.3 Consistency of changes in physical and biological systems with warming

Changes in the ocean and on land, including observed decreases in snow cover and Northern Hemisphere sea ice extent, thinner sea ice, shorter freezing seasons of lake and river ice, glacier melt, decreases in permafrost extent, increases in soil temperatures and borehole temperature profiles, and sea level rise, provide additional evidence that the world is warming. *{WGI 3.9}*

Of the more than 29,000 observational data series, from 75 studies, that show significant change in many physical and biological systems, more than 89% are consistent with the direction of change expected as a response to warming (Figure 1.2). *{WGII 1.4, SPM}*

1.4 Some aspects of climate have not been observed to change

Some aspects of climate appear not to have changed and, for some, data inadequacies mean that it cannot be determined if they have changed. Antarctic sea ice extent shows inter-annual variability and localised changes but no statistically significant average multi-decadal trend, consistent with the lack of rise in near-surface atmospheric temperatures averaged across the continent. There is insufficient evidence to determine whether trends exist in some other variables, for example the meridional overturning circulation (MOC) of the global ocean or small-scale phenomena such as tornadoes, hail, lightning and dust storms. There is no clear trend in the annual numbers of tropical cyclones. *{WGI 3.2, 3.8, 4.4, 5.3, SPM}*

2

Causes of change

Causes of change

This Topic considers both natural and anthropogenic drivers of climate change, including the chain from greenhouse gas (GHG) emissions to atmospheric concentrations to radiative forcing[4] to climate responses and effects.

2.1 Emissions of long-lived GHGs

The radiative forcing of the climate system is dominated by the long-lived GHGs, and this section considers those whose emissions are covered by the UNFCCC.

Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 (Figure 2.1).[5] ***{WGIII 1.3, SPM}***

Carbon dioxide (CO_2) is the most important anthropogenic GHG. Its annual emissions have grown between 1970 and 2004 by about 80%, from 21 to 38 gigatonnes (Gt), and represented 77% of total anthropogenic GHG emissions in 2004 (Figure 2.1). The rate of growth of CO_2-eq emissions was much higher during the recent 10-year period of 1995-2004 (0.92 $GtCO_2$-eq per year) than during the previous period of 1970-1994 (0.43 $GtCO_2$-eq per year). *{WGIII 1.3, TS.1, SPM}*

Carbon dioxide-equivalent (CO_2-eq) emissions and concentrations

GHGs differ in their warming influence (radiative forcing) on the global climate system due to their different radiative properties and lifetimes in the atmosphere. These warming influences may be expressed through a common metric based on the radiative forcing of CO_2.

- ***CO_2-equivalent emission*** is the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs. The equivalent CO_2 emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon.[6] For a mix of GHGs it is obtained by summing the equivalent CO_2 emissions of each gas. Equivalent CO_2 emission is a standard and useful metric for comparing emissions of different GHGs but does not imply the same climate change responses (see WGI 2.10).
- ***CO_2-equivalent concentration*** is the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other forcing components.[7]

The largest growth in GHG emissions between 1970 and 2004 has come from energy supply, transport and industry, while residential and commercial buildings, forestry (including deforestation) and agriculture sectors have been growing at a lower rate. The

Global anthropogenic GHG emissions

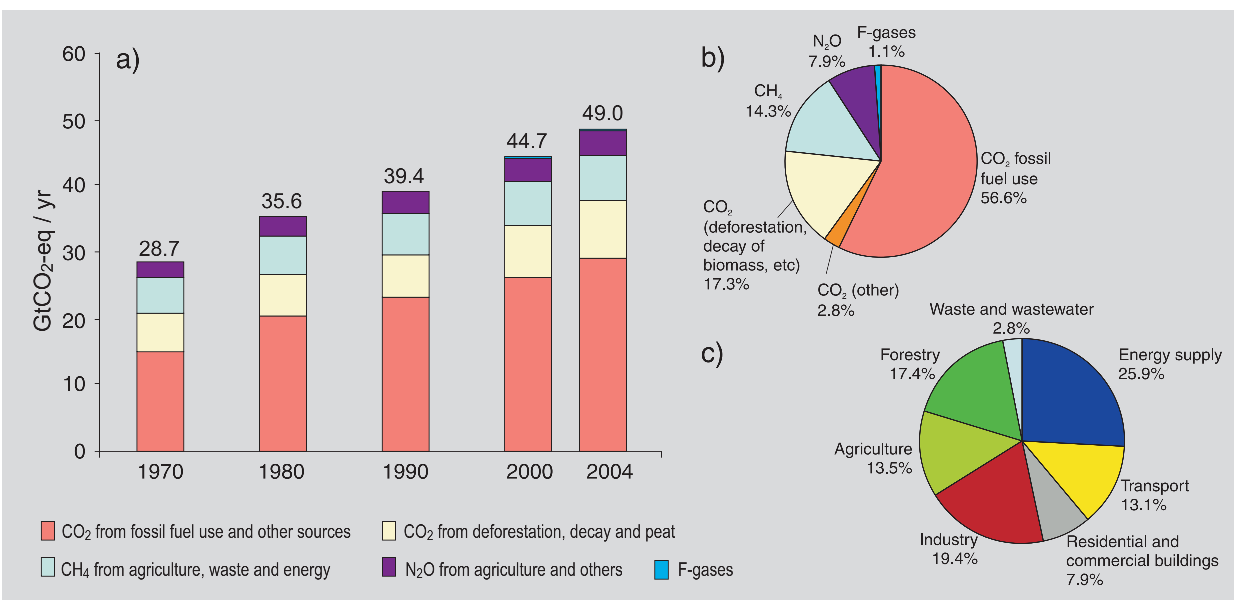

Figure 2.1. *(a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.[5] (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation.) {WGIII Figures TS.1a, TS.1b, TS.2b}*

[4] *Radiative forcing* is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report radiative forcing values are for changes relative to pre-industrial conditions defined at 1750 and are expressed in watts per square metre (W/m^2).

[5] Includes only carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF_6), whose emissions are covered by the UNFCCC. These GHGs are weighted by their 100-year Global Warming Potentials (GWPs), using values consistent with reporting under the UNFCCC.

[6] This report uses 100-year GWPs and numerical values consistent with reporting under the UNFCCC.

[7] Such values may consider only GHGs, or a combination of GHGs and aerosols.

sectoral sources of GHGs in 2004 are considered in Figure 2.1c. *{WGIII 1.3, SPM}*

The effect on global emissions of the decrease in global energy intensity (-33%) during 1970 to 2004 has been smaller than the combined effect of global income growth (77%) and global population growth (69%); both drivers of increasing energy-related CO_2 emissions. The long-term trend of declining CO_2 emissions per unit of energy supplied reversed after 2000. *{WGIII 1.3, Figure SPM.2, SPM}*

Differences in per capita income, per capita emissions and energy intensity among countries remain significant. In 2004, UNFCCC Annex I countries held a 20% share in world population, produced 57% of the world's Gross Domestic Product based on Purchasing Power Parity (GDP_{ppp}) and accounted for 46% of global GHG emissions (Figure 2.2). *{WGIII 1.3, SPM}*

2.2 Drivers of climate change

Changes in the atmospheric concentrations of GHGs and aerosols, land cover and solar radiation alter the energy balance of the climate system and are drivers of climate change. They affect the absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface. The resulting positive or negative changes in energy balance due to these factors are expressed as radiative forcing[4], which is used to compare warming or cooling influences on global climate. *{WGI TS.2}*

Human activities result in emissions of four long-lived GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O) and halocarbons (a group of gases containing fluorine, chlorine or bromine). Atmospheric concentrations of GHGs increase when emissions are larger than removal processes.

Global atmospheric concentrations of CO_2, CH_4 and N_2O have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (Figure 2.3). The atmospheric concentrations of CO_2 and CH_4 in 2005 exceed by far the natural range over the last 650,000 years. Global increases in CO_2 concentrations are due primarily to fossil fuel use, with land-use change providing another significant but smaller contribution. It is *very likely* that the observed increase in CH_4 concentration is predominantly due to agriculture and fossil fuel use. The increase in N_2O concentration is primarily due to agriculture. *{WGI 2.3, 7.3, SPM}*

The global atmospheric concentration of CO_2 increased from a pre-industrial value of about 280ppm to 379ppm in 2005. The annual CO_2 concentration growth rate was larger during the last 10 years (1995-2005 average: 1.9ppm per year) than it has been since the beginning of continuous direct atmospheric measurements (1960-2005 average: 1.4ppm per year), although there is year-to-year variability in growth rates. *{WGI 2.3, 7.3, SPM; WGIII 1.3}*

The global atmospheric concentration of CH_4 has increased from a pre-industrial value of about 715ppb to 1732ppb in the early 1990s, and was 1774ppb in 2005. Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period. *{WGI 2.3, 7.4, SPM}*

The global atmospheric N_2O concentration increased from a pre-industrial value of about 270ppb to 319ppb in 2005. *{WGI 2.3, 7.4, SPM}*

Many halocarbons (including hydrofluorocarbons) have increased from a near-zero pre-industrial background concentration, primarily due to human activities. *{WGI 2.3, SPM; SROC SPM}*

There is *very high confidence* that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W/m² (Figure 2.4). *{WGI 2.3, 6.5, 2.9, SPM}*

The combined radiative forcing due to increases in CO_2, CH_4 and N_2O is +2.3 [+2.1 to +2.5] W/m², and its rate of increase during

Regional distribution of GHG emissions by population and by GDP_{PPP}

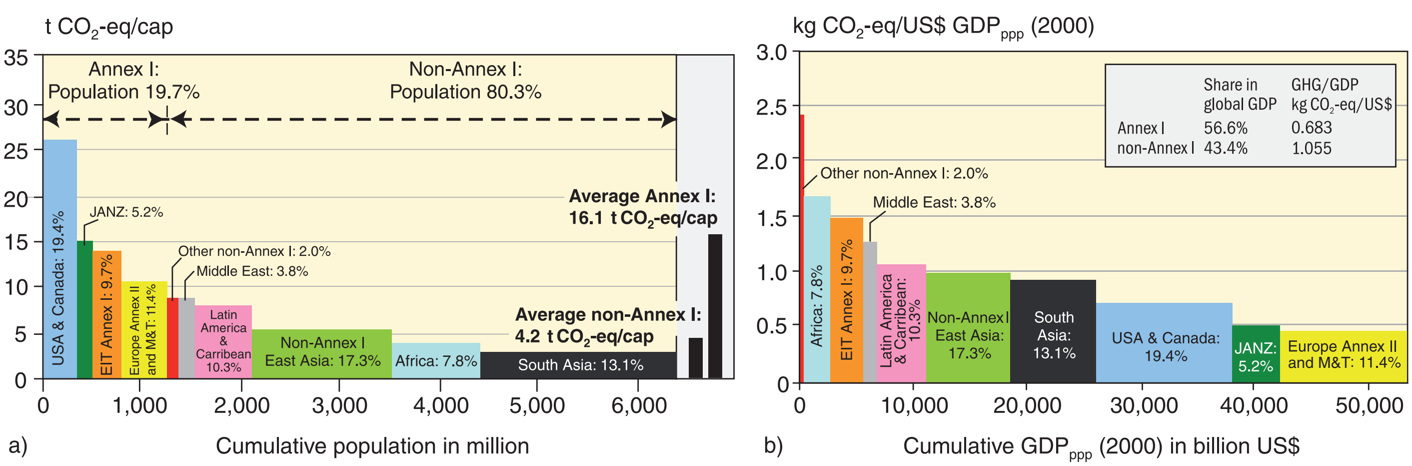

Figure 2.2. *(a) Distribution of regional per capita GHG emissions according to the population of different country groupings in 2004 (see appendix for definitions of country groupings). (b) Distribution of regional GHG emissions per US\$ of GDP_{PPP} over the GDP of different country groupings in 2004. The percentages in the bars in both panels indicate a region's share in global GHG emissions. {WGIII Figures SPM.3a, SPM.3b}*

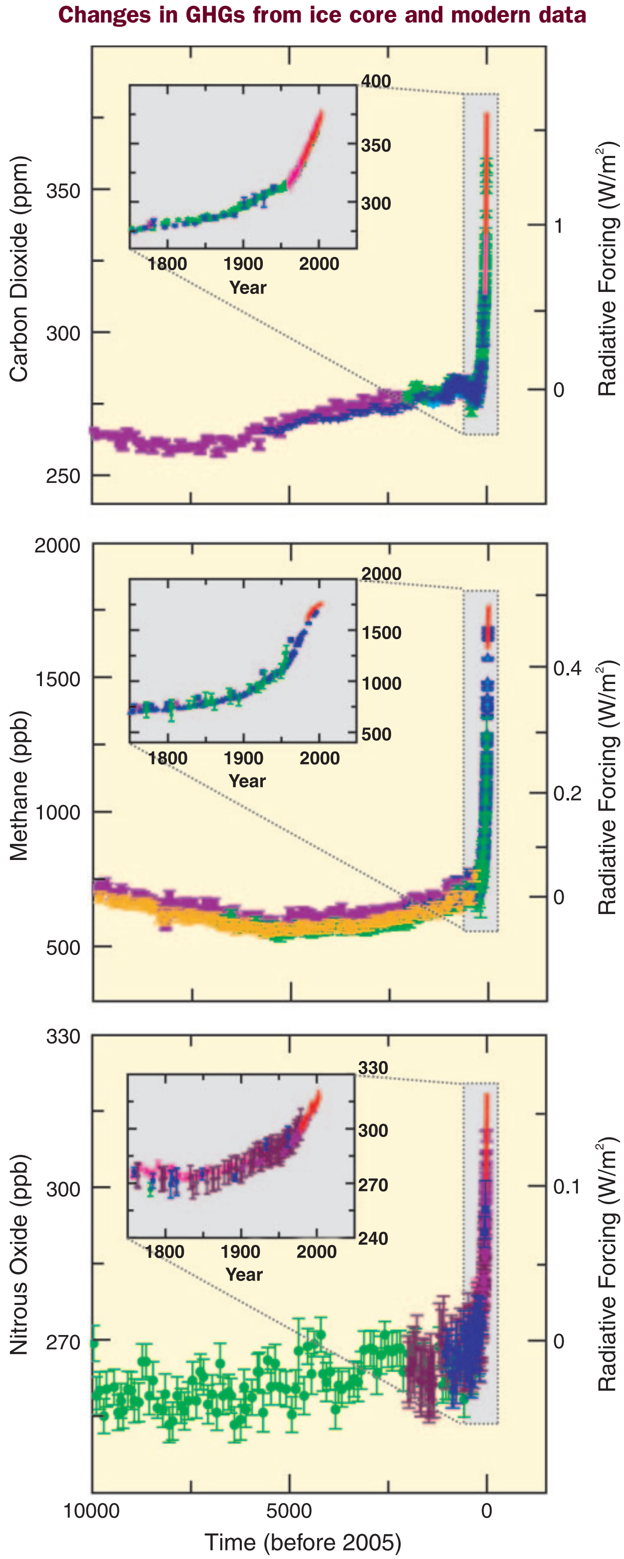

Figure 2.3. Atmospheric concentrations of CO_2, CH_4 and N_2O over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings relative to 1750 are shown on the right hand axes of the large panels. {WGI Figure SPM.1}

the industrial era is *very likely* to have been unprecedented in more than 10,000 years (Figures 2.3 and 2.4). The CO_2 radiative forcing increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years. *{WGI 2.3, 6.4, SPM}*

Anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produce a cooling effect, with a total direct radiative forcing of -0.5 [-0.9 to -0.1] W/m^2 and an indirect cloud albedo forcing of -0.7 [-1.8 to -0.3] W/m^2. Aerosols also influence precipitation. *{WGI 2.4, 2.9, 7.5, SPM}*

In comparison, changes in solar irradiance since 1750 are estimated to have caused a small radiative forcing of +0.12 [+0.06 to +0.30] W/m^2, which is less than half the estimate given in the TAR. *{WGI 2.7, SPM}*

2.3 Climate sensitivity and feedbacks

The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 concentration. Progress since the TAR enables an assessment that climate sensitivity is *likely* to be in the range of 2 to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values. *{WGI 8.6, 9.6, Box 10.2, SPM}*

Feedbacks can amplify or dampen the response to a given forcing. Direct emission of water vapour (a greenhouse gas) by human activities makes a negligible contribution to radiative forcing. However, as global average temperature increases, tropospheric water vapour concentrations increase and this represents a key positive feedback but not a forcing of climate change. Water vapour changes represent the largest feedback affecting equilibrium climate sensitivity and are now better understood than in the TAR. Cloud feedbacks remain the largest source of uncertainty. Spatial patterns of climate response are largely controlled by climate processes and feedbacks. For example, sea-ice albedo feedbacks tend to enhance the high latitude response. *{WGI 2.8, 8.6, 9.2, TS.2.1.3, TS.2.5, SPM}*

Warming reduces terrestrial and ocean uptake of atmospheric CO_2, increasing the fraction of anthropogenic emissions remaining in the atmosphere. This positive carbon cycle feedback leads to larger atmospheric CO_2 increases and greater climate change for a given emissions scenario, but the strength of this feedback effect varies markedly among models. *{WGI 7.3, TS.5.4, SPM; WGII 4.4}*

2.4 Attribution of climate change

Attribution evaluates whether observed changes are quantitatively consistent with the expected response to external forcings (e.g. changes in solar irradiance or anthropogenic GHGs) and inconsistent with alternative physically plausible explanations. *{WGI TS.4, SPM}*

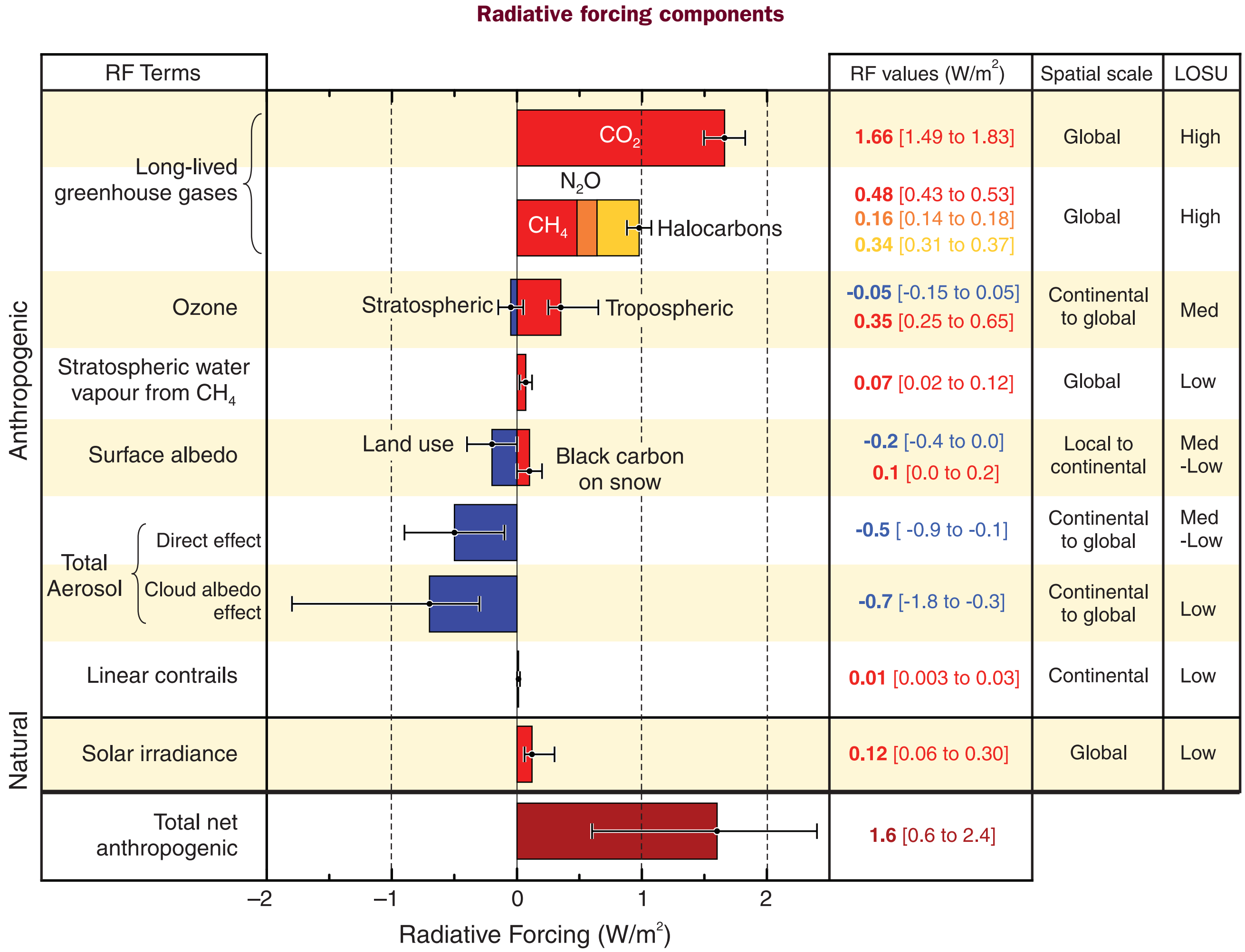

Figure 2.4. *Global average radiative forcing (RF) in 2005 (best estimates and 5 to 95% uncertainty ranges) with respect to 1750 for CO_2, CH_4, N_2O and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). Aerosols from explosive volcanic eruptions contribute an additional episodic cooling term for a few years following an eruption. The range for linear contrails does not include other possible effects of aviation on cloudiness. {WGI Figure SPM.2}*

Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations.[8] This is an advance since the TAR's conclusion that "most of the observed warming over the last 50 years is *likely* to have been due to the increase in GHG concentrations" (Figure 2.5). ***{WGI 9.4, SPM}***

The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is *extremely unlikely* that global climate change of the past 50 years can be explained without external forcing and *very likely* that it is not due to known natural causes alone. During this period, the sum of solar and volcanic forcings would *likely* have produced cooling, not warming. Warming of the climate system has been detected in changes in surface and atmospheric temperatures and in temperatures of the upper several hundred metres of the ocean. The observed pattern of tropospheric warming and stratospheric cooling is *very likely* due to the combined influences of GHG increases and stratospheric ozone depletion. It is *likely* that increases in GHG concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place. *{WGI 2.9, 3.2, 3.4, 4.8, 5.2, 7.5, 9.4, 9.5, 9.7, TS.4.1, SPM}*

It is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica) (Figure 2.5). ***{WGI 3.2, 9.4, SPM}***

The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are simulated only by models that include anthropogenic forcing. No coupled global climate model that has used natural forcing only has reproduced the continental mean warming trends in individual continents (except Antarctica) over the second half of the 20th century. *{WGI 3.2, 9.4, TS.4.2, SPM}*

[8] Consideration of remaining uncertainty is based on current methodologies.

Global and continental temperature change

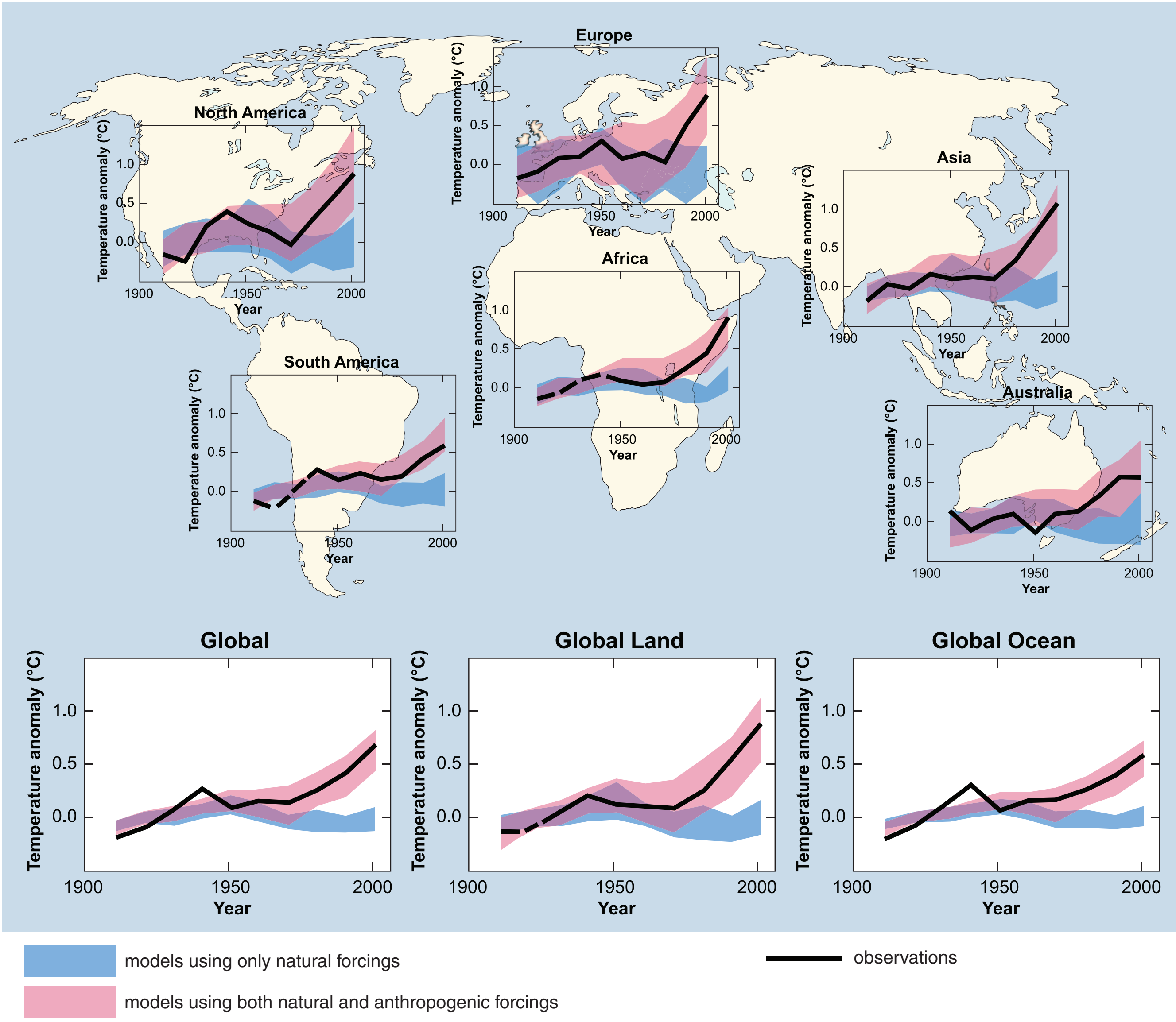

Figure 2.5. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using either natural or both natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906-2005 (black line) plotted against the centre of the decade and relative to the corresponding average for the 1901-1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5 to 95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5 to 95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. {WGI Figure SPM.4}

Difficulties remain in simulating and attributing observed temperature changes at smaller scales. On these scales, natural climate variability is relatively larger, making it harder to distinguish changes expected due to external forcings. Uncertainties in local forcings, such as those due to aerosols and land-use change, and feedbacks also make it difficult to estimate the contribution of GHG increases to observed small-scale temperature changes. *{WGI 8.3, 9.4, SPM}*

Advances since the TAR show that discernible human influences extend beyond average temperature to other aspects of climate, including temperature extremes and wind patterns. ***{WGI 9.4, 9.5, SPM}***

Temperatures of the most extreme hot nights, cold nights and cold days are *likely* to have increased due to anthropogenic forcing. It is *more likely than not* that anthropogenic forcing has increased the risk of heat waves. Anthropogenic forcing is *likely* to have contributed to changes in wind patterns, affecting extra-tropical storm tracks and temperature patterns in both hemispheres. However, the observed changes in the Northern Hemisphere circulation are larger than simulated by models in response to 20th century forcing change. *{WGI 3.5, 3.6, 9.4, 9.5, 10.3, SPM}*

It is *very likely* that the response to anthropogenic forcing contributed to sea level rise during the latter half of the 20th century. There is some evidence of the impact of human climatic influence on the hydrological cycle, including the observed large-scale patterns of changes in land precipitation over the 20th century. It is *more likely than not* that human influence has contributed to a global trend towards increases in area affected by drought since the 1970s and the frequency of heavy precipitation events. *{WGI 3.3, 5.5, 9.5, TS.4.1, TS.4.3}*

Anthropogenic warming over the last three decades has *likely* had a discernible influence at the global scale on observed changes in many physical and biological systems. ***{WGII 1.4}***

A synthesis of studies strongly demonstrates that the spatial agreement between regions of significant warming across the globe and the locations of significant observed changes in many natural systems consistent with warming is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems. Several modelling studies have linked some specific responses in physical and biological systems to anthropogenic warming, but only a few such studies have been performed. Taken together with evidence of significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica), it is *likely* that anthropogenic warming over the last three decades has had a discernible influence on many natural systems. *{WGI 3.2, 9.4, SPM; WGII 1.4, SPM}*

Limitations and gaps currently prevent more complete attribution of the causes of observed natural system responses to anthropogenic warming. The available analyses are limited in the number of systems, length of records and locations considered. Natural temperature variability is larger at the regional than the global scale, thus affecting identification of changes to external forcing. At the regional scale, other non-climate factors (such as land-use change, pollution and invasive species) are influential. *{WGII 1.2, 1.3, 1.4, SPM}*

3

Climate change and its impacts in the near and long term under different scenarios

3.1 Emissions scenarios

There is *high agreement* and *much evidence*[9] that with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades. Baseline emissions scenarios published since the IPCC Special Report on Emissions Scenarios (SRES, 2000) are comparable in range to those presented in SRES (see Box on SRES scenarios and Figure 3.1).[10] *{WGIII 1.3, 3.2, SPM}*

The SRES scenarios project an increase of baseline global GHG emissions by a range of 9.7 to 36.7 $GtCO_2$-eq (25 to 90%) between 2000 and 2030. In these scenarios, fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Hence CO_2 emissions from energy use between 2000 and 2030 are projected to grow 40 to 110% over that period. *{WGIII 1.3, SPM}*

Studies published since SRES (i.e. post-SRES scenarios) have used lower values for some drivers for emissions, notably population projections. However, for those studies incorporating these new population projections, changes in other drivers, such as economic growth, result in little change in overall emission levels. Economic growth projections for Africa, Latin America and the Middle East to 2030 in post-SRES baseline scenarios are lower than in SRES, but this has only minor effects on global economic growth and overall emissions. *{WGIII 3.2, TS.3, SPM}*

Aerosols have a net cooling effect and the representation of aerosol and aerosol precursor emissions, including sulphur dioxide, black carbon and organic carbon, has improved in the post-SRES scenarios. Generally, these emissions are projected to be lower than reported in SRES. *{WGIII 3.2, TS.3, SPM}*

Available studies indicate that the choice of exchange rate for Gross Domestic Product (GDP) (Market Exchange Rate, MER or Purchasing Power Parity, PPP) does not appreciably affect the projected emissions, when used consistently.[11] The differences, if any, are small compared to the uncertainties caused by assumptions on other parameters in the scenarios, e.g. technological change. *{WGIII 3.2, TS.3, SPM}*

Scenarios for GHG emissions from 2000 to 2100 in the absence of additional climate policies

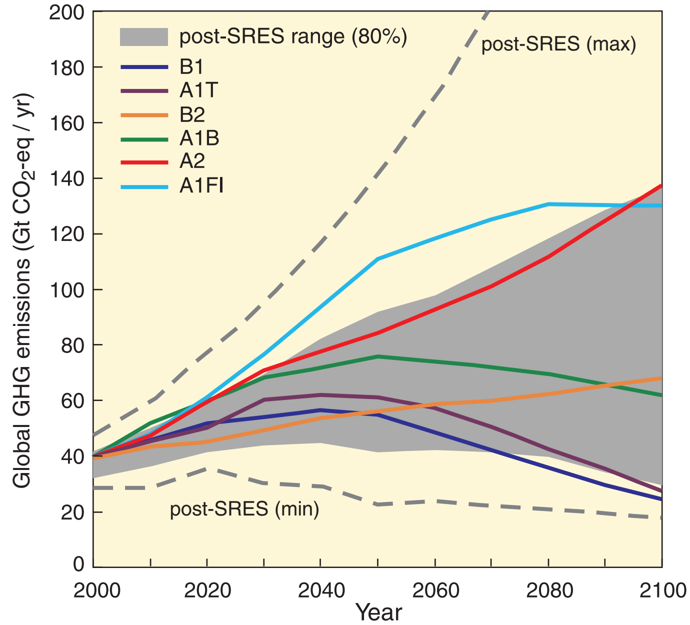

Figure 3.1. *Global GHG emissions (in $GtCO_2$-eq per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (coloured lines) and 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N_2O and F-gases. {WGIII 1.3, 3.2, Figure SPM.4}*

SRES scenarios

SRES refers to the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The emissions projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socio-economic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments. *{WGI 10.1; WGII 2.4; WGIII TS.1, SPM}*

The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. No likelihood has been attached to any of the SRES scenarios. *{WGIII TS.1, SPM}*

[9] Agreement/evidence statements in italics represent calibrated expressions of uncertainty and confidence. See Box 'Treatment of uncertainty' in the Introduction for an explanation of these terms.

[10] Baseline scenarios do not include additional climate policies above current ones; more recent studies differ with respect to UNFCCC and Kyoto Protocol inclusion. Emission pathways of mitigation scenarios are discussed in Topic 5.

[11] Since the TAR, there has been a debate on the use of different exchange rates in emissions scenarios. Two metrics are used to compare GDP between countries. Use of MER is preferable for analyses involving internationally traded products. Use of PPP is preferable for analyses involving comparisons of income between countries at very different stages of development. Most of the monetary units in this report are expressed in MER. This reflects the large majority of emissions mitigation literature that is calibrated in MER. When monetary units are expressed in PPP, this is denoted by GDP_{PPP}. {WGIII SPM}

3.2 Projections of future changes in climate

For the next two decades a warming of about 0.2°C per decade is projected for a range of SRES emissions scenarios. Even if the concentrations of all GHGs and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. Afterwards, temperature projections increasingly depend on specific emissions scenarios (Figure 3.2). *{WGI 10.3, 10.7; WGIII 3.2}*

Since the IPCC's first report in 1990, assessed projections have suggested global averaged temperature increases between about 0.15 and 0.3°C per decade from 1990 to 2005. This can now be compared with observed values of about 0.2°C per decade, strengthening confidence in near-term projections. *{WGI 1.2, 3.2}*

3.2.1 21st century global changes

Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century. *{WGI 10.3}*

Advances in climate change modelling now enable best estimates and *likely* assessed uncertainty ranges to be given for projected warming for different emissions scenarios. Table 3.1 shows best estimates and *likely* ranges for global average surface air warming for the six SRES marker emissions scenarios (including climate-carbon cycle feedbacks). *{WGI 10.5}*

Although these projections are broadly consistent with the span quoted in the TAR (1.4 to 5.8°C), they are not directly comparable. Assessed upper ranges for temperature projections are larger than in the TAR mainly because the broader range of models now available suggests stronger climate-carbon cycle feedbacks. For the A2 scenario, for example, the climate-carbon cycle feedback increases the corresponding global average warming at 2100 by more than 1°C. Carbon feedbacks are discussed in Topic 2.3. *{WGI 7.3, 10.5, SPM}*

Because understanding of some important effects driving sea level rise is too limited, this report does not assess the likelihood, nor provide a best estimate or an upper bound for sea level rise. Model-based projections of global average sea level rise at the end of the 21st century (2090-2099) are shown in Table 3.1. For each scenario, the mid-point of the range in Table 3.1 is within 10% of the TAR model average for 2090-2099. The ranges are narrower than in the TAR mainly because of improved information about some uncertainties in the projected contributions.[12] The sea level projections do not include uncertainties in climate-carbon cycle feedbacks nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. Therefore the upper values of the ranges given are not to be considered upper bounds for sea level rise. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993-2003, but these flow rates could increase or decrease in the future. If this contribution were to grow linearly with global average temperature change, the upper ranges of sea level rise for SRES scenarios shown in Table 3.1 would increase by 0.1 to 0.2m.[13] *{WGI 10.6, SPM}*

Table 3.1. *Projected global average surface warming and sea level rise at the end of the 21st century. {WGI 10.5, 10.6, Table 10.7, Table SPM.3}*

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:

a) These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity, and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs) as well as observational constraints.

b) Year 2000 constant composition is derived from AOGCMs only.

c) All scenarios above are six SRES marker scenarios. Approximate CO_2-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the WGI TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550ppm, respectively.

d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5°C.

[12] TAR projections were made for 2100, whereas the projections for this report are for 2090-2099. The TAR would have had similar ranges to those in Table 3.1 if it had treated uncertainties in the same way.

[13] For discussion of the longer term see Sections 3.2.3 and 5.2.

3.2.2 21st century regional changes

There is now higher confidence than in the TAR in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes and sea ice. ***{WGI 8.2, 8.3, 8.4, 8.5, 9.4, 9.5, 10.3, 11.1}***

Projected warming in the 21st century shows scenario-independent geographical patterns similar to those observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean (near Antarctica) and northern North Atlantic, continuing recent observed trends (Figure 3.2 right panels). *{WGI 10.3, SPM}*

Snow cover area is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions. Sea ice is projected to shrink in both the Arctic and Antarctic under all SRES scenarios. In some projections, Arctic late-summer sea ice disappears almost entirely by the latter part of the 21st century. *{WGI 10.3, 10.6, SPM; WGII 15.3.4}*

It is *very likely* that hot extremes, heat waves and heavy precipitation events will become more frequent. *{SYR Table 3.2; WGI 10.3, SPM}*

Based on a range of models, it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea-surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period. *{WGI 3.8, 9.5, 10.3, SPM}*

Extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns, continuing the broad pattern of observed trends over the last half-century. *{WGI 3.6, 10.3, SPM}*

Since the TAR there is an improving understanding of projected patterns of precipitation. Increases in the amount of precipitation are *very likely* in high-latitudes, while decreases are *likely* in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100, Figure 3.3), continuing observed patterns in recent trends. *{WGI 3.3, 8.3, 9.5, 10.3, 11.2-11.9, SPM}*

3.2.3 Changes beyond the 21st century

Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if GHG concentrations were to be stabilised. ***{WGI 10.4, 10.5, 10.7, SPM}***

If radiative forcing were to be stabilised, keeping all the radiative forcing agents constant at B1 or A1B levels in 2100, model experiments show that a further increase in global average temperature of about 0.5°C would still be expected by 2200. In addition, thermal expansion alone would lead to 0.3 to 0.8m of sea level rise by 2300 (relative to 1980-1999). Thermal expansion would continue for many centuries, due to the time required to transport heat into the deep ocean. *{WGI 10.7, SPM}*

Atmosphere-Ocean General Circulation Model projections of surface warming

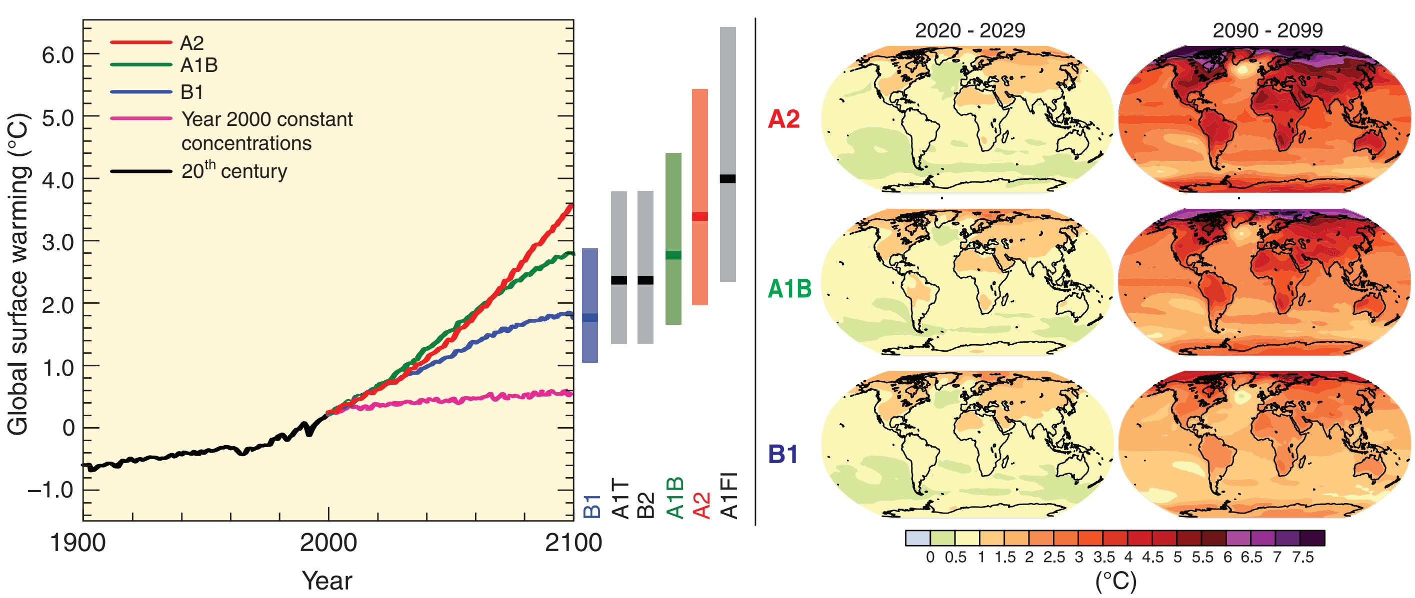

Figure 3.2. ***Left panel:*** *Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the SRES scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. The orange line is for the experiment where concentrations were held constant at year 2000 values. The bars in the middle of the figure indicate the best estimate (solid line within each bar) and the* likely *range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999. The assessment of the best estimate and* likely *ranges in the bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.* ***Right panels:*** *Projected surface temperature changes for the early and late 21st century relative to the period 1980-1999. The panels show the multi-AOGCM average projections for the A2 (top), A1B (middle) and B1 (bottom) SRES scenarios averaged over decades 2020-2029 (left) and 2090-2099 (right). {WGI 10.4, 10.8, Figures 10.28, 10.29, SPM}*

Multi-model projected patterns of precipitation changes

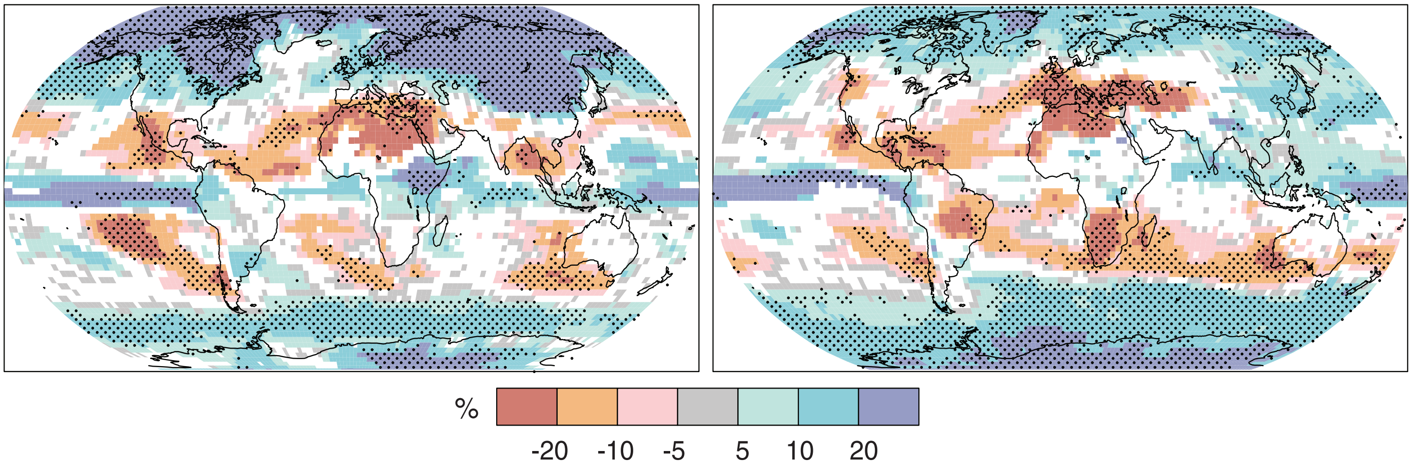

Figure 3.3. *Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {WGI Figure 10.9, SPM}*

Contraction of the Greenland ice sheet is projected to continue to contribute to sea level rise after 2100. Current models suggest ice mass losses increase with temperature more rapidly than gains due to increased precipitation and that the surface mass balance becomes negative (net ice loss) at a global average warming (relative to pre-industrial values) in excess of 1.9 to 4.6°C. If such a negative surface mass balance were sustained for millennia, that would lead to virtually complete elimination of the Greenland ice sheet and a resulting contribution to sea level rise of about 7m. The corresponding future temperatures in Greenland (1.9 to 4.6°C global) are comparable to those inferred for the last interglacial period 125,000 years ago, when palaeoclimatic information suggests reductions of polar land ice extent and 4 to 6m of sea level rise. *{WGI 6.4, 10.7, SPM}*

Dynamical processes related to ice flow – which are not included in current models but suggested by recent observations – could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude. *{WGI 4.6, 10.7, SPM}*

Current global model studies project that the Antarctic ice sheet will remain too cold for widespread surface melting and gain mass due to increased snowfall. However, net loss of ice mass could occur if dynamical ice discharge dominates the ice sheet mass balance. *{WGI 10.7, SPM}*

Both past and future anthropogenic CO_2 emissions will continue to contribute to warming and sea level rise for more than a millennium, due to the time scales required for the removal of this gas from the atmosphere. *{WGI 7.3, 10.3, Figure 7.12, Figure 10.35, SPM}*

Estimated long-term (multi-century) warming corresponding to the six AR4 WG III stabilisation categories is shown in Figure 3.4.

Estimated multi-century warming relative to 1980-1999 for AR4 stabilisation categories

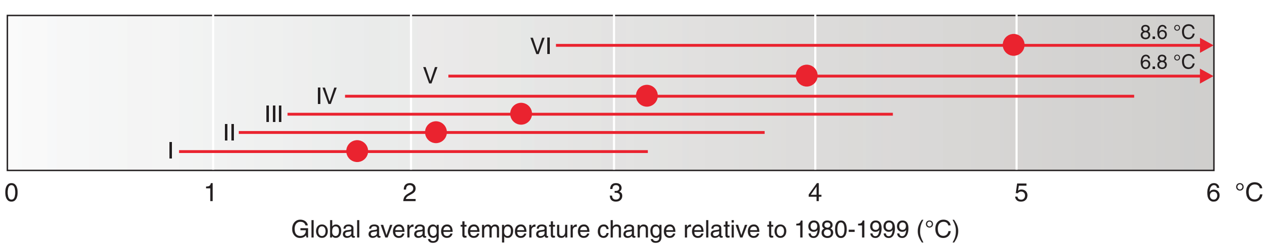

Figure 3.4. *Estimated long-term (multi-century) warming corresponding to the six AR4 WG III stabilisation categories (Table 5.1). The temperature scale has been shifted by -0.5°C compared to Table 5.1 to account approximately for the warming between pre-industrial and 1980-1999. For most stabilisation levels global average temperature is approaching the equilibrium level over a few centuries. For GHG emissions scenarios that lead to stabilisation at levels comparable to SRES B1 and A1B by 2100 (600 and 850 ppm CO_2-eq; category IV and V), assessed models project that about 65 to 70% of the estimated global equilibrium temperature increase, assuming a climate sensitivity of 3°C, would be realised at the time of stabilisation. For the much lower stabilisation scenarios (category I and II, Figure 5.1), the equilibrium temperature may be reached earlier. {WGI 10.7.2}*

3.3 Impacts of future climate changes

More specific information is now available across a wide range of systems and sectors concerning the nature of future impacts, including some fields not covered in previous assessments. ***{WGII TS.4, SPM}***

The following is a selection of key findings[14] regarding the impacts of climate change on systems, sectors and regions, as well as some findings on vulnerability[15], for the range of climate changes projected over the 21st century. Unless otherwise stated, the confidence level in the projections is *high*. Global average temperature increases are given relative to 1980-1999. Additional information on impacts can be found in the WG II report. *{WGII SPM}*

3.3.1 Impacts on systems and sectors

Ecosystems

- The resilience of many ecosystems is *likely* to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g. flooding, drought, wildfire, insects, ocean acidification) and other global change drivers (e.g. land-use change, pollution, fragmentation of natural systems, over-exploitation of resources). *{WGII 4.1-4.6, SPM}*
- Over the course of this century, net carbon uptake by terrestrial ecosystems is *likely* to peak before mid-century and then weaken or even reverse[16], thus amplifying climate change. *{WGII 4.ES, Figure 4.2, SPM}*
- Approximately 20 to 30% of plant and animal species assessed so far are *likely* to be at increased risk of extinction if increases in global average temperature exceed 1.5 to 2.5°C (*medium confidence*). *{WGII 4.ES, Figure 4.2, SPM}*
- For increases in global average temperature exceeding 1.5 to 2.5°C and in concomitant atmospheric CO_2 concentrations, there are projected to be major changes in ecosystem structure and function, species' ecological interactions and shifts in species' geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services, e.g. water and food supply. *{WGII 4.4, Box TS.6, SPM}*

Food

- Crop productivity is projected to increase slightly at mid- to high latitudes for local mean temperature increases of up to 1 to 3°C depending on the crop, and then decrease beyond that in some regions (*medium confidence*). *{WGII 5.4, SPM}*
- At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1 to 2°C), which would increase the risk of hunger (*medium confidence*). *{WGII 5.4, SPM}*
- Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1 to 3°C, but above this it is projected to decrease (*medium confidence*). *{WGII 5.4, 5.5, SPM}*

Coasts

- Coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea level rise. The effect will be exacerbated by increasing human-induced pressures on coastal areas (*very high confidence*). *{WGII 6.3, 6.4, SPM}*
- By the 2080s, many millions more people than today are projected to experience floods every year due to sea level rise. The numbers affected will be largest in the densely populated and low-lying megadeltas of Asia and Africa while small islands are especially vulnerable (*very high confidence*). *{WGII 6.4, 6.5, Table 6.11, SPM}*

Industry, settlements and society

- The most vulnerable industries, settlements and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources and those in areas prone to extreme weather events, especially where rapid urbanisation is occurring. *{WGII 7.1, 7.3, 7.4, 7.5, SPM}*
- Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. *{WGII 7.2, 7.4, 5.4, SPM}*

Health

- The health status of millions of people is projected to be affected through, for example, increases in malnutrition; increased deaths, diseases and injury due to extreme weather events; increased burden of diarrhoeal diseases; increased frequency of cardio-respiratory diseases due to higher concentrations of ground-level ozone in urban areas related to climate change; and the altered spatial distribution of some infectious diseases. *{WGI 7.4, Box 7.4; WGII 8.ES, 8.2, 8.4, SPM}*
- Climate change is projected to bring some benefits in temperate areas, such as fewer deaths from cold exposure, and some mixed effects such as changes in range and transmission potential of malaria in Africa. Overall it is expected that benefits will be outweighed by the negative health effects of rising temperatures, especially in developing countries. *{WGII 8.4, 8.7, 8ES, SPM}*
- Critically important will be factors that directly shape the health of populations such as education, health care, public health initiatives, and infrastructure and economic development. *{WGII 8.3, SPM}*

Water

- Water impacts are key for all sectors and regions. These are discussed below in the Box 'Climate change and water'.

[14] Criteria of choice: magnitude and timing of impact, confidence in the assessment, representative coverage of the system, sector and region.

[15] Vulnerability to climate change is the degree to which systems are susceptible to, and unable to cope with, adverse impacts.

[16] Assuming continued GHG emissions at or above current rates and other global changes including land-use changes.

Climate change and water

Climate change is expected to exacerbate current stresses on water resources from population growth and economic and land-use change, including urbanisation. On a regional scale, mountain snow pack, glaciers and small ice caps play a crucial role in freshwater availability. Widespread mass losses from glaciers and reductions in snow cover over recent decades are projected to accelerate throughout the 21st century, reducing water availability, hydropower potential, and changing seasonality of flows in regions supplied by meltwater from major mountain ranges (e.g. Hindu-Kush, Himalaya, Andes), where more than one-sixth of the world population currently lives. *{WGI 4.1, 4.5; WGII 3.3, 3.4, 3.5}*

Changes in precipitation (Figure 3.3) and temperature (Figure 3.2) lead to changes in runoff (Figure 3.5) and water availability. Runoff is projected with *high confidence* to increase by 10 to 40% by mid-century at higher latitudes and in some wet tropical areas, including populous areas in East and South-East Asia, and decrease by 10 to 30% over some dry regions at mid-latitudes and dry tropics, due to decreases in rainfall and higher rates of evapotranspiration. There is also *high confidence* that many semi-arid areas (e.g. the Mediterranean Basin, western United States, southern Africa and north-eastern Brazil) will suffer a decrease in water resources due to climate change. Drought-affected areas are projected to increase in extent, with the potential for adverse impacts on multiple sectors, e.g. agriculture, water supply, energy production and health. Regionally, large increases in irrigation water demand as a result of climate changes are projected. *{WGI 10.3, 11.2-11.9; WGII 3.4, 3.5, Figure 3.5, TS.4.1, Box TS.5, SPM}*

The negative impacts of climate change on freshwater systems outweigh its benefits (*high confidence*). Areas in which runoff is projected to decline face a reduction in the value of the services provided by water resources (*very high confidence*). The beneficial impacts of increased annual runoff in some areas are *likely* to be tempered by negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality and flood risk. *{WGII 3.4, 3.5, TS.4.1}*

Available research suggests a significant future increase in heavy rainfall events in many regions, including some in which the mean rainfall is projected to decrease. The resulting increased flood risk poses challenges to society, physical infrastructure and water quality. It is *likely* that up to 20% of the world population will live in areas where river flood potential could increase by the 2080s. Increases in the frequency and severity of floods and droughts are projected to adversely affect sustainable development. Increased temperatures will further affect the physical, chemical and biological properties of freshwater lakes and rivers, with predominantly adverse impacts on many individual freshwater species, community composition and water quality. In coastal areas, sea level rise will exacerbate water resource constraints due to increased salinisation of groundwater supplies. *{WGI 11.2-11.9; WGII 3.2, 3.3, 3.4, 4.4}*

Projections and model consistency of relative changes in runoff by the end of the 21st century

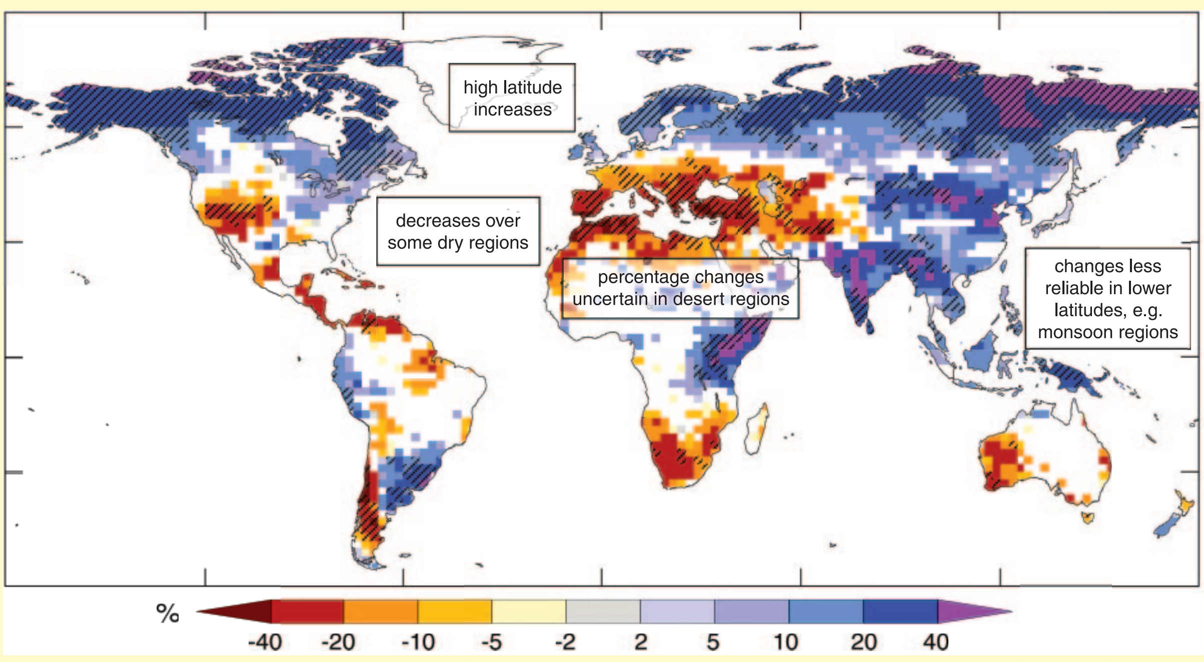

Figure 3.5. *Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. The quality of the simulation of the observed large-scale 20th century runoff is used as a basis for selecting the 12 models from the multi-model ensemble. The global map of annual runoff illustrates a large scale and is not intended to refer to smaller temporal and spatial scales. In areas where rainfall and runoff is very low (e.g. desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from few climate models can be considerably different from the results presented here. {WGII Figure 3.4, adjusted to match the assumptions of Figure SYR 3.3; WGII 3.3.1, 3.4.1, 3.5.1}*

Studies since the TAR have enabled more systematic understanding of the timing and magnitude of impacts related to differing amounts and rates of climate change. *{WGII SPM}*

Examples of this new information for systems and sectors are presented in Figure 3.6. The upper panel shows impacts increasing with increasing temperature change. Their estimated magnitude and timing is also affected by development pathways (lower panel). *{WGII SPM}*

Depending on circumstances, some of the impacts shown in Figure 3.6 could be associated with 'key vulnerabilities', based on a number of criteria in the literature (magnitude, timing, persistence/ reversibility, the potential for adaptation, distributional aspects, likelihood and 'importance' of the impacts) (see Topic 5.2). *{WGII SPM}*

3.3.2 Impacts on regions[17]

Africa

- By 2020, between 75 and 250 million of people are projected to be exposed to increased water stress due to climate change. *{WGII 9.4, SPM}*
- By 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%. Agricultural production, including access to food, in many African countries is projected to be severely compromised. This would further adversely affect food security and exacerbate malnutrition. *{WGII 9.4, SPM}*
- Towards the end of the 21st century, projected sea level rise will affect low-lying coastal areas with large populations. The cost of adaptation could amount to at least 5 to 10% of GDP. *{WGII 9.4, SPM}*
- By 2080, an increase of 5 to 8% of arid and semi-arid land in Africa is projected under a range of climate scenarios (*high confidence*). *{WGII Box TS.6, 9.4.4}*

Asia

- By the 2050s, freshwater availability in Central, South, East and South-East Asia, particularly in large river basins, is projected to decrease. *{WGII 10.4, SPM}*
- Coastal areas, especially heavily populated megadelta regions in South, East and South-East Asia, will be at greatest risk due to increased flooding from the sea and, in some megadeltas, flooding from the rivers. *{WGII 10.4, SPM}*
- Climate change is projected to compound the pressures on natural resources and the environment associated with rapid urbanisation, industrialisation and economic development. *{WGII 10.4, SPM}*
- Endemic morbidity and mortality due to diarrhoeal disease primarily associated with floods and droughts are expected to rise in East, South and South-East Asia due to projected changes in the hydrological cycle. *{WGII 10.4, SPM}*

Australia and New Zealand

- By 2020, significant loss of biodiversity is projected to occur in some ecologically rich sites, including the Great Barrier Reef and Queensland Wet Tropics. *{WGII 11.4, SPM}*
- By 2030, water security problems are projected to intensify in southern and eastern Australia and, in New Zealand, in Northland and some eastern regions. *{WGII 11.4, SPM}*
- By 2030, production from agriculture and forestry is projected to decline over much of southern and eastern Australia, and over parts of eastern New Zealand, due to increased drought and fire. However, in New Zealand, initial benefits are projected in some other regions. *{WGII 11.4, SPM}*
- By 2050, ongoing coastal development and population growth in some areas of Australia and New Zealand are projected to exacerbate risks from sea level rise and increases in the severity and frequency of storms and coastal flooding. *{WGII 11.4, SPM}*

Europe

- Climate change is expected to magnify regional differences in Europe's natural resources and assets. Negative impacts will include increased risk of inland flash floods and more frequent coastal flooding and increased erosion (due to storminess and sea level rise). *{WGII 12.4, SPM}*
- Mountainous areas will face glacier retreat, reduced snow cover and winter tourism, and extensive species losses (in some areas up to 60% under high emissions scenarios by 2080). *{WGII 12.4, SPM}*
- In southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability, hydropower potential, summer tourism and, in general, crop productivity. *{WGII 12.4, SPM}*
- Climate change is also projected to increase the health risks due to heat waves and the frequency of wildfires. *{WGII 12.4, SPM}*

Latin America

- By mid-century, increases in temperature and associated decreases in soil water are projected to lead to gradual replacement of tropical forest by savanna in eastern Amazonia. Semi-arid vegetation will tend to be replaced by arid-land vegetation. *{WGII 13.4, SPM}*
- There is a risk of significant biodiversity loss through species extinction in many areas of tropical Latin America. *{WGII 13.4, SPM}*
- Productivity of some important crops is projected to decrease and livestock productivity to decline, with adverse consequences for food security. In temperate zones, soybean yields are projected to increase. Overall, the number of people at risk of hunger is projected to increase (*medium confidence*). *{WGII 13.4, Box TS.6}*
- Changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture and energy generation. *{WGII 13.4, SPM}*

[17] Unless stated explicitly, all entries are from WG II SPM text, and are either *very high confidence* or *high confidence* statements, reflecting different sectors (agriculture, ecosystems, water, coasts, health, industry and settlements). The WG II SPM refers to the source of the statements, timelines and temperatures. The magnitude and timing of impacts that will ultimately be realised will vary with the amount and rate of climate change, emissions scenarios, development pathways and adaptation.

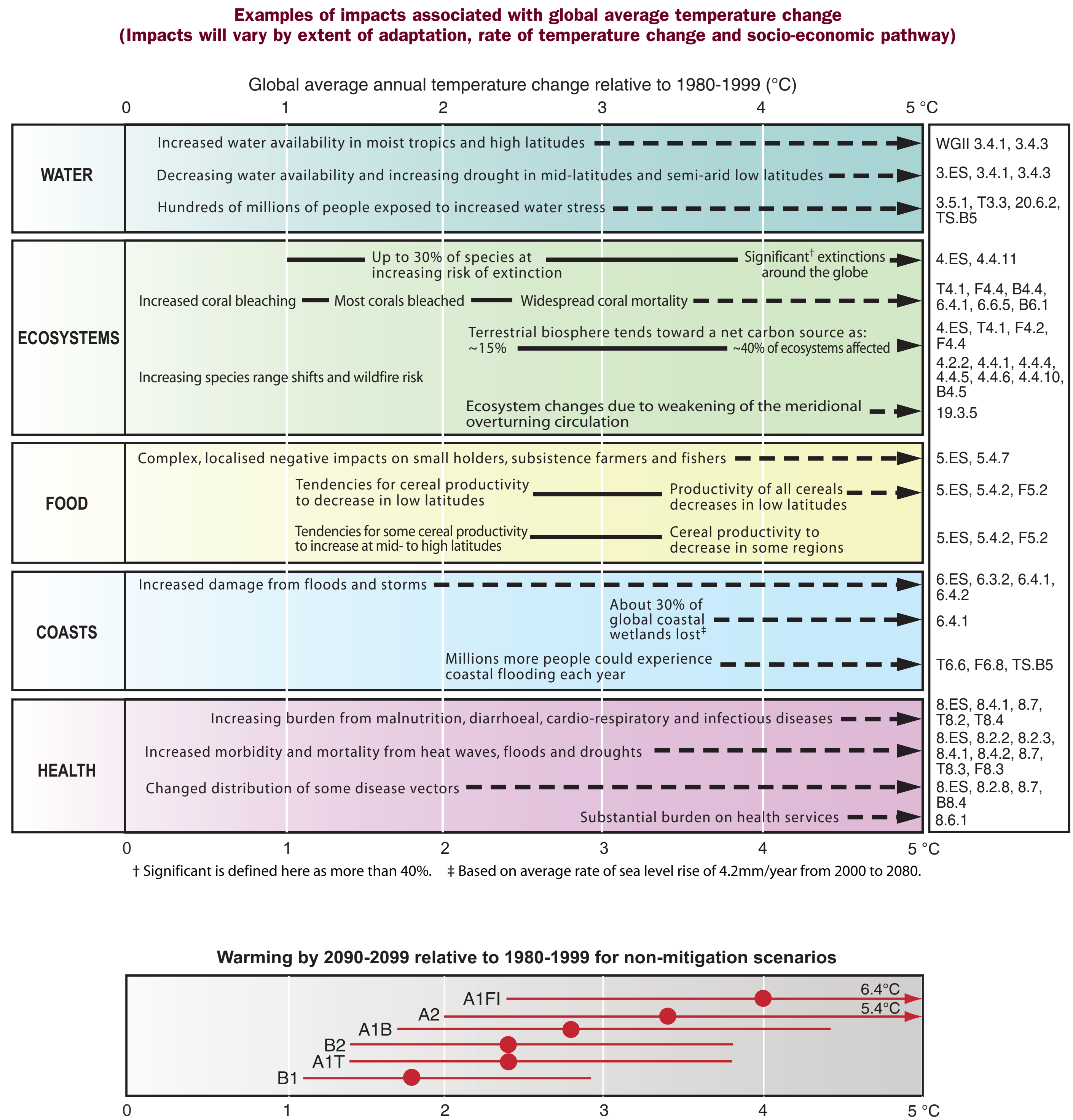

Figure 3.6. *Examples of impacts associated with global average temperature change.* ***Upper panel:*** *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric CO_2 where relevant) associated with different amounts of increase in global average surface temperature in the 21st century. The black lines link impacts; broken-line arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of text indicates the approximate level of warming that is associated with the onset of a given impact. Quantitative entries for water scarcity and flooding represent the additional impacts of climate change relative to the conditions projected across the range of SRES scenarios A1FI, A2, B1 and B2. Adaptation to climate change is not included in these estimations. Confidence levels for all statements are* high. *The upper right panel gives the WG II references for the statements made in the upper left panel.** ***Lower panel:*** *Dots and bars indicate the best estimate and* likely *ranges of warming assessed for the six SRES marker scenarios for 2090-2099 relative to 1980-1999. {WGI Figure SPM.5, 10.7; WGII Figure SPM.2; WGIII Table TS.2, Table 3.10}*

*Where ES = Executive Summary, T = Table, B = Box and F = Figure. Thus B4.5 indicates Box 4.5 in Chapter 4 and 3.5.1 indicates Section 3.5.1 in Chapter 3.

North America

- Warming in western mountains is projected to cause decreased snowpack, more winter flooding and reduced summer flows, exacerbating competition for over-allocated water resources. *{WGII 14.4, SPM}*
- In the early decades of the century, moderate climate change is projected to increase aggregate yields of rain-fed agriculture by 5 to 20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or which depend on highly utilised water resources. *{WGII 14.4, SPM}*
- Cities that currently experience heat waves are expected to be further challenged by an increased number, intensity and duration of heat waves during the course of the century, with potential for adverse health impacts. *{WGII 14.4, SPM}*
- Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. *{WGII 14.4, SPM}*

Polar Regions

- The main projected biophysical effects are reductions in thickness and extent of glaciers, ice sheets and sea ice, and changes in natural ecosystems with detrimental effects on many organisms including migratory birds, mammals and higher predators. *{WGII 15.4, SPM}*
- For human communities in the Arctic, impacts, particularly those resulting from changing snow and ice conditions, are projected to be mixed. *{WGII 15.4, SPM}*
- Detrimental impacts would include those on infrastructure and traditional indigenous ways of life. *{WGII 15.4, SPM}*
- In both polar regions, specific ecosystems and habitats are projected to be vulnerable, as climatic barriers to species invasions are lowered. {WGII 15.4, SPM}

Small Islands

- Sea level rise is expected to exacerbate inundation, storm surge, erosion and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of island communities. *{WGII 16.4, SPM}*
- Deterioration in coastal conditions, for example through erosion of beaches and coral bleaching, is expected to affect local resources. *{WGII 16.4, SPM}*
- By mid-century, climate change is expected to reduce water resources in many small islands, e.g. in the Caribbean and Pacific, to the point where they become insufficient to meet demand during low-rainfall periods. *{WGII 16.4, SPM}*
- With higher temperatures, increased invasion by non-native species is expected to occur, particularly on mid- and high-latitude islands. *{WGII 16.4, SPM}*

3.3.3 Especially affected systems, sectors and regions

Some systems, sectors and regions are *likely* to be especially affected by climate change.[18] ***{WGII TS.4.5}***

Systems and sectors: *{WGII TS.4.5}*

- particular ecosystems:
  - terrestrial: tundra, boreal forest and mountain regions because of sensitivity to warming; mediterranean-type ecosystems because of reduction in rainfall; and tropical rainforests where precipitation declines
  - coastal: mangroves and salt marshes, due to multiple stresses
  - marine: coral reefs due to multiple stresses; the sea-ice biome because of sensitivity to warming
- water resources in some dry regions at mid-latitudes[19] and in the dry tropics, due to changes in rainfall and evapotranspiration, and in areas dependent on snow and ice melt
- agriculture in low latitudes, due to reduced water availability
- low-lying coastal systems, due to threat of sea level rise and increased risk from extreme weather events
- human health in populations with low adaptive capacity.

Regions: *{WGII TS.4.5}*

- the Arctic, because of the impacts of high rates of projected warming on natural systems and human communities
- Africa, because of low adaptive capacity and projected climate change impacts
- small islands, where there is high exposure of population and infrastructure to projected climate change impacts
- Asian and African megadeltas, due to large populations and high exposure to sea level rise, storm surges and river flooding.

Within other areas, even those with high incomes, some people (such as the poor, young children and the elderly) can be particularly at risk, and also some areas and some activities. *{WGII 7.1, 7.2, 7.4, 8.2, 8.4, TS.4.5}*

3.3.4 Ocean acidification

The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic with an average decrease in pH of 0.1 units. Increasing atmospheric CO_2 concentrations lead to further acidification. Projections based on SRES scenarios give a reduction in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century. While the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (e.g. corals) and their dependent species. *{WGI SPM; WGII SPM}*

3.3.5 Extreme events

Altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems (Table 3.2). ***{WGII SPM}***

Examples for selected extremes and sectors are shown in Table 3.2.

[18] Identified on the basis of expert judgement of the assessed literature and considering the magnitude, timing and projected rate of climate change, sensitivity and adaptive capacity.

[19] Including arid and semi-arid regions.

***Table 3.2.** Examples of possible impacts of climate change due to changes in extreme weather and climate events, based on projections to the mid- to late 21st century. These do not take into account any changes or developments in adaptive capacity. The likelihood estimates in column two relate to the phenomena listed in column one. {WGII Table SPM.1}*

Phenomenon[a] and direction of trend	Likelihood of future trends based on projections for 21st century using SRES scenarios	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems *{WGII 4.4, 5.4}*	Water resources *{WGII 3.4}*	Human health *{WGII 8.2, 8.4}*	Industry, settlement and society *{WGII 7.4}*
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	*Virtually certain*[b]	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snowmelt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land areas	*Very likely*	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g. algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas	*Very likely*	Damage to crops; soil erosion, inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding: pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	*Likely*	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortage for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	*Likely*	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers; potential for population migrations; loss of property
Increased incidence of extreme high sea level (excludes tsunamis)[c]	*Likely*[d]	Salinisation of irrigation water, estuaries and fresh-water systems	Decreased fresh-water availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

Notes:
a) See WGI Table 3.7 for further details regarding definitions.
b) Warming of the most extreme days and nights each year.
c) Extreme high sea level depends on average sea level and on regional weather systems. It is defined as the highest 1% of hourly values of observed sea level at a station for a given reference period.
d) In all scenarios, the projected global average sea level at 2100 is higher than in the reference period. The effect of changes in regional weather systems on sea level extremes has not been assessed. *{WGI 10.6}*

3.4 Risk of abrupt or irreversible changes

Anthropogenic warming could lead to some impacts that are abrupt or irreversible, depending upon the rate and magnitude of the climate change. ***{WGII 12.6, 19.3, 19.4, SPM}***

Abrupt climate change on decadal time scales is normally thought of as involving ocean circulation changes. In addition on longer time scales, ice sheet and ecosystem changes may also play a role. If a large-scale abrupt climate change were to occur, its impact could be quite high (see Topic 5.2). *{WGI 8.7, 10.3, 10.7; WGII 4.4, 19.3}*

Partial loss of ice sheets on polar land and/or the thermal expansion of seawater over very long time scales could imply metres of sea level rise, major changes in coastlines and inundation of low-lying areas, with greatest effects in river deltas and low-lying islands. Current models project that such changes would occur over very long time scales (millennial) if a global temperature increase of 1.9 to 4.6°C (relative to pre-industrial) were to be sustained. Rapid sea level rise on century time scales cannot be excluded. *{SYR 3.2.3; WGI 6.4, 10.7; WGII 19.3, SPM}*

Climate change is *likely* to lead to some irreversible impacts. There is *medium confidence* that approximately 20 to 30% of species assessed so far are *likely* to be at increased risk of extinction if increases in global average warming exceed 1.5 to 2.5°C (relative to 1980-1999). As global average temperature increase exceeds about 3.5°C, model projections suggest significant extinctions (40 to 70% of species assessed) around the globe. *{WGII 4.4, Figure SPM.2}*

Based on current model simulations, it is *very likely* that the meridional overturning circulation (MOC) of the Atlantic Ocean will slow down during the 21st century; nevertheless temperatures in the region are projected to increase. It is *very unlikely* that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence. *{WGI 10.3, 10.7; WGII Figure, Table TS.5, SPM.2}*

Impacts of large-scale and persistent changes in the MOC are *likely* to include changes in marine ecosystem productivity, fisheries, ocean CO_2 uptake, oceanic oxygen concentrations and terrestrial vegetation. Changes in terrestrial and ocean CO_2 uptake may feed back on the climate system. *{WGII 12.6, 19.3, Figure SPM.2}*

4

Adaptation and mitigation options and responses, and the inter-relationship with sustainable development, at global and regional levels

4.1 Responding to climate change

Societies can respond to climate change by adapting to its impacts and by reducing GHG emissions (mitigation), thereby reducing the rate and magnitude of change. This Topic focuses on adaptation and mitigation options that can be implemented over the next two to three decades, and their inter-relationship with sustainable development. These responses can be complementary. Topic 5 addresses their complementary roles on a more conceptual basis over a longer timeframe.

The capacity to adapt and mitigate is dependent on socio-economic and environmental circumstances and the availability of information and technology[20]. However, much less information is available about the costs and effectiveness of adaptation measures than about mitigation measures. *{WGII 17.1, 17.3; WGIII 1.2}*

4.2 Adaptation options

Adaptation can reduce vulnerability, both in the short and the long term. ***{WGII 17.2, 18.1, 18.5, 20.3, 20.8}***

Vulnerability to climate change can be exacerbated by other stresses. These arise from, for example, current climate hazards, poverty, unequal access to resources, food insecurity, trends in economic globalisation, conflict and incidence of diseases such as HIV/AIDS. *{WGII 7.2, 7.4, 8.3, 17.3, 20.3, 20.4, 20.7, SPM}*

Societies across the world have a long record of adapting and reducing their vulnerability to the impacts of weather- and climate-related events such as floods, droughts and storms. Nevertheless, additional adaptation measures will be required at regional and local levels to reduce the adverse impacts of projected climate change and variability, regardless of the scale of mitigation undertaken over the next two to three decades. However, adaptation alone is not expected to cope with all the projected effects of climate change, especially not over the long term as most impacts increase in magnitude. *{WGII 17.2, SPM; WGIII 1.2}*

A wide array of adaptation options is available, but more extensive adaptation than is currently occurring is required to reduce vulnerability to climate change. There are barriers, limits and costs, which are not fully understood. Some planned adaptation is already occurring on a limited basis. Table 4.1 provides examples of planned adaptation options by sector. Many adaptation actions have multiple drivers, such as economic development and poverty alleviation, and are embedded within broader development, sectoral, regional and local planning initiatives such as water resources planning, coastal defence and disaster risk reduction strategies. Examples of this approach are the Bangladesh National Water Management Plan and the coastal defence plans of The Netherlands and Norway, which incorporate specific climate change scenarios. *{WGII 1.3, 5.5.2, 11.6, 17.2}*

Comprehensive estimates of the costs and benefits of adaptation at the global level are limited in number. However, the number of adaptation cost and benefit estimates at the regional and project levels for impacts on specific sectors, such as agriculture, energy demand for heating and cooling, water resources management and infrastructure, is growing. Based on these studies there is *high confidence* that there are viable adaptation options that can be implemented in some of these sectors at low cost and/or with high benefit-cost ratios. Empirical research also suggests that higher benefit-cost ratios can be achieved by implementing some adaptation measures at an early stage compared to retrofitting long-lived infrastructure at a later date. *{WGII 17.2}*

Adaptive capacity is intimately connected to social and economic development, but it is not evenly distributed across and within societies. ***{WGII 7.1, 7.2, 7.4, 17.3}***

The capacity to adapt is dynamic and is influenced by a society's productive base, including natural and man-made capital assets, social networks and entitlements, human capital and institutions, governance, national income, health and technology. It is also affected by multiple climate and non-climate stresses, as well as development policy. *{WGII 17.3}*

Recent studies reaffirm the TAR finding that adaptation will be vital and beneficial. However, financial, technological, cognitive, behavioural, political, social, institutional and cultural constraints limit both the implementation and effectiveness of adaptation measures. Even societies with high adaptive capacity remain vulnerable to climate change, variability and extremes. For example, a heat wave in 2003 caused high levels of mortality in European cities (especially among the elderly), and Hurricane Katrina in 2005 caused large human and financial costs in the United States. *{WGII 7.4, 8.2, 17.4}*

[20] Technology is defined as the practical application of knowledge to achieve particular tasks that employs both technical artefacts (hardware, equipment) and (social) information ('software', know-how for production and use of artefacts).

Table 4.1. *Selected examples of planned adaptation by sector.*

Sector	Adaptation option/strategy	Underlying policy framework	Key constraints and opportunities to implementation (Normal font = constraints; *italics = opportunities*)
Water {WGII, 5.5, 16.4; Tables 3.5, 11.6,17.1}	Expanded rainwater harvesting; water storage and conservation techniques; water reuse; desalination; water-use and irrigation efficiency	National water policies and integrated water resources management; water-related hazards management	Financial, human resources and physical barriers; *integrated water resources management; synergies with other sectors*
Agriculture {WGII 10.5, 13.5; Table 10.8}	Adjustment of planting dates and crop variety; crop relocation; improved land management, e.g. erosion control and soil protection through tree planting	R&D policies; institutional reform; land tenure and land reform; training; capacity building; crop insurance; financial incentives, e.g. subsidies and tax credits	Technological and financial constraints; access to new varieties; markets; *longer growing season in higher latitudes; revenues from 'new' products*
Infrastructure/ settlement (including coastal zones) {WGII 3.6, 11.4; Tables 6.11, 17.1}	Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural barriers	Standards and regulations that integrate climate change considerations into design; land-use policies; building codes; insurance	Financial and technological barriers; availability of relocation space; *integrated policies and management; synergies with sustainable development goals*
Human health {WGII 14.5, Table 10.8}	Heat-health action plans; emergency medical services; improved climate-sensitive disease surveillance and control; safe water and improved sanitation	Public health policies that recognise climate risk; strengthen health services; regional and international cooperation	Limits to human tolerance (vulnerable groups); knowledge limitations; financial capacity; *upgraded health services; improved quality of life*
Tourism {WGII 12.5, 15.5, 17.5; Table 17.1}	Diversification of tourism attractions and revenues; shifting ski slopes to higher altitudes and glaciers; artificial snow-making	Integrated planning (e.g. carrying capacity; linkages with other sectors); financial incentives, e.g. subsidies and tax credits	Appeal/marketing of new attractions; financial and logistical challenges; potential adverse impact on other sectors (e.g. artificial snow-making may increase energy use); *revenues from 'new' attractions; involvement of wider group of stakeholders*
Transport {WGII 7.6, 17.2}	Realignment/relocation; design standards and planning for roads, rail and other infrastructure to cope with warming and drainage	Integrating climate change considerations into national transport policy; investment in R&D for special situations, e.g. permafrost areas	Financial and technological barriers; availability of less vulnerable routes; *improved technologies and integration with key sectors (e.g. energy)*
Energy {WGII 7.4, 16.2}	Strengthening of overhead transmission and distribution infrastructure; underground cabling for utilities; energy efficiency; use of renewable sources; reduced dependence on single sources of energy	National energy policies, regulations, and fiscal and financial incentives to encourage use of alternative sources; incorporating climate change in design standards	Access to viable alternatives; financial and technological barriers; acceptance of new technologies; *stimulation of new technologies; use of local resources*

Note:
Other examples from many sectors would include early warning systems.

4.3 Mitigation options

Both bottom-up and top-down studies[21] indicate that there is *high agreement* and *much evidence* of substantial economic potential[21] for the mitigation of global GHG emissions over the coming decades that could offset the projected growth of global emissions or reduce emissions below current levels. ***{WGIII 11.3, SPM}***

Figure 4.1 compares global economic mitigation potential in 2030 with the projected emissions increase from 2000 to 2030. Bottom-up studies suggest that mitigation opportunities with net negative costs[22] have the potential to reduce emissions by about 6 $GtCO_2$-eq/yr in 2030. Realising these requires dealing with implementation barriers. The economic mitigation potential, which is generally greater than the market mitigation potential, can only be achieved when adequate policies are in place and barriers removed.[21] *{WGIII 11.3, SPM}*

Sectoral estimates of economic mitigation potential and marginal costs derived from bottom-up studies corrected for double counting of mitigation potential are shown in Figure 4.2. While top-down and bottom-up studies are in line at the global level, there are considerable differences at the sectoral level. *{WGIII 11.3, SPM}*

No single technology can provide all of the mitigation potential in any sector. Table 4.2 lists selected examples of key technologies, policies, constraints and opportunities by sector. *{WGIII SPM}*

Future energy infrastructure investment decisions, expected to total over US$20 trillion[23] between 2005 and 2030, will have long-term impacts on GHG emissions, because of the long lifetimes of energy plants and other infrastructure capital stock. The widespread diffusion of low-carbon technologies may take many decades, even if early investments in these technologies are made attractive. Initial estimates show that returning global energy-related CO_2 emissions to 2005 levels by 2030 would require a large shift in the pattern of investment, although the net additional investment required ranges from negligible to 5 to 10%. *{WGIII 4.1, 4.4, 11.6, SPM}*

Comparison between global economic mitigation potential and projected emissions increase in 2030

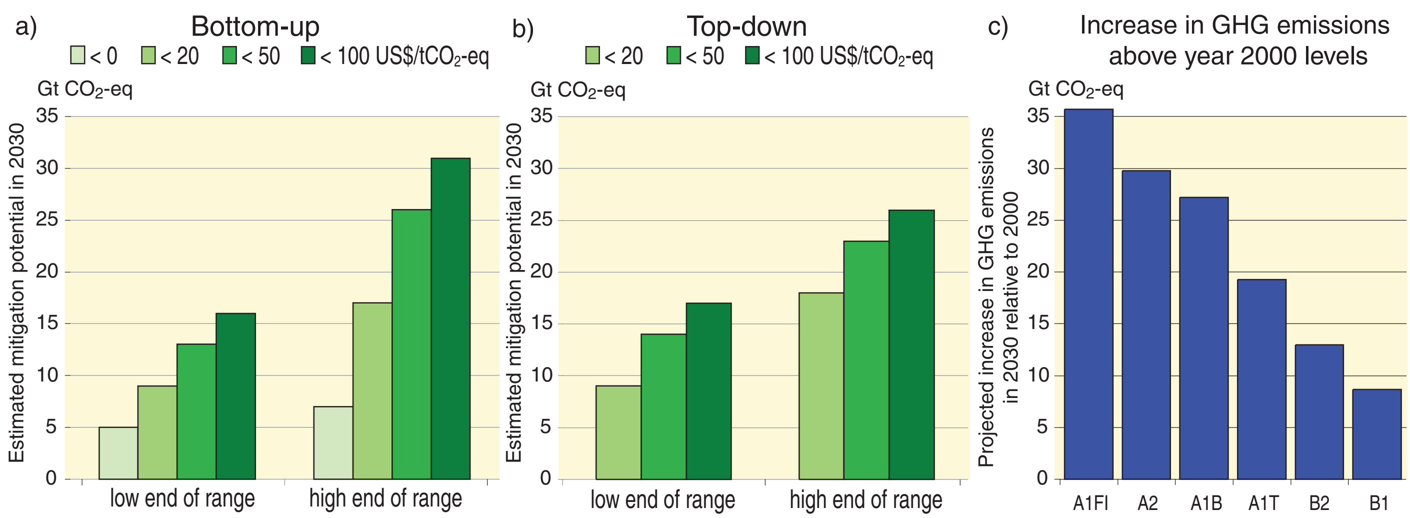

Figure 4.1. *Global economic mitigation potential in 2030 estimated from bottom-up (Panel a) and top-down (Panel b) studies, compared with the projected emissions increases from SRES scenarios relative to year 2000 GHG emissions of 40.8 $GtCO_2$-eq (Panel c). Note: GHG emissions in 2000 are exclusive of emissions of decay of above-ground biomass that remains after logging and deforestation and from peat fires and drained peat soils, to ensure consistency with the SRES emissions results. {WGIII Figures SPM.4, SPM.5a, SPM.5b}*

[21] The concept of **'mitigation potential'** has been developed to assess the scale of GHG reductions that could be made, relative to emission baselines, for a given level of carbon price (expressed in cost per unit of carbon dioxide equivalent emissions avoided or reduced). Mitigation potential is further differentiated in terms of 'market mitigation potential' and 'economic mitigation potential'.

Market mitigation potential is the mitigation potential based on private costs and private discount rates (reflecting the perspective of private consumers and companies), which might be expected to occur under forecast market conditions, including policies and measures currently in place, noting that barriers limit actual uptake.

Economic mitigation potential is the mitigation potential that takes into account social costs and benefits and social discount rates (reflecting the perspective of society; social discount rates are lower than those used by private investors), assuming that market efficiency is improved by policies and measures and barriers are removed.

Mitigation potential is estimated using different types of approaches. ***Bottom-up studies*** are based on assessment of mitigation options, emphasising specific technologies and regulations. They are typically sectoral studies taking the macro-economy as unchanged. ***Top-down studies*** assess the economy-wide potential of mitigation options. They use globally consistent frameworks and aggregated information about mitigation options and capture macro-economic and market feedbacks.

[22] Net negative costs (no regrets opportunities) are defined as those options whose benefits such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change.

[23] 20 trillion = 20,000 billion = 20×10^{12}

Economic mitigation potentials by sector in 2030 estimated from bottom-up studies

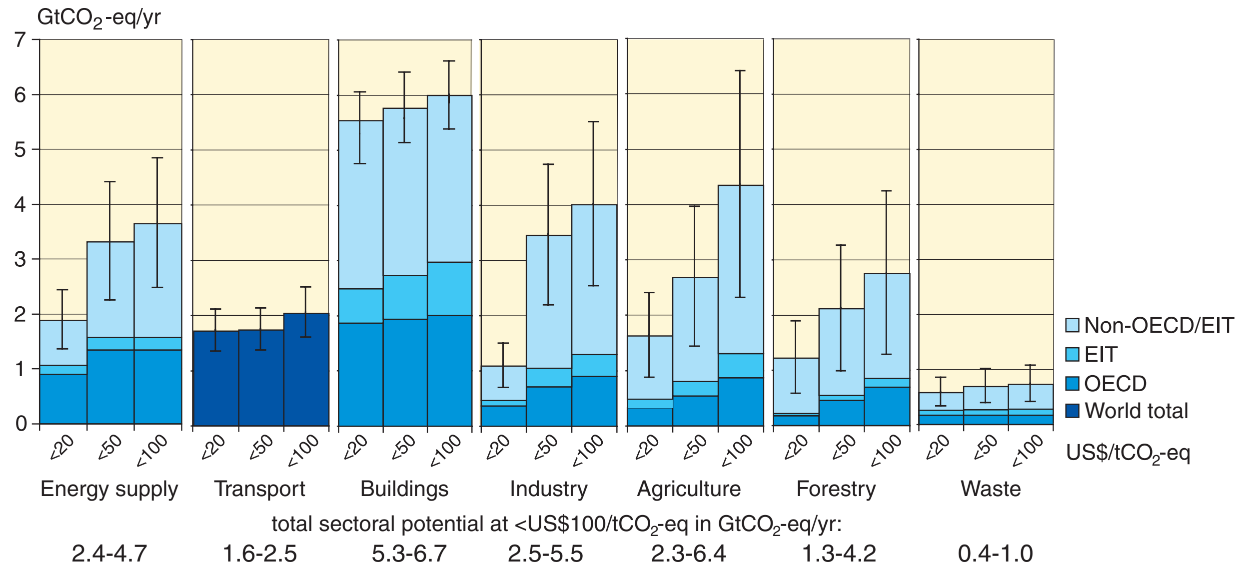

Figure 4.2. *Estimated economic mitigation potential by sector and region using technologies and practices expected to be available in 2030. The potentials do not include non-technical options such as lifestyle changes. {WGIII Figure SPM.6}*

Notes:

a) The ranges for global economic potentials as assessed in each sector are shown by vertical lines. The ranges are based on end-use allocations of emissions, meaning that emissions of electricity use are counted towards the end-use sectors and not to the energy supply sector.

b) The estimated potentials have been constrained by the availability of studies particularly at high carbon price levels.

c) Sectors used different baselines. For industry the SRES B2 baseline was taken, for energy supply and transport the World Energy Outlook (WEO) 2004 baseline was used; the building sector is based on a baseline in between SRES B2 and A1B; for waste, SRES A1B driving forces were used to construct a waste-specific baseline; agriculture and forestry used baselines that mostly used B2 driving forces.

d) Only global totals for transport are shown because international aviation is included.

e) Categories excluded are non-CO_2 emissions in buildings and transport, part of material efficiency options, heat production and cogeneration in energy supply, heavy duty vehicles, shipping and high-occupancy passenger transport, most high-cost options for buildings, wastewater treatment, emission reduction from coal mines and gas pipelines, and fluorinated gases from energy supply and transport. The underestimation of the total economic potential from these emissions is of the order of 10 to 15%.

While studies use different methodologies, there is *high agreement* and *much evidence* that in all analysed world regions near-term health co-benefits from reduced air pollution, as a result of actions to reduce GHG emissions, can be substantial and may offset a substantial fraction of mitigation costs. *{WGIII 11.8, SPM}*

Energy efficiency and utilisation of renewable energy offer synergies with sustainable development. In least developed countries, energy substitution can lower mortality and morbidity by reducing indoor air pollution, reduce the workload for women and children and decrease the unsustainable use of fuelwood and related deforestation. *{WGIII 11.8, 11.9, 12.4}*

Literature since the TAR confirms with *high agreement* and *medium evidence* that there may be effects from Annex I countries' action on the global economy and global emissions, although the scale of carbon leakage remains uncertain. *{WGIII 11.7, SPM}*

Fossil fuel exporting nations (in both Annex I and non-Annex I countries) may expect, as indicated in the TAR, lower demand and prices and lower GDP growth due to mitigation policies. The extent of this spillover depends strongly on assumptions related to policy decisions and oil market conditions. *{WGIII 11.7, SPM}*

Critical uncertainties remain in the assessment of carbon leakage. Most equilibrium modelling supports the conclusion in the TAR of economy-wide leakage from Kyoto action in the order of 5 to 20%, which would be less if competitive low-emissions technologies were effectively diffused. *{WGIII 11.7, SPM}*

There is also *high agreement* and *medium evidence* that changes in lifestyle and behaviour patterns can contribute to climate change mitigation across all sectors. Management practices can also have a positive role. *{WGIII SPM}*

Examples that can have positive impacts on mitigation include changes in consumption patterns, education and training, changes in building occupant behaviour, transport demand management and management tools in industry. *{WGIII 4.1, 5.1, 6.7, 7.3, SPM}*

Policies that provide a real or implicit price of carbon could create incentives for producers and consumers to significantly invest in low-GHG products, technologies and processes. *{WGIII SPM}*

An effective carbon-price signal could realise significant mitigation potential in all sectors. Modelling studies show that global carbon prices rising to US\$20-80/tCO_2-eq by 2030 are consistent with stabilisation at around 550ppm CO_2-eq by 2100. For the same

Table 4.2 *Selected examples of key sectoral mitigation technologies, policies and measures, constraints and opportunities. {WGIII Tables SPM.3, SPM.7}*

Sector	Key mitigation technologies and practices currently commercially available. ***Key mitigation technologies and practices projected to be commercialised before 2030 shown in italics.***	Policies, measures and instruments shown to be environmentally effective	Key constraints or opportunities (Normal font = constraints; *italics = opportunities*)
Energy Supply {WGIII 4.3, 4.4}	Improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); combined heat and power; early applications of carbon dioxide capture and storage (CCS) (e.g. storage of removed CO_2 from natural gas); *CCS for gas, biomass and coal-fired electricity generating facilities; advanced nuclear power; advanced renewable energy, including tidal and wave energy, concentrating solar, and solar photovoltaics*	Reduction of fossil fuel subsidies; taxes or carbon charges on fossil fuels	Resistance by vested interests may make them difficult to implement
		Feed-in tariffs for renewable energy technologies; renewable energy obligations; producer subsidies	*May be appropriate to create markets for low-emissions technologies*
Transport {WGIII 5.4}	More fuel-efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorised transport (cycling, walking); land-use and transport planning; *second generation biofuels; higher efficiency aircraft; advanced electric and hybrid vehicles with more powerful and reliable batteries*	Mandatory fuel economy; biofuel blending and CO_2 standards for road transport	Partial coverage of vehicle fleet may limit effectiveness
		Taxes on vehicle purchase, registration, use and motor fuels; road and parking pricing	Effectiveness may drop with higher incomes
		Influence mobility needs through land-use regulations and infrastructure planning; investment in attractive public transport facilities and non-motorised forms of transport	*Particularly appropriate for countries that are building up their transportation systems*
Buildings {WGIII 6.5}	Efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases; *integrated design of commercial buildings including technologies, such as intelligent meters that provide feedback and control; solar photovoltaics integrated in buildings*	Appliance standards and labelling	Periodic revision of standards needed
		Building codes and certification	*Attractive for new buildings*. Enforcement can be difficult
		Demand-side management programmes	Need for regulations so that utilities may profit
		Public sector leadership programmes, including procurement	*Government purchasing can expand demand for energy-efficient products*
		Incentives for energy service companies (ESCOs)	*Success factor: Access to third party financing*
Industry {WGIII 7.5}	More efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO_2 gas emissions; and a wide array of process-specific technologies; *advanced energy efficiency; CCS for cement, ammonia, and iron manufacture; inert electrodes for aluminium manufacture*	Provision of benchmark information; performance standards; subsidies; tax credits	*May be appropriate to stimulate technology uptake.* Stability of national policy important in view of international competitiveness
		Tradable permits	Predictable allocation mechanisms and stable price signals important for investments
		Voluntary agreements	Success factors include: clear targets, a baseline scenario, third-party involvement in design and review and formal provisions of monitoring, close cooperation between government and industry
Agriculture {WGIII 8.4}	Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH_4 emissions; improved nitrogen fertiliser application techniques to reduce N_2O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency; *improvements of crop yields*	Financial incentives and regulations for improved land management; maintaining soil carbon content; efficient use of fertilisers and irrigation	*May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation*
Forestry/forests {WGIII 9.4}	Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use; *tree species improvement to increase biomass productivity and carbon sequestration; improved remote sensing technologies for analysis of vegetation/soil carbon sequestration potential and mapping land-use change*	Financial incentives (national and international) to increase forest area, to reduce deforestation and to maintain and manage forests; land-use regulation and enforcement	Constraints include lack of investment capital and land tenure issues. *Can help poverty alleviation.*
Waste {WGIII 10.4}	Landfill CH_4 recovery; waste incineration with energy recovery; composting of organic waste; controlled wastewater treatment; recycling and waste minimisation; *biocovers and biofilters to optimise CH_4 oxidation*	Financial incentives for improved waste and wastewater management	*May stimulate technology diffusion*
		Renewable energy incentives or obligations	Local availability of low-cost fuel
		Waste management regulations	Most effectively applied at national level with enforcement strategies

stabilisation level, studies since the TAR that take into account induced technological change may lower these price ranges to US$5-65/t$CO_2$-eq in 2030.[24] *{WGIII 3.3, 11.4, 11.5, SPM}*

There is *high agreement* and *much evidence* that a wide variety of national policies and instruments are available to governments to create the incentives for mitigation action. Their applicability depends on national circumstances and an understanding of their interactions, but experience from implementation in various countries and sectors shows there are advantages and disadvantages for any given instrument. ***{WGIII 13.2, SPM}***

Four main criteria are used to evaluate policies and instruments: environmental effectiveness, cost effectiveness, distributional effects including equity, and institutional feasibility. *{WGIII 13.2, SPM}*

General findings about the performance of policies are: *{WGIII 13.2, SPM}*

- ***Integrating climate policies in broader development policies*** makes implementation and overcoming barriers easier.
- ***Regulations and standards*** generally provide some certainty about emission levels. They may be preferable to other instruments when information or other barriers prevent producers and consumers from responding to price signals. However, they may not induce innovations and more advanced technologies.
- ***Taxes and charges*** can set a price for carbon, but cannot guarantee a particular level of emissions. Literature identifies taxes as an efficient way of internalising costs of GHG emissions.
- ***Tradable permits*** will establish a carbon price. The volume of allowed emissions determines their environmental effectiveness, while the allocation of permits has distributional consequences. Fluctuation in the price of carbon makes it difficult to estimate the total cost of complying with emission permits.
- ***Financial incentives*** (subsidies and tax credits) are frequently used by governments to stimulate the development and diffusion of new technologies. While economic costs are generally higher than for the instruments listed above, they are often critical to overcome barriers.
- ***Voluntary agreements*** between industry and governments are politically attractive, raise awareness among stakeholders and have played a role in the evolution of many national policies. The majority of agreements have not achieved significant emissions reductions beyond business as usual. However, some recent agreements, in a few countries, have accelerated the application of best available technology and led to measurable emission reductions.
- ***Information instruments*** (e.g. awareness campaigns) may positively affect environmental quality by promoting informed choices and possibly contributing to behavioural change, however, their impact on emissions has not been measured yet.
- ***Research, development and demonstration (RD&D)*** can stimulate technological advances, reduce costs and enable progress toward stabilisation.

Some corporations, local and regional authorities, NGOs and civil groups are adopting a wide variety of voluntary actions. These voluntary actions may limit GHG emissions, stimulate innovative policies and encourage the deployment of new technologies. On their own, they generally have limited impact on national- or regional-level emissions. *{WGIII 13.4, SPM}*

4.4 Relationship between adaptation and mitigation options and relationship with sustainable development

There is growing understanding of the possibilities to choose and implement climate response options in several sectors to realise synergies and avoid conflicts with other dimensions of sustainable development. ***{WGIII SPM}***

Climate change policies related to energy efficiency and renewable energy are often economically beneficial, improve energy security and reduce local pollutant emissions. Reducing both loss of natural habitat and deforestation can have significant biodiversity, soil and water conservation benefits, and can be implemented in a socially and economically sustainable manner. Forestation and bioenergy plantations can restore degraded land, manage water runoff, retain soil carbon and benefit rural economies, but could compete with food production and may be negative for biodiversity, if not properly designed. *{WGII 20.3, 20.8; WGIII 4.5, 9.7, 12.3, SPM}*

There is growing evidence that decisions about macro-economic policy, agricultural policy, multilateral development bank lending, insurance practices, electricity market reform, energy security and forest conservation, for example, which are often treated as being apart from climate policy, can significantly reduce emissions (Table 4.3). Similarly, non-climate policies can affect adaptive capacity and vulnerability. *{WGII 20.3; WGIII SPM, 12.3}*

Both synergies and trade-offs exist between adaptation and mitigation options. ***{WGII 18.4.3; WGIII 11.9)***

Examples of synergies include properly designed biomass production, formation of protected areas, land management, energy use in buildings, and forestry, but synergies are rather limited in other sectors. Potential trade-offs include increased GHG emissions due to increased consumption of energy related to adaptive responses. *{WGII 18.4.3, 18.5, 18.7, TS.5.2; WGIII 4.5, 6.9, 8.5, 9.5, SPM}*

[24] Studies on mitigation portfolios and macro-economic costs assessed in this report are based on top-down modelling. Most models use a global least-cost approach to mitigation portfolios, with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century. Costs are given for a specific point in time. Global modelled costs will increase if some regions, sectors (e.g. land use), options or gases are excluded. Global modelled costs will decrease with lower baselines, use of revenues from carbon taxes and auctioned permits, and if induced technological learning is included. These models do not consider climate benefits and generally also co-benefits of mitigation measures, or equity issues. Significant progress has been achieved in applying approaches based on induced technological change to stabilisation studies; however, conceptual issues remain. In the models that consider induced technological change, projected costs for a given stabilisation level are reduced; the reductions are greater at lower stabilisation level.

Table 4.3. *Integrating climate change considerations into development policies – selected examples in the area of mitigation. {WGIII 12.2.4.6}*

Selected sectors	Non-climate change policy instruments and actions	Potentially affects:
Macro-economy	Implement non-climate taxes/subsidies and/or other fiscal and regulatory policies that promote sustainable development	Total global GHG emissions
Forestry	Adoption of forest conservation and sustainable management practices	GHG emissions from deforestation
Electricity	Adoption of cost-effective renewables, demand-side management programmes, and transmission and distribution loss reduction	Electricity sector CO_2 emissions
Petroleum imports	Diversifying imported and domestic fuel mix and reducing economy's energy intensity to improve energy security	Emissions from crude oil and product imports
Insurance for building, transport sectors	Differentiated premiums, liability insurance exclusions, improved terms for green products	Transport and building sector GHG emissions
International finance	Country and sector strategies and project lending that reduces emissions	Emissions from developing countries

4.5 International and regional cooperation

There is *high agreement* and *much evidence* that notable achievements of the UNFCCC and its Kyoto Protocol are the establishment of a global response to the climate change problem, stimulation of an array of national policies, the creation of an international carbon market and the establishment of new institutional mechanisms that may provide the foundation for future mitigation efforts. Progress has also been made in addressing adaptation within the UNFCCC and additional initiatives have been suggested. *{WGII 18.7; WGIII 13.3, SPM}*

The impact of the Protocol's first commitment period relative to global emissions is projected to be limited. Its economic impacts on participating Annex-B countries are projected to be smaller than presented in the TAR, which showed 0.2 to 2% lower GDP in 2012 without emissions trading and 0.1 to 1.1% lower GDP with emissions trading among Annex-B countries. To be more environmentally effective, future mitigation efforts would need to achieve deeper reductions covering a higher share of global emissions (see Topic 5). *{WGIII 1.4, 11.4, 13.3, SPM}*

The literature provides *high agreement* and *much evidence* of many options for achieving reductions of global GHG emissions at the international level through cooperation. It also suggests that successful agreements are environmentally effective, cost-effective, incorporate distributional considerations and equity, and are institutionally feasible. *{WGIII 13.3, SPM}*

Greater cooperative efforts to reduce emissions will help to reduce global costs for achieving a given level of mitigation, or will improve environmental effectiveness. Improving and expanding the scope of market mechanisms (such as emission trading, Joint Implementation and Clean Development Mechanism) could reduce overall mitigation costs. *{WGIII 13.3, SPM}*

Efforts to address climate change can include diverse elements such as emissions targets; sectoral, local, sub-national and regional actions; RD&D programmes; adopting common policies; implementing development-oriented actions; or expanding financing instruments. These elements can be implemented in an integrated fashion, but comparing the efforts made by different countries quantitatively would be complex and resource intensive. *{WGIII 13.3, SPM}*

Actions that could be taken by participating countries can be differentiated both in terms of when such action is undertaken, who participates and what the action will be. Actions can be binding or non-binding, include fixed or dynamic targets, and participation can be static or vary over time. *{WGIII 13.3, SPM}*

5

The long-term perspective: scientific and socio-economic aspects relevant to adaptation and mitigation, consistent with the objectives and provisions of the Convention, and in the context of sustainable development

5.1 Risk management perspective

Responding to climate change involves an iterative risk management process that includes both mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity and attitudes to risk. ***{WGII 20. 9, SPM; WGIII SPM}***

Risk management techniques can explicitly accommodate sectoral, regional and temporal diversity, but their application requires information about not only impacts resulting from the most likely climate scenarios, but also impacts arising from lower-probability but higher-consequence events and the consequences of proposed policies and measures. Risk is generally understood to be the product of the likelihood of an event and its consequences. Climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations. *{SYR 3.3, Figure 3.6; WGII 20.2, 20.9, SPM; WGIII 3.5, 3.6, SPM}*

5.2 Key vulnerabilities, impacts and risks – long-term perspectives

The five 'reasons for concern' identified in the TAR are now assessed to be stronger with many risks identified with higher confidence. Some are projected to be larger or to occur at lower increases in temperature. This is due to (1) better understanding of the magnitude of impacts and risks associated with increases in global average temperature and GHG concentrations, including vulnerability to present-day climate variability, (2) more precise identification of the circumstances that make systems, sectors, groups and regions especially vulnerable and (3) growing evidence that the risk of very large impacts on multiple century time scales would continue to increase as long as GHG concentrations and temperature continue to increase. Understanding about the relationship between impacts (the basis for 'reasons for concern' in the TAR) and vulnerability (that includes the ability to adapt to impacts) has improved. ***{WGII 4.4, 5.4, 19.ES, 19.3.7, TS.4.6; WGIII 3.5, SPM}***

The TAR concluded that vulnerability to climate change is a function of exposure, sensitivity and adaptive capacity. Adaptation can reduce sensitivity to climate change while mitigation can reduce the exposure to climate change, including its rate and extent. Both conclusions are confirmed in this assessment. *{WGII 20.2, 20.7.3}*

No single metric can adequately describe the diversity of key vulnerabilities or support their ranking. A sample of relevant impacts is provided in Figure 3.6. The estimation of key vulnerabilities in any system, and damage implied, will depend on exposure (the rate and magnitude of climate change), sensitivity, which is determined in part and where relevant by development status, and adaptive capacity. Some key vulnerabilities may be linked to thresholds; in some cases these may cause a system to shift from one state to another, whereas others have thresholds that are defined subjectively and thus depend on societal values. *{WGII 19.ES, 19.1}*

The five 'reasons for concern' that were identified in the TAR were intended to synthesise information on climate risks and key vulnerabilities and to "aid readers in making their own determination" about risk. These remain a viable framework to consider key vulnerabilities, and they have been updated in the AR4. *{TAR WGII Chapter 19; WGII SPM}*

- ***Risks to unique and threatened systems.*** There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase further. An increasing risk of species extinction and coral reef damage is projected with higher confidence than in the TAR as warming proceeds. There is *medium confidence* that approximately 20 to 30% of plant and animal species assessed so far are *likely* to be at increased risk of extinction if increases in global average temperature exceed 1.5 to 2.5°C over 1980-1999 levels. Confidence has increased that a 1 to 2°C increase in global mean temperature above 1990 levels (about 1.5 to 2.5°C above pre-indus-

Key Vulnerabilities and Article 2 of the UNFCCC

Article 2 of the UNFCCC states:

"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

Determining what constitutes "dangerous anthropogenic interference with the climate system" in relation to Article 2 of the UNFCCC involves value judgements. Science can support informed decisions on this issue, including by providing criteria for judging which vulnerabilities might be labelled 'key'. *{SYR 3.3, WGII 19.ES}*

Key vulnerabilities[25] may be associated with many climate-sensitive systems, including food supply, infrastructure, health, water resources, coastal systems, ecosystems, global biogeochemical cycles, ice sheets and modes of oceanic and atmospheric circulation. *{WGII 19.ES}*

More specific information is now available across the regions of the world concerning the nature of future impacts, including for some places not covered in previous assessments. *{WGII SPM}*

[25] Key Vulnerabilities can be identified based on a number of criteria in the literature, including magnitude, timing, persistence/reversibility, the potential for adaptation, distributional aspects, likelihood and 'importance' of the impacts.

trial) poses significant risks to many unique and threatened systems including many biodiversity hotspots. Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1 to 3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatisation by corals. Increasing vulnerability of Arctic indigenous communities and small island communities to warming is projected. *{SYR 3.3, 3.4, Figure 3.6, Table 3.2; WGII 4.ES, 4.4, 6.4, 14.4.6, 15.ES, 15.4, 15.6, 16.ES, 16.2.1, 16.4, Table 19.1, 19.3.7, TS.5.3, Figure TS.12, Figure TS.14}*

- ***Risks of extreme weather events.*** Responses to some recent extreme climate events reveal higher levels of vulnerability in both developing and developed countries than was assessed in the TAR. There is now higher confidence in the projected increases in droughts, heat waves and floods, as well as their adverse impacts. As summarised in Table 3.2, increases in drought, heat waves and floods are projected in many regions and would have mostly adverse impacts, including increased water stress and wild fire frequency, adverse effects on food production, adverse health effects, increased flood risk and extreme high sea level, and damage to infrastructure. *{SYR 3.2, 3.3, Table 3.2; WGI 10.3, Table SPM.2; WGII 1.3, 5.4, 7.1, 7.5, 8.2, 12.6, 19.3, Table 19.1, Table SPM.1}*
- ***Distribution of impacts and vulnerabilities.*** There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change and are frequently the most susceptible to climate-related damages, especially when they face multiple stresses. There is increasing evidence of greater vulnerability of specific groups such as the poor and elderly not only in developing but also in developed countries. There is greater confidence in the projected regional patterns of climate change (see Topic 3.2) and in the projections of regional impacts, enabling better identification of particularly vulnerable systems, sectors and regions (see Topic 3.3). Moreover, there is increased evidence that low-latitude and less-developed areas generally face greater risk, for example in dry areas and megadeltas. New studies confirm that Africa is one of the most vulnerable continents because of the range of projected impacts, multiple stresses and low adaptive capacity. Substantial risks due to sea level rise are projected particularly for Asian megadeltas and for small island communities. *{SYR 3.2, 3.3, 5.4; WGI 11.2-11.7, SPM; WGII 3.4.3, 5.3, 5.4, Boxes 7.1 and 7.4, 8.1.1, 8.4.2, 8.6.1.3, 8.7, 9.ES, Table 10.9, 10.6, 16.3, 19.ES, 19.3, Table 19.1, 20.ES, TS.4.5, TS.5.4, Tables TS.1, TS.3, TS.4, SPM}*
- ***Aggregate impacts.*** Compared to the TAR, initial net market-based benefits from climate change are projected to peak at a lower magnitude and therefore sooner than was assessed in the TAR. It is *likely* that there will be higher damages for larger magnitudes of global temperature increase than estimated in the TAR, and the net costs of impacts of increased warming are projected to increase over time. Aggregate impacts have also been quantified in other metrics (see Topic 3.3): for example, climate change over the next century is *likely* to adversely affect hundreds of millions of people through increased coastal flooding, reductions in water supplies, increased malnutrition and increased health impacts. *{SYR 3.3, Figure 3.6; WGII 19.3.7, 20.7.3, TS.5.3}*
- ***Risks of large-scale singularities.***[26] As discussed in Topic 3.4, during the current century, a large-scale abrupt change in the meridional overturning circulation is *very unlikely*. There is *high confidence* that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales. This is because ice dynamical processes seen in recent observations but not fully included in ice sheet models assessed in the AR4 could increase the rate of ice loss. Complete deglaciation of the Greenland ice sheet would raise sea level by 7m and could be irreversible. *{SYR 3.4; WGI 10.3, Box 10.1; WGII 19.3.7, SPM}*

5.3 Adaptation and mitigation

There is *high confidence* that neither adaptation nor mitigation alone can avoid all climate change impacts. Adaptation is necessary both in the short term and longer term to address impacts resulting from the warming that would occur even for the lowest stabilisation scenarios assessed. There are barriers, limits and costs that are not fully understood. Adaptation and mitigation can complement each other and together can significantly reduce the risks of climate change. ***{WGII 4.ES, TS 5.1, 18.4, 18.6, 20.7, SPM; WGIII 1.2, 2.5, 3.5, 3.6}***

Adaptation will be ineffective for some cases such as natural ecosystems (e.g. loss of Arctic sea ice and marine ecosystem viability), the disappearance of mountain glaciers that play vital roles in water storage and supply, or adaptation to sea level rise of several metres[27]. It will be less feasible or very costly in many cases for the projected climate change beyond the next several decades (such as deltaic regions and estuaries). There is *high confidence* that the ability of many ecosystems to adapt naturally will be exceeded this century. In addition, multiple barriers and constraints to effective adaptation exist in human systems (see Topic 4.2). *{SYR 4.2; WGII 17.4.2, 19.2, 19.4.1}*

Unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt. Reliance on adaptation alone could eventually lead to a magnitude of climate change to which effective adaptation is not possible, or will only be available at very high social, environmental and economic costs. *{WGII 18.1, SPM}*

[26] See glossary

[27] While it is technically possible to adapt to several metres of sea level rise, the resources required are so unevenly distributed that in reality this risk is outside the scope of adaptation. {WGII 17.4.2, 19.4.1}

Efforts to mitigate GHG emissions to reduce the rate and magnitude of climate change need to account for inertia in the climate and socio-economic systems. ***{SYR 3.2; WGI 10.3, 10.4, 10.7, SPM; WGIII 2.3.4}***

After GHG concentrations are stabilised, the rate at which the global average temperature increases is expected to slow within a few decades. Small increases in global average temperature could still be expected for several centuries. Sea level rise from thermal expansion would continue for many centuries at a rate that eventually decreases from that reached before stabilisation, due to ongoing heat uptake by oceans. *{SYR 3.2, WGI 10.3, 10.4, 10.7, SPM}*

Delayed emission reductions significantly constrain the opportunities to achieve lower stabilisation levels and increase the risk of more severe climate change impacts. Even though benefits of mitigation measures in terms of avoided climate change would take several decades to materialise, mitigation actions begun in the short term would avoid locking in both long-lived carbon intensive infrastructure and development pathways, reduce the rate of climate change and reduce the adaptation needs associated with higher levels of warming. *{WGII 18.4, 20.6, 20.7, SPM; WGIII 2.3.4, 3.4, 3.5, 3.6, SPM}*

5.4 Emission trajectories for stabilisation

In order to stabilise the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter.[28] The lower the stabilisation level, the more quickly this peak and decline would need to occur (Figure 5.1).[29] ***{WGIII 3.3, 3.5, SPM}***

Advances in modelling since the TAR permit the assessment of multi-gas mitigation strategies for exploring the attainability and costs for achieving stabilisation of GHG concentrations. These scenarios explore a wider range of future scenarios, including lower levels of stabilisation, than reported in the TAR. *{WGIII 3.3, 3.5, SPM}*

Mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels (Table 5.1 and Figure 5.1). ***{WGIII 3.5, SPM}***

Table 5.1 summarises the required emission levels for different groups of stabilisation concentrations and the resulting equilibrium

CO_2 emissions and equilibrium temperature increases for a range of stabilisation levels

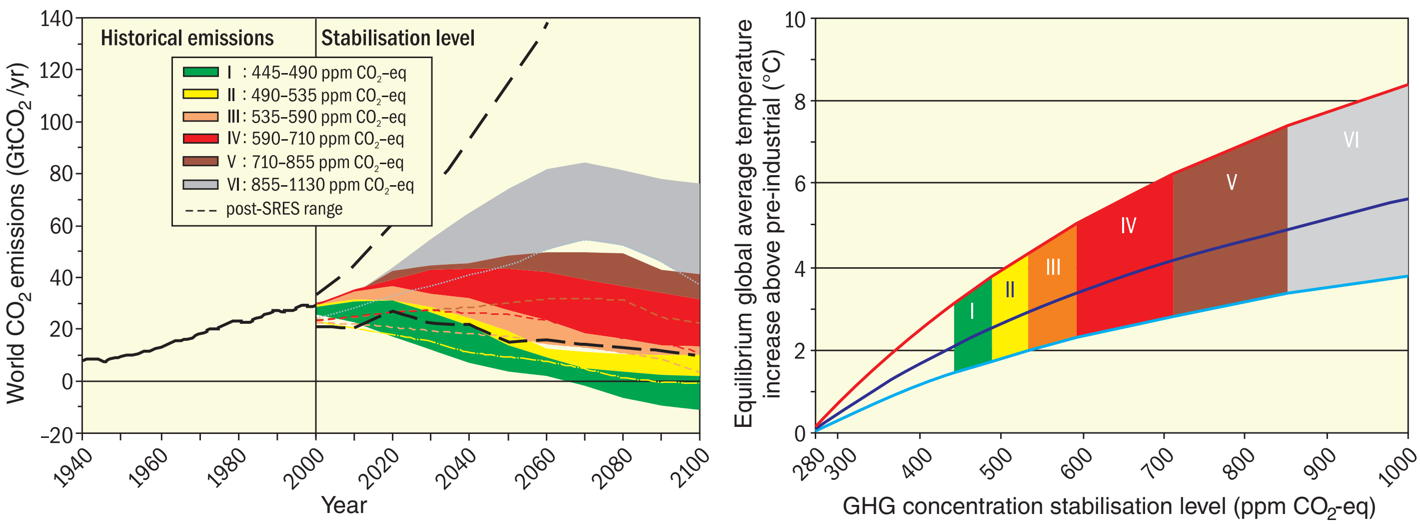

Figure 5.1. Global CO_2 emissions for 1940 to 2000 and emissions ranges for categories of stabilisation scenarios from 2000 to 2100 (left-hand panel); and the corresponding relationship between the stabilisation target and the likely *equilibrium global average temperature increase above pre-industrial (right-hand panel). Approaching equilibrium can take several centuries, especially for scenarios with higher levels of stabilisation. Coloured shadings show stabilisation scenarios grouped according to different targets (stabilisation category I to VI). The right-hand panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of* likely *range of climate sensitivity of 4.5°C (red line at top of shaded area) (iii) lower bound of* likely *range of climate sensitivity of 2°C (blue line at bottom of shaded area). Black dashed lines in the left panel give the emissions range of recent baseline scenarios published since the SRES (2000). Emissions ranges of the stabilisation scenarios comprise CO_2-only and multigas scenarios and correspond to the 10^{th} to 90^{th} percentile of the full scenario distribution. Note: CO_2 emissions in most models do not include emissions from decay of above ground biomass that remains after logging and deforestation, and from peat fires and drained peat soils. {WGIII Figures SPM.7 and SPM.8}*

[28] Peaking means that the emissions need to reach a maximum before they decline later.

[29] For the lowest mitigation scenario category assessed, emissions would need to peak by 2015 and for the highest by 2090 (see Table 5.1). Scenarios that use alternative emission pathways show substantial differences on the rate of global climate change. {WGII 19.4}

Table 5.1. *Characteristics of post-TAR stabilisation scenarios and resulting long-term equilibrium global average temperature and the sea level rise component from thermal expansion only.[a] {WGI 10.7; WGIII Table TS.2, Table 3.10, Table SPM.5}*

Category	CO_2 concentration at stabilisation (2005 = 379 ppm)[b]	CO_2-equivalent concentration at stabilisation including GHGs and aerosols (2005=375 ppm)[b]	Peaking year for CO_2 emissions[a,c]	Change in global CO_2 emissions in 2050 (percent of 2000 emissions)[a,c]	Global average temperature increase above pre-industrial at equilibrium, using 'best estimate' climate sensitivity[d,e]	Global average sea level rise above pre-industrial at equilibrium from thermal expansion only[f]	Number of assessed scenarios
	ppm	ppm	year	percent	°C	metres	
I	350 – 400	445 – 490	2000 – 2015	-85 to -50	2.0 – 2.4	0.4 – 1.4	6
II	400 – 440	490 – 535	2000 – 2020	-60 to -30	2.4 – 2.8	0.5 – 1.7	18
III	440 – 485	535 – 590	2010 – 2030	-30 to +5	2.8 – 3.2	0.6 – 1.9	21
IV	485 – 570	590 – 710	2020 – 2060	+10 to +60	3.2 – 4.0	0.6 – 2.4	118
V	570 – 660	710 – 855	2050 – 2080	+25 to +85	4.0 – 4.9	0.8 – 2.9	9
VI	660 – 790	855 – 1130	2060 – 2090	+90 to +140	4.9 – 6.1	1.0 – 3.7	5

Notes:

a) The emission reductions to meet a particular stabilisation level reported in the mitigation studies assessed here might be underestimated due to missing carbon cycle feedbacks (see also Topic 2.3).

b) Atmospheric CO_2 concentrations were 379ppm in 2005. The best estimate of total CO_2-eq concentration in 2005 for all long-lived GHGs is about 455ppm, while the corresponding value including the net effect of all anthropogenic forcing agents is 375ppm CO_2-eq.

c) Ranges correspond to the 15th to 85th percentile of the post-TAR scenario distribution. CO_2 emissions are shown so multi-gas scenarios can be compared with CO_2-only scenarios (see Figure 2.1).

d) The best estimate of climate sensitivity is 3°C.

e) Note that global average temperature at equilibrium is different from expected global average temperature at the time of stabilisation of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilisation of GHG concentrations occurs between 2100 and 2150 (see also Footnote 30).

f) Equilibrium sea level rise is for the contribution from ocean thermal expansion only and does not reach equilibrium for at least many centuries. These values have been estimated using relatively simple climate models (one low-resolution AOGCM and several EMICs based on the best estimate of 3°C climate sensitivity) and do not include contributions from melting ice sheets, glaciers and ice caps. Long-term thermal expansion is projected to result in 0.2 to 0.6m per degree Celsius of global average warming above pre-industrial. (AOGCM refers to Atmosphere-Ocean General Circulation Model and EMICs to Earth System Models of Intermediate Complexity.)

global average temperature increases, using the 'best estimate' of climate sensitivity (see Figure 5.1 for the *likely* range of uncertainty). Stabilisation at lower concentration and related equilibrium temperature levels advances the date when emissions need to peak and requires greater emissions reductions by 2050.[30] Climate sensitivity is a key uncertainty for mitigation scenarios that aim to meet specific temperature levels. The timing and level of mitigation to reach a given temperature stabilisation level is earlier and more stringent if climate sensitivity is high than if it is low. *{WGIII 3.3, 3.4, 3.5, 3.6, SPM}*

Sea level rise under warming is inevitable. Thermal expansion would continue for many centuries after GHG concentrations have stabilised, for any of the stabilisation levels assessed, causing an eventual sea level rise much larger than projected for the 21st century (Table 5.1). If GHG and aerosol concentrations had been stabilised at year 2000 levels, thermal expansion alone would be expected to lead to further sea level rise of 0.3 to 0.8m. The eventual contributions from Greenland ice sheet loss could be several metres, and larger than from thermal expansion, should warming in excess of 1.9 to 4.6°C above pre-industrial be sustained over many centuries. These long-term consequences would have major implications for world coastlines. The long time scale of thermal expansion and ice sheet response to warming imply that mitigation strategies that seek to stabilise GHG concentrations (or radiative forcing) at or above present levels do not stabilise sea level for many centuries. *{WGI 10.7}*

Feedbacks between the carbon cycle and climate change affect the required mitigation and adaptation response to climate change. Climate-carbon cycle coupling is expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms (see Topics 2.3 and 3.2.1), but mitigation studies have not yet incorporated the full range of these feedbacks. As a consequence, the emission reductions to meet a particular stabilisation level reported in the mitigation studies assessed in Table 5.1 might be underestimated. Based on current understanding of climate-carbon cycle feedbacks, model studies suggest that stabilising CO_2 concentrations at, for example, 450ppm[31] could require cumulative emissions over the 21st century to be less than 1800 [1370 to 2200] $GtCO_2$, which is about 27% less than the 2460 [2310 to 2600] $GtCO_2$ determined without consideration of carbon cycle feedbacks. *{SYR 2.3, 3.2.1; WGI 7.3, 10.4, SPM}*

[30] Estimates for the evolution of temperature over the course of this century are not available in the AR4 for the stabilisation scenarios. For most stabilisation levels global average temperature is approaching the equilibrium level over a few centuries. For the much lower stabilisation scenarios (category I and II, Figure 5.1), the equilibrium temperature may be reached earlier.

[31] To stabilise at 1000ppm CO_2, this feedback could require that cumulative emissions be reduced from a model average of approximately 5190 [4910 to 5460] $GtCO_2$ to approximately 4030 [3590 to 4580] $GtCO_2$. {WGI 7.3, 10.4, SPM}

5.5 Technology flows and development

There is *high agreement* and *much evidence* that all stabilisation levels assessed can be achieved by deployment of a portfolio of technologies that are either currently available or expected to be commercialised in coming decades, assuming appropriate and effective incentives are in place for development, acquisition, deployment and diffusion of technologies and addressing related barriers. ***{WGIII SPM}***

Worldwide deployment of low-GHG emission technologies as well as technology improvements through public and private RD&D would be required for achieving stabilisation targets as well as cost reduction.[32] Figure 5.2 gives illustrative examples of the contribution of the portfolio of mitigation options. The contribution of different technologies varies over time and region and depends on the baseline development path, available technologies and relative costs, and the analysed stabilisation levels. Stabilisation at the lower of the assessed levels (490 to 540ppm CO_2-eq) requires early investments and substantially more rapid diffusion and commercialisation of advanced low-emissions technologies over the next decades (2000-2030) and higher contributions across abatement options in the long term (2000-2100). This requires that barriers to development, acquisition, deployment and diffusion of technologies are effectively addressed with appropriate incentives. *{WGIII 2.7, 3.3, 3.4, 3.6, 4.3, 4.4, 4.6, SPM}*

Without sustained investment flows and effective technology transfer, it may be difficult to achieve emission reduction at a significant scale. Mobilising financing of incremental costs of low-carbon technologies is important. *{WGIII 13.3, SPM}*

There are large uncertainties concerning the future contribution of different technologies. However, all assessed stabilisation scenarios concur that 60 to 80% of the reductions over the course of the century would come from energy supply and use and industrial processes. Including non-CO_2 and CO_2 land-use and forestry mitigation options provides greater flexibility and cost-effectiveness. Energy efficiency plays a key role across many scenarios for most regions and time scales. For lower stabilisation levels, scenarios put more emphasis on the use of low-carbon energy sources, such as renewable energy, nuclear power and the use of CO_2 capture and storage (CCS). In these scenarios, improvements of carbon intensity of energy supply and the whole economy needs to be much faster than in the past (Figure 5.2). *{WGIII 3.3, 3.4, TS.3, SPM}*

Illustrative mitigation portfolios for achieving stabilisation of GHG concentrations

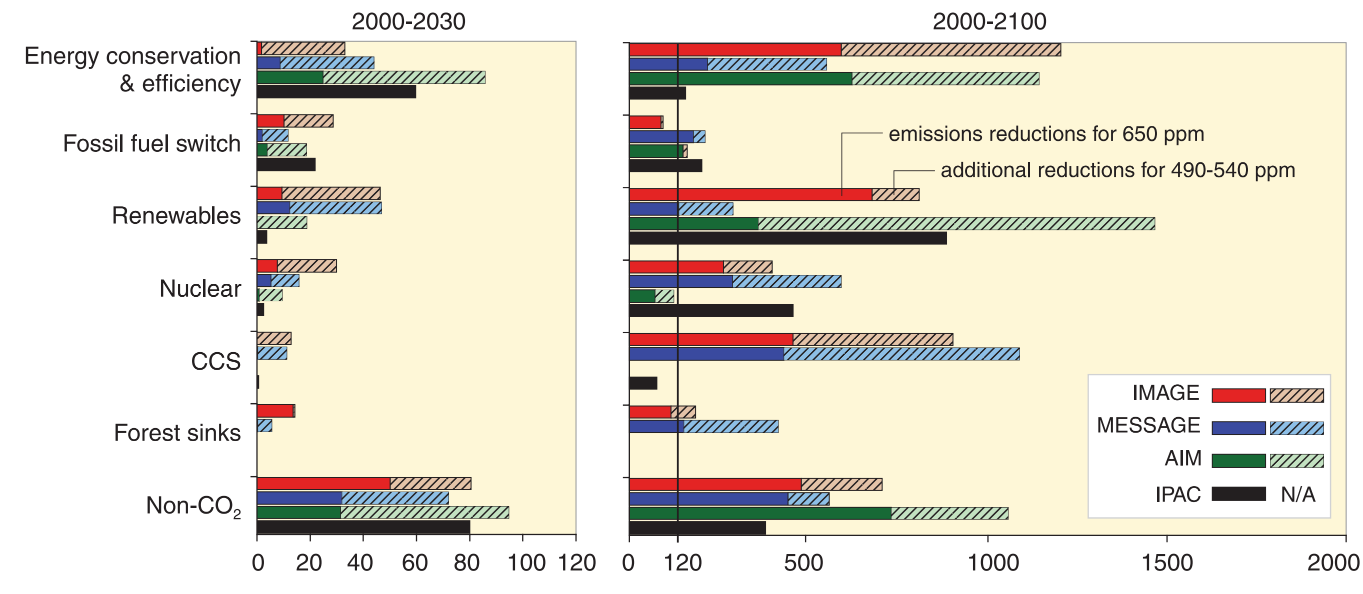

Figure 5.2 *Cumulative emissions reductions for alternative mitigation measures for 2000-2030 (left-hand panel) and for 2000-2100 (right-hand panel). The figure shows illustrative scenarios from four models (AIM, IMAGE, IPAC and MESSAGE) aiming at the stabilisation at low (490 to 540ppm CO_2-eq) and intermediate levels (650ppm CO_2-eq) respectively. Dark bars denote reductions for a target of 650ppm CO_2-eq and light bars denote the additional reductions to achieve 490 to 540ppm CO_2-eq. Note that some models do not consider mitigation through forest sink enhancement (AIM and IPAC) or CCS (AIM) and that the share of low-carbon energy options in total energy supply is also determined by inclusion of these options in the baseline. CCS includes CO_2 capture and storage from biomass. Forest sinks include reducing emissions from deforestation. The figure shows emissions reductions from baseline scenarios with cumulative emissions between 6000 to 7000 $GtCO_2$-eq (2000-2100). {WGIII Figure SPM.9}*

[32] By comparison, government funding in real absolute terms for most energy research programmes has been flat or declining for nearly two decades (even after the UNFCCC came into force) and is now about half of the 1980 level. {WGIII 2.7, 3.4, 4.5, 11.5, 13.2}

5.6 Costs of mitigation and long-term stabilisation targets

The macro-economic costs of mitigation generally rise with the stringency of the stabilisation target and are relatively higher when derived from baseline scenarios characterised by high emission levels. ***{WGIII SPM}***

There is *high agreement* and *medium evidence* that in 2050 global average macro-economic costs for multi-gas mitigation towards stabilisation between 710 and 445ppm CO_2-eq are between a 1% gain to a 5.5% decrease of global GDP (Table 5.2). This corresponds to slowing average annual global GDP growth by less than 0.12 percentage points. Estimated GDP losses by 2030 are on average lower and show a smaller spread compared to 2050 (Table 5.2). For specific countries and sectors, costs vary considerably from the global average.[33] *{WGIII 3.3, 13.3, SPM}*

5.7 Costs, benefits and avoided climate impacts at global and regional levels

Impacts of climate change will vary regionally. Aggregated and discounted to the present, they are *very likely* to impose net annual costs, which will increase over time as global temperatures increase. ***{WGII SPM}***

For increases in global average temperature of less than 1 to 3°C above 1980-1999 levels, some impacts are projected to produce market benefits in some places and sectors while, at the same time, imposing costs in other places and sectors. Global mean losses could be 1 to 5% of GDP for 4°C of warming, but regional losses could be substantially higher. *{WGII 9.ES, 10.6, 15.ES, 20.6, SPM}*

Peer-reviewed estimates of the social cost of carbon (net economic costs of damages from climate change aggregated across the globe and discounted to the present) for 2005 have an average value of US$12 per tonne of CO_2, but the range from 100 estimates is large (-$3 to $95/t$CO_2$). The range of published evidence indicates that the net damage costs of climate change are projected to be significant and to increase over time. *{WGII 20.6, SPM}*

It is *very likely* that globally aggregated figures underestimate the damage costs because they cannot include many non-quantifiable impacts. It is *virtually certain* that aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries and populations. In some locations and amongst some groups of people with high exposure, high sensitivity and/or low adaptive capacity, net costs will be significantly larger than the global average. *{WGII 7.4, 20.ES, 20.6, 20.ES, SPM}*

Limited and early analytical results from integrated analyses of the global costs and benefits of mitigation indicate that these are broadly comparable in magnitude, but do not as yet permit an unambiguous determination of an emissions pathway or stabilisation level where benefits exceed costs. ***{WGIII SPM}***

Comparing the costs of mitigation with avoided damages would require the reconciliation of welfare impacts on people living in different places and at different points in time into a global aggregate measure of well-being. *{WGII 18.ES}*

Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay. *{WGIII SPM}*

Many impacts can be avoided, reduced or delayed by mitigation. ***{WGII SPM}***

Although the small number of impact assessments that evaluate stabilisation scenarios do not take full account of uncertainties in projected climate under stabilisation, they nevertheless provide indications of damages avoided and risks reduced for different

Table 5.2. *Estimated global macro-economic costs in 2030 and 2050. Costs are relative to the baseline for least-cost trajectories towards different long-term stabilisation levels. {WGIII 3.3, 13.3, Tables SPM.4 and SPM.6}*

Stabilisation levels (ppm CO_2-eq)	Median GDP reduction[a] (%)		Range of GDP reduction[b] (%)		Reduction of average annual GDP growth rates (percentage points)[c,e]	
	2030	2050	2030	2050	2030	2050
445 – 535[d]	Not available		<3	<5.5	< 0.12	< 0.12
535 – 590	0.6	1.3	0.2 to 2.5	slightly negative to 4	< 0.1	< 0.1
590 – 710	0.2	0.5	-0.6 to 1.2	-1 to 2	< 0.06	< 0.05

Notes:
Values given in this table correspond to the full literature across all baselines and mitigation scenarios that provide GDP numbers.
a) Global GDP based on market exchange rates.
b) The 10th and 90th percentile range of the analysed data are given where applicable. Negative values indicate GDP gain. The first row (445-535ppm CO_2-eq) gives the upper bound estimate of the literature only.
c) The calculation of the reduction of the annual growth rate is based on the average reduction during the assessed period that would result in the indicated GDP decrease by 2030 and 2050 respectively.
d) The number of studies is relatively small and they generally use low baselines. High emissions baselines generally lead to higher costs.
e) The values correspond to the highest estimate for GDP reduction shown in column three.

[33] See Footnote 24 for further details on cost estimates and model assumptions.

amounts of emissions reduction. The rate and magnitude of future human-induced climate change and its associated impacts are determined by human choices defining alternative socio-economic futures and mitigation actions that influence emission pathways. Figure 3.2 demonstrates that alternative SRES emission pathways could lead to substantial differences in climate change throughout the 21st century. Some of the impacts at the high temperature end of Figure 3.6 could be avoided by socio-economic development pathways that limit emissions and associated climate change towards the lower end of the ranges illustrated in Figure 3.6. *{SYR 3.2, 3.3; WGIII 3.5, 3.6, SPM}*

Figure 3.6 illustrates how reduced warming could reduce the risk of, for example, affecting a significant number of ecosystems, the risk of extinctions, and the likelihood that cereal productivity in some regions would tend to fall. *{SYR 3.3, Figure 3.6; WGII 4.4, 5.4, Table 20.6}*

5.8 Broader environmental and sustainability issues

Sustainable development can reduce vulnerability to climate change, and climate change could impede nations' abilities to achieve sustainable development pathways. ***{WGII SPM}***

It is *very likely* that climate change can slow the pace of progress toward sustainable development either directly through increased exposure to adverse impacts or indirectly through erosion of the capacity to adapt. Over the next half-century, climate change could impede achievement of the Millennium Development Goals. *{WGII SPM}*

Climate change will interact at all scales with other trends in global environmental and natural resource concerns, including water, soil and air pollution, health hazards, disaster risk, and deforestation. Their combined impacts may be compounded in future in the absence of integrated mitigation and adaptation measures. *{WGII 20.3, 20.7, 20.8, SPM}*

Making development more sustainable can enhance mitigative and adaptive capacities, reduce emissions, and reduce vulnerability, but there may be barriers to implementation. ***{WGII 20.8; WGIII 12.2, SPM}***

Both adaptive and mitigative capacities can be enhanced through sustainable development. Sustainable development can, thereby, reduce vulnerability to climate change by reducing sensitivities (through adaptation) and/or exposure (through mitigation). At present, however, few plans for promoting sustainability have explicitly included either adapting to climate change impacts, or promoting adaptive capacity. Similarly, changing development paths can make a major contribution to mitigation but may require resources to overcome multiple barriers. *{WGII 20.3, 20.5, SPM; WGIII 2.1, 2.5, 12.1, SPM}*

6

Robust findings, key uncertainties

Robust findings, key uncertainties

As in the TAR, a robust finding for climate change is defined as one that holds under a variety of approaches, methods, models and assumptions, and is expected to be relatively unaffected by uncertainties. Key uncertainties are those that, if reduced, could lead to new robust findings. *{TAR SYR Q.9}*

Robust findings do not encompass all key findings of the AR4. Some key findings may be policy-relevant even though they are associated with large uncertainties. *{WGII 20.9}*

The robust findings and key uncertainties listed below do not represent an exhaustive list.

6.1 Observed changes in climate and their effects, and their causes

Robust findings

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. *{WGI 3.9, SPM}*

Many natural systems, on all continents and in some oceans, are being affected by regional climate changes. Observed changes in many physical and biological systems are consistent with warming. As a result of the uptake of anthropogenic CO_2 since 1750, the acidity of the surface ocean has increased. *{WGI 5.4, WGII 1.3}*

Global total annual anthropogenic GHG emissions, weighted by their 100-year GWPs, have grown by 70% between 1970 and 2004. As a result of anthropogenic emissions, atmospheric concentrations of N_2O now far exceed pre-industrial values spanning many thousands of years, and those of CH_4 and CO_2 now far exceed the natural range over the last 650,000 years. *{WGI SPM; WGIII 1.3}*

Most of the global average warming over the past 50 years is *very likely* due to anthropogenic GHG increases and it is *likely* that there is a discernible human-induced warming averaged over each continent (except Antarctica). *{WGI 9.4, SPM}*

Anthropogenic warming over the last three decades has *likely* had a discernible influence at the global scale on observed changes in many physical and biological systems. *{WGII 1.4, SPM}*

Key uncertainties

Climate data coverage remains limited in some regions and there is a notable lack of geographic balance in data and literature on observed changes in natural and managed systems, with marked scarcity in developing countries. *{WGI SPM; WGII 1.3, SPM}*

Analysing and monitoring changes in extreme events, including drought, tropical cyclones, extreme temperatures and the frequency and intensity of precipitation, is more difficult than for climatic averages as longer data time-series of higher spatial and temporal resolutions are required. *{WGI 3.8, SPM}*

Effects of climate changes on human and some natural systems are difficult to detect due to adaptation and non-climatic drivers. *{WGII 1.3}*

Difficulties remain in reliably simulating and attributing observed temperature changes to natural or human causes at smaller than continental scales. At these smaller scales, factors such as land-use change and pollution also complicate the detection of anthropogenic warming influence on physical and biological systems. *{WGI 8.3, 9.4, SPM; WGII 1.4, SPM}*

The magnitude of CO_2 emissions from land-use change and CH_4 emissions from individual sources remain as key uncertainties. *{WGI 2.3, 7.3, 7.4; WGIII 1.3, TS.14}*

6.2 Drivers and projections of future climate changes and their impacts

Robust findings

With current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades. *{WGIII 3.2, SPM}*

For the next two decades a warming of about 0.2°C per decade is projected for a range of SRES emissions scenarios. *{WGI 10.3, 10.7, SPM}*

Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century. *{WGI 10.3, 11.1, SPM}*

The pattern of future warming where land warms more than the adjacent oceans and more in northern high latitudes is seen in all scenarios. *{WGI 10.3, 11.1, SPM}*

Warming tends to reduce terrestrial ecosystem and ocean uptake of atmospheric CO_2, increasing the fraction of anthropogenic emissions that remains in the atmosphere. *{WGI 7.3, 10.4, 10.5, SPM}*

Anthropogenic warming and sea level rise would continue for centuries even if GHG emissions were to be reduced sufficiently for GHG concentrations to stabilise, due to the time scales associated with climate processes and feedbacks. *{WGI 10.7, SPM}*

Equilibrium climate sensitivity is *very unlikely* to be less than 1.5°C. *{WGI 8.6, 9.6, Box 10.2, SPM}*

Some systems, sectors and regions are *likely* to be especially affected by climate change. The systems and sectors are some ecosystems (tundra, boreal forest, mountain, mediterranean-type, mangroves, salt marshes, coral reefs and the sea-ice biome), low-lying coasts, water resources in some dry regions at mid-latitudes and in the dry topics and in areas dependent on snow and ice melt, agriculture in low-latitude regions, and human health in areas with low adaptive capacity. The regions are the Arctic, Africa, small islands and Asian and African megadeltas. Within other regions, even those with high incomes, some people, areas and activities can be particularly at risk. *{WGII TS.4.5}*

Impacts are *very likely* to increase due to increased frequencies and intensities of some extreme weather events. Recent events have demonstrated the vulnerability of some sectors and regions, including in developed countries, to heat waves, tropical cyclones, floods and drought, providing stronger reasons for concern as compared to the findings of the TAR. *{WGII Table SPM.2, 19.3}*

Key uncertainties

Uncertainty in the equilibrium climate sensitivity creates uncertainty in the expected warming for a given CO_2-eq stabilisation scenario. Uncertainty in the carbon cycle feedback creates uncertainty in the emissions trajectory required to achieve a particular stabilisation level. *{WGI 7.3, 10.4, 10.5, SPM}*

Models differ considerably in their estimates of the strength of different feedbacks in the climate system, particularly cloud feedbacks, oceanic heat uptake and carbon cycle feedbacks, although progress has been made in these areas. Also, the confidence in projections is higher for some variables (e.g. temperature) than for others (e.g. precipitation), and it is higher for larger spatial scales and longer time averaging periods. *{WGI 7.3, 8.1-8.7, 9.6, 10.2, 10.7, SPM; WGII 4.4}*

Aerosol impacts on the magnitude of the temperature response, on clouds and on precipitation remain uncertain. *{WGI 2.9, 7.5, 9.2, 9.4, 9.5}*

Future changes in the Greenland and Antarctic ice sheet mass, particularly due to changes in ice flow, are a major source of uncertainty that could increase sea level rise projections. The uncertainty in the penetration of the heat into the oceans also contributes to the future sea level rise uncertainty. *{WGI 4.6, 6.4, 10.3, 10.7, SPM}*

Large-scale ocean circulation changes beyond the 21st century cannot be reliably assessed because of uncertainties in the meltwater supply from the Greenland ice sheet and model response to the warming. *{WGI 6.4, 8.7, 10.3 }*

Projections of climate change and its impacts beyond about 2050 are strongly scenario- and model-dependent, and improved projections would require improved understanding of sources of uncertainty and enhancements in systematic observation networks. *{WGII TS.6}*

Impacts research is hampered by uncertainties surrounding regional projections of climate change, particularly precipitation. *{WGII TS.6}*

Understanding of low-probability/high-impact events and the cumulative impacts of sequences of smaller events, which is required for risk-based approaches to decision-making, is generally limited. *{WGII 19.4, 20.2, 20.4, 20.9, TS.6}*

6.3 Responses to climate change

Robust findings

Some planned adaptation (of human activities) is occurring now; more extensive adaptation is required to reduce vulnerability to climate change. *{WGII 17.ES, 20.5, Table 20.6, SPM}*

Unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt. *{WGII 20.7, SPM}*

A wide range of mitigation options is currently available or projected to be available by 2030 in all sectors. The economic mitigation potential, at costs that range from net negative up to US$100/ tCO_2-equivalent, is sufficient to offset the projected growth of global emissions or to reduce emissions to below current levels in 2030. *{WGIII 11.3, SPM}*

Many impacts can be reduced, delayed or avoided by mitigation. Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels. Delayed emissions reductions significantly constrain the opportunities to achieve lower stabilisation levels and increase the risk of more severe climate change impacts. *{WGII SPM, WGIII SPM}*

The range of stabilisation levels for GHG concentrations that have been assessed can be achieved by deployment of a portfolio of technologies that are currently available and those that are expected to be commercialised in coming decades, provided that appropriate and effective incentives are in place and barriers are removed. In addition, further RD&D would be required to improve the technical performance, reduce the costs and achieve social acceptability of new technologies. The lower the stabilisation levels, the greater the need for investment in new technologies during the next few decades. *{WGIII 3.3, 3.4}*

Making development more sustainable by changing development paths can make a major contribution to climate change mitigation and adaptation and to reducing vulnerability. *{WGII 18.7, 20.3, SPM; WGIII 13.2, SPM}*

Decisions about macro-economic and other policies that seem unrelated to climate change can significantly affect emissions. *{WGIII 12.2}*

Key uncertainties

Understanding of how development planners incorporate information about climate variability and change into their decisions is limited. This limits the integrated assessment of vulnerability. *{WGII 18.8, 20.9}*

The evolution and utilisation of adaptive and mitigative capacity depend on underlying socio-economic development pathways. *{WGII 17.3, 17.4, 18.6, 19.4, 20.9}*

Barriers, limits and costs of adaptation are not fully understood, partly because effective adaptation measures are highly dependent on specific geographical and climate risk factors as well as institutional, political and financial constraints. *{WGII SPM}*

Estimates of mitigation costs and potentials depend on assumptions about future socio-economic growth, technological change and consumption patterns. Uncertainty arises in particular from assumptions regarding the drivers of technology diffusion and the potential of long-term technology performance and cost improvements. Also little is known about the effects of changes in behaviour and lifestyles. *{WGIII 3.3, 3.4, 11.3}*

The effects of non-climate policies on emissions are poorly quantified. *{WGIII 12.2}*

APPENDIX 3 – CSIRO CLIMATE CHANGE IN AUSTRALIA TECHNICAL REPORT (AND UPDATES)

Executive summary extracted from: CSIRO (2007) *Climate Change in Australia – Technical Report 2007*, CSIRO, Melbourne

CSIRO (2009) *Climate Change in Australia – Science update 2009 issue one*, CSIRO, Melbourne

CSIRO (2009) *Climate Change in Australia – Science update 2009 issue two*, CSIRO, Melbourne

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Contents

Executive summary

Climate Change in Australia is based on international climate change research including conclusions from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and builds on a large body of climate research that has been undertaken for the Australian region in recent years. This includes research completed within the Australian Climate Change Science Program by CSIRO and the Australian Bureau of Meteorology in partnership with the Australian Greenhouse Office.

The purpose of this report is to provide an up-to-date assessment of observed climate change over Australia, the likely causes, and projections of future changes to Australia's climate. It also provides information on how to apply the projections in impact studies and in risk assessments. The two main strategies for managing climate risk are mitigation (net reductions in greenhouse gas emissions) to slow climate change and adaptation to climate impacts that are unavoidable.

A number of major advances have been made since the last report on climate change projections in Australia (CSIRO 2001) including:

- a much larger number of climate and ocean variables are projected (21 and 6 respectively)
- a much larger number (23) of climate models are used
- the provision of probabilistic information on some of the projections, including the probability of exceeding the 10th, 50th and 90th percentiles
- greater emphasis on projections from models that are better able to simulate observed Australian climate
- a detailed assessment of observed changes in Australian climate and likely causes; and
- information on risk assessment, to provide guidance for using climate projections in impact studies.

Past climate change

Temperature and rainfall

Australian average temperatures have increased by 0.9ºC since 1950, with significant regional variations. The frequency of hot nights has increased and the frequency of cold nights has declined.

Rainfall trends from 1900 to 1949 were generally rather weak and spatially incoherent. Rainfall trends since 1950 are both large and spatially coherent. The east coast, Victoria, and south-west Australia have all experienced substantial rainfall declines since 1950. Across New South Wales and Queensland these rainfall trends partly reflect a very wet period around the 1950s, and recent years that have been unusually dry. In stark contrast, north-west Australia has experienced an increase in rainfall over this period.

Trends in extreme daily rainfall vary across Australia. From 1950 to 2005, there have been increases in north-western and central Australia and over the western tablelands of New South Wales, but decreases in the south-east, south-west and central east coast. Trends in most extreme rainfall events are rising faster than trends in the mean.

Since the start of the 20th century, the period with the lowest rainfall was from the 1930s to the early 1940s. However recent droughts have been hotter, with both the maximum and minimum temperatures higher than in the earlier dry periods.

Maximum winter snow depth at Spencers Creek in the Snowy Mountains has decreased slightly since 1962, and the snow depth in spring has declined strongly (by about 40%).

Tropical cyclones and hail

Large changes have occurred in our ability to detect tropical cyclones since the advent of regular radar observations in the 1950s and with the development of meteorological satellite-based detection techniques in the 1970s and 1980s. Our ability to detect significant trends in the intensity of tropical cyclones in the Australian region is limited because of changes to techniques, and particularly the use of less accurate methods in the past.

There are no comprehensive studies of changes in hail occurrence in Australia, but one study for the Sydney region showed a 30% decline in the number of hailstorms affecting Sydney from 1989-2002 compared with 1953-1988. However, the most severe hail storm affecting Sydney occurred in April 1999, causing Australia's largest insurance loss ($1.7 billion) due to a natural disaster.

Oceans

Global sea levels rose by approximately 17 cm during the twentieth century. The average rate between 1950 and 2000 was 1.8 ± 0.3 mm per year, but for the period when satellite data are available (i.e. from 1993), the rate increased to 3 mm per year. Since 1990, the observed rate of global sea level rise corresponds to the upper limit of IPCC projections. For the period 1950 to 2000, sea level rose at all of the Australian coastal sites monitored, with substantial variability in trends from location to location. Over the period 1920 to 2000 the estimated average relative sea level rise around Australia was 1.2 mm per year.

Substantial warming has occurred in the three oceans surrounding Australia. Warming has been large off the south-east coast of Australia and in the Indian Ocean. The tropical Pacific Ocean has warmed over recent decades. Long term observations off Maria Island near Tasmania reveal a warming trend far greater than the global average, and this may be due to changes in the East Australian Current.

Southern Ocean temperatures have warmed since the 1950s to a depth of 1000 m in some locations. The warming is associated with a 50 km southward migration of the Antarctic Circumpolar Current. Seawater near the bottom of the ocean off Antarctica has rapidly become less salty and less dense. This freshening may be the signature of increased melt from Antarctic glaciers.

El Niño – Southern Oscillation and the Southern Annular Mode

Instrumental and palaeo-climate records show large variations in the frequency and intensity of the El Niño – Southern Oscillation (ENSO), and the impact of ENSO on Australia has varied from decade to decade. This variability has been accompanied by a downward trend in the Southern Oscillation Index (SOI, an index used to track ENSO) since 1876, consistent with a weakening of the Walker Circulation. While there has been an increase in the frequency of El Niño events in recent years, there is no consensus amongst current climate models that global warming should cause an increase. The increase might therefore reflect naturally occurring variability.

The relationship between the SOI and Australian temperature and rainfall has changed. For example, all-Australia rainfall and temperature since the mid 1970s have been higher for any given value of the SOI than they were previously.

Mid-latitude westerly winds appear to have decreased, with a corresponding increase in wind speed in the polar latitudes in most seasons from 1979 to the late 1990s. There has been a 20% reduction in the strength of the subtropical jet over Australia and an associated reduction in the likelihood of low pressure systems developing over south-west Western Australia since the early 1970s. This is linked to winter rainfall declines along the southern coastal regions of Australia and a poleward shift of storm tracks in winter.

Palaeo-records

Pollen records of past vegetation in eastern Australia indicate precipitation was generally higher than present between 9,000 and 3,500 years ago. This is consistent with a regional climatic shift, possibly related to the movement of the subtropical anti-cyclone belt, the westerlies and/or the monsoon. Evidence from lakes in Victoria suggests that conditions between about 1800 to 1840 were wetter than present, after which the dry conditions of the recent instrumental period became established. There is less information relating to past temperature variations.

The tropical cyclone palaeo-record from the past 5,000 years for Cairns and the Great Barrier Reef suggests that the historical record may greatly underestimate the frequency of the most severe tropical cyclones likely to strike the region.

Evidence from Tasmanian tree rings indicates significant shifts in the intensity of climate variability over the last 3,000 years, with a recent shift occurring around 1900.

Causes of past climate change

Climate can change as a result of both natural and anthropogenic factors. Detection and attribution studies attempt to tease out the anthropogenic component of this variability.

Temperature

Australian surface temperatures have risen significantly over the past century. Warming since the middle of the 20th century is likely to be mostly due to anthropogenic increases in greenhouse gases.

Rainfall

The rainfall decrease in south-western Australia since the mid-1970s is likely to be at least partly due to anthropogenic increases in greenhouse gases. It is not yet possible to attribute the post-1950 rainfall decreases in eastern Australia and rainfall increases in north-western Australia to human activities.

Drought

Recent Australian droughts have been accompanied by higher surface temperatures due to anthropogenic warming. This may have exacerbated the impact of drought in regions where warming increases water demand and surface water loss.

Snow

The decline in snow cover observed in recent decades is probably due to anthropogenic warming.

Extremes

There has been an increase in the frequency of warm days and warm nights and a decrease in the frequency of cool days and cool nights. It is likely that these changes are mostly due to anthropogenic warming.

Oceans

Rapid warming in the Tasman Sea is likely to have been partly driven by Antarctic ozone depletion.

Global climate change projections

Scenarios of greenhouse gas emissions, concentrations and radiative forcing

The greenhouse gas and aerosol emissions described here are those due to human activities, such as energy generation, transport, agriculture, land clearing, industrial processes and waste. The IPCC (SRES) emission scenarios used in this report combine a variety of assumptions about demographic, economic and technological factors likely to influence future emissions. They allow projected carbon dioxide, methane, nitrous oxide and sulfate aerosol emissions to be determined. Carbon cycle models are used to convert emissions into atmospheric concentrations, allowing for uptake of emissions by the land and ocean, climate feedbacks, and transport and chemical reactions in the atmosphere. The projected greenhouse gas concentrations are converted to a radiative forcing of the climate system, where positive forcing warms the Earth, and negative forcing cools the Earth. Changes in radiative forcing are used as input to climate models.

Using global climate models to estimate future climate change

Climate models are the best available tools we have for projecting climate. A climate model is a mathematical representation of the Earth's climate system based on well-established laws of physics, such as conservation of mass, energy and momentum. As our understanding of the underlying processes that govern the climate system improves, so too does our ability to represent the processes in climate models.

While projections of global and regional climate change contain uncertainties, global climate models continue to improve in their ability to represent current global and regional patterns of temperature, precipitation and other variables. Simulation of major patterns of climatic variability particularly relevant to Australia (e.g. ENSO, the Southern Annular Mode and the Madden-Julian Oscillation) has improved as well, increasing our confidence in the models.

A new set of experiments from 23 models from research groups around the world is now available and has been used in the generation of the climate projections for Australia. The models in this database represent the current state-of-the-art in climate modelling, with more sophisticated representations of physical and dynamical processes, and finer spatial resolution than in the past.

Each of the 23 models was given a skill score based on its ability to simulate the average (1961-1990) patterns of Australian temperature, rainfall and mean sea level pressure. These skill scores were used to weight regional climate projections based on the assumption that models with higher skill scores are likely to give more reliable projections of future climate.

Probability distributions were developed to represent the models' varying global warming projections for each year and emission scenario. These global warming probability distributions were essential for the creation probabilistic regional climate change projections.

Regional climate change projections

For annual and seasonal mean changes to temperature, precipitation, humidity, solar radiation, wind speed, potential evaporation and sea surface temperature, projections are provided in a probabilistic form. The other climate variables could not be treated similarly due either to the necessary data being unavailable, our assessment that the assumptions underlying the probabilistic approach may not be applicable (particularly relevant for some aspects of extremes), or that understanding of the topic was such that a qualitative assessment was all that was warranted.

Projections for 2030 demonstrate different patterns of regional change between climate models but little variation due to the different emission scenarios. This is because near-term changes in climate are strongly affected by greenhouse gases that have already been emitted. Climate changes centred on 2050 and 2070 are more dependent on the greenhouse gas emissions scenario, so variations due to emission scenarios are more significant. In each case, the best estimate is the median or 50th percentile, while the range of uncertainty is the difference between the 10th and 90th percentile.

Temperature

Projected warming by 2030

The best estimate of annual warming over Australia by 2030 relative to the climate of 1990 is approximately 1.0ºC, with warmings of around 0.7-0.9ºC in coastal areas and 1-1.2ºC inland. Mean warming in winter is a little less than in the other seasons, as low as 0.5ºC in the far south. The range of uncertainty is about 0.6ºC to 1.5ºC in each season for most of Australia. These warmings are based on the A1B emission scenario, but allowing for emission scenario uncertainty expands the range only slightly - warming is still at least 0.4ºC in all regions and can be as large as 1.8ºC in some inland regions. Natural variability in decadal temperatures is small relative to these projected warmings.

Projected warming for 2050 and 2070

Later in the century the warming is more dependent upon the assumed emission scenario. By 2050, annual warming over Australia ranges from around 0.8 to 1.8ºC (best estimate 1.2ºC) for the B1 (low emissions) scenario and 1.5 to 2.8ºC (best estimate 2.2ºC) for the A1FI (high emissions) scenario. By 2070, the annual warming ranges from around 1.0 to 2.5ºC (best estimate 1.8ºC) for the B1 scenario to 2.2 to 5.0ºC (best estimate 3.4ºC) for the A1FI scenario. Regional variation follows the pattern seen for 2030, with less warming in the south and north-east and more inland. In 2070, the risk of a warming above 4ºC in 2070 exceeds 30% over inland Australia under the A1FI scenario, whereas under the B1 scenario the warming is likely to be less than 2.0ºC except in the north-west.

Local variations to projected warming

Projected warming may vary significantly from that given by the global climate models in mountainous areas and near the coast. This has been demonstrated through the application of fine-resolution spatial downscaling techniques.

Extreme temperatures

Projected changes in maximum and minimum temperature indicate an increase in the diurnal temperature range in the south and a decrease in the north. This is associated with a projected strong increase in frequency of hot days and warm nights and a moderate decrease in frost. For the Murray-Darling Basin, a simulated increase in the day-to-day variability of minimum temperature reduced the impact of the mean warming on simulated frost frequency.

Precipitation

Projected precipitation change for 2030

Best estimates of annual precipitation indicate little change in the far north and decreases of 2% to 5% elsewhere. Decreases of around 5% prevail in winter and spring, particularly in the south-west where they reach 10%. In summer and autumn decreases are smaller and there are slight increases in the east.

The range of precipitation change in 2030 allowing for model-to-model differences is large. Annually averaged, the range is around -10% to +5% in northern areas and -10% to little change in southern areas. Decreases in rainfall are thus more consistently indicated for southern areas compared to northern areas. Winter and spring changes range from decreases of around 10% to little change in southern areas of the south-east of the continent, decreases of 15% to little change in the south-west, and decreases of around 15% to possible increases of 5% in eastern areas. In summer and autumn, the range is typically -15% to +10%. Decadal-scale natural variability in precipitation is comparable in magnitude to these projected changes and may therefore mask, or significantly enhance, the greenhouse-forced changes.

Projected change for 2050 and 2070

Later in the century, the projected precipitation changes are larger and vary more according to emission scenario.

By 2050 under the B1 (low emissions) scenario, the range of annual precipitation change is -15% to +7.5% in central, eastern and northern areas, with a best estimate of little change in the far north grading southwards to a decrease of 5%. The range of change in southern areas is from -15% to little change, with a best estimate of approximately -5%. Under the A1FI (high emissions) scenario, changes in precipitation are larger. The range of annual precipitation change is -20% to +10% in central, eastern and northern areas, with a best estimate of little change in the far north grading to around -7.5% decrease elsewhere. The range of change in southern areas is from a 20% decrease to little change, with a best estimate of around -7.5%. Seasonal changes follow the pattern seen for 2030, but are larger under A1FI in 2050. The projected decreases in the south-west in winter and spring are up to 30%.

In 2070, precipitation changes under the B1 scenario are comparable to those for 2050 under the A1FI scenario. Those under the A1FI scenario in 2070 are substantially larger. The range of annual precipitation change is -30% to +20% in central, eastern and northern areas, with a best estimate of little change in the far north grading to around -10% in the south. The range of change in southern areas is from -30% to +5%, with a best estimate of around -10%. Seasonal changes may be larger, with the projected decreases in the south-west of up to 40%.

Local variations to projected change

As for temperature, statistical downscaling studies have shown that projected precipitation change can vary significantly at fine spatial scales, particularly in coastal and mountainous areas.

Daily precipitation intensity, frequency of dry days and extreme precipitation

Models show an increase in daily precipitation intensity but also in the number of dry days. Extreme daily precipitation tends to increase in many areas but not in the south in winter and spring when there is a strong decrease in mean precipitation.

Snow

Snow cover, average season lengths and peak snow depths are projected to decrease in Australian alpine regions, and there is a tendency for the time of maximum snow depth to occur earlier in the season.

Solar radiation, relative humidity and potential evaporation

Solar radiation

Projections of solar radiation generally show little change although a tendency for increases in southern areas of Australia is evident, particularly in winter and spring. The projected range of change is typically -1% to +2% in 2030. The magnitude of changes is larger in 2050 and 2070, particularly under higher emission scenarios.

Relative humidity

Small decreases in relative humidity are projected over most of Australia. The range of change in annual humidity by 2030 is around -2% to +0.5% with a best estimate of around a 1% decline. The projected changes are larger for 2050 and 2070, particularly under the higher emission scenarios.

Potential evapotranspiration

Annual potential evapotranspiration is projected to increase over Australia. Largest increases are in the north and east, where the change by 2030 ranges from little change to a 6% increase, with best estimate of around a 2% increase. By 2070, the B1 scenario gives increases of 0% to 6% (best estimate around 3%) in the south and west and 2% to 8% (best estimate around 6%) in the north and east, while the A1FI emissions scenario gives increases of 2% to 10% (best estimate of around 6%) in the south and west and 6% to 16% (best estimate around 10%) in the north and east.

Drought

Drought occurrence is projected to increase over most of Australia, but particularly in south-western Australia.

Wind

Average wind speed projections

There is a tendency for increased wind speed in most coastal areas in 2030 (range of -2.5% to +7.5% with best estimates of +2% to +5%) except for the band around latitude 30°S in winter and 40°S in summer where there are decreases (-7.5% to +2.0%, with best estimates of -2% to -5%).

Later in the century, changes of wind strength can be larger, depending on the emission scenario. Under the A1FI scenario in 2070, best estimate increases of more than 15% apply in some regions, whereas under the B1 scenario increases are less than 10% everywhere.

Extreme wind speed projections

In winter, changes to extreme wind speed are likely to be similar to the changes to seasonal mean wind speed. However, there is little relationship between summer mean and extreme wind speed changes. Extreme winds in summer are likely to be governed more by small scale systems (including tropical cyclones). On the other hand, winter extreme wind events are more likely to be governed by larger scale systems (e.g. trade winds, mid-latitude cyclones).

Fire weather

A substantial increase in fire weather risk is likely at most sites in south-eastern Australia. Such a risk may exist elsewhere in Australia, but this has yet to be examined.

Sea level rise

Mean sea level rise

Global sea level rise is projected by the IPCC to be 18-59 cm by 2100, with a possible additional contribution from ice sheets of 10 to 20 cm. However, further ice sheet contributions, that cannot be quantified at this time, may substantially increase the upper limit of sea level rise.

Sea level extremes

Storm surges occurring in conditions of higher mean sea levels will enable inundation and damaging waves to penetrate further inland, increasing flooding, erosion and the subsequent impacts on built infrastructure and natural ecosystems. Changes to wind speed will also affect storm surge height.

Storm surge studies for portions of the Victorian and Queensland coasts demonstrate the potential for significant increases in inundation due to higher mean sea level and more intense weather systems.

Marine projections

Sea surface temperature

By 2030 the best estimate of sea surface temperature rise is 0.6-0.9ºC in the southern Tasman Sea and off the north-west shelf of Western Australia and 0.3-0.6ºC elsewhere. Allowing for model-to-model variations, the ranges are 0.4-1.4ºC in the southern Tasman Sea and 0.4-1.0ºC off the north-west coast.

Beyond the first few decades of the 21st century, the magnitude of the sea surface temperature change will become increasingly dependent on the emission scenario. Under the B1 scenario in 2070, the sea surface temperature best estimate increase is 0.6 to 1.0ºC along the south coast of Australia while elsewhere it is 1.2 to 1.5ºC. Under the A1FI emission scenario, the regions of highest warming are about 1.0ºC higher than those for the B1 scenario.

Ocean acidification

Increases in ocean acidity are expected in the Australian region with the largest increases in the high- to mid-latitudes. Under-saturation of aragonite could occur by the middle of the century in the higher latitudes, affecting the capacity for shell and endoskeleton creation by marine organisms.

East Australian Current

The East Australian Current is likely to strengthen throughout the 21st century, which will result in warmer waters extending further southward.

Severe weather

Tropical cyclones

Similar to studies for other basins, Australian region studies indicate a likely increase in the proportion of the tropical cyclones in the more intense categories, but a possible decrease in the total number of cyclones.

Severe thunderstorms

Conditions will become less suitable for the occurrence of tornadoes in southern Australia in the cool season (May to October). There is an indication that hail risk may increase over the south-east coast of Australia.

ENSO, the Southern Annular Mode and storm tracks

ENSO's impact on Australia under global warming

In south-eastern Australia, models analysed indicate that El Niño events will tend to become drier and La Niña events will tend to become wetter, even if Pacific Ocean variability linked to ENSO does not increase.

The Southern Annular Mode

All climate models exhibit a trend in the Southern Annular Mode towards its positive phase (weaker westerly winds over southern Australia, stronger westerly winds at higher latitudes) when driven with increasing greenhouse gas concentrations.

Storm tracks

A decrease in the occurrence of winter low pressure systems over south-west Western Australia is likely during the 21st century.

Application of climate projections in impact and risk assessments

Risk management is an iterative process, where scoping and risk identification usually takes place before more detailed assessments are carried out. Care must be exercised when using the projections in any risk assessment, particularly when selecting climate variables, determining temporal and/or spatial resolution, and dealing with uncertainty.

Detailed risk assessments generally require purpose-built climate projections, including time series, or probabilistic representations of future climate. Various tools have been developed which represent different methods for enhancing the delivery of climate information to stakeholders both for education and for risk assessment and management. Nevertheless, significant challenges remain for communicating climate risk in ways that can be effectively used in risk management.

climatechange in Australia




science update **2009**

issue**one**

This document has been compiled by the Australian Climate Change Science Program in order to provide a succinct update of recently published climate change science.

The document aims to provide a reliable and concise summary of climate change science useful for a wide audience. Information is aimed at the needs of policy makers, government agencies, scientists, science communicators and media.

The information presented comes from research within the Australian Climate Change Science Program, Australian universities and international research agencies. The update provides a summary of relevant climate change science with further references cited.

Recent research has shown that:

- Concentrations of greenhouse gases are on the rise, with an unexpected increase in methane.
- Carbon sinks remove considerable amounts of anthropogenic carbon dioxide, but they are becoming less efficient.
- Sea levels are rising, with current projections of up to 80 cm by the end of the century.
- Southern Ocean acidity has increased, while salinity has decreased.
- Rainfall in southern Australia has declined over a 30-year period, caused by changes in climate systems over the region.

These findings indicate stronger than expected and sooner than expected forcing of climate change.

To subscribe to this publication you can visit **www.climatechangeinaustralia.gov.au**

Summary of recent climate change science

1 Greenhouse gas concentrations

- Anthropogenic carbon dioxide emissions are currently tracking above the worst case scenario of the Intergovernmental Panel on Climate Change: Special Report on Emissions Scenarios.
- In 2007 the atmospheric carbon dioxide concentration was 383 parts per million, 37% above the concentration at the start of the industrial revolution.
- Global emissions from the combustion of fossil fuel and land use change reached 10 billion tonnes of carbon in 2007, up from about 2 billion tonnes in 1950.
- Australia is increasing output of greenhouse gases (by two per cent per year).
- Atmospheric methane concentrations have increased significantly (by more than 25.4 million tonnes from June 2006 to October 2007).

2 Carbon sinks and sources

- Oceans and land currently absorb 29% and 26% respectively of anthropogenic emissions.
- The efficiency of natural carbon sinks has decreased over the past 50 years.

3 Sea level

- There has been a global average sea-level rise of 0.17 m during the 20th century.
- Sea levels are projected to rise up to 80 cm by the end of the century.
- Melting of the Greenland and West Antarctic ice sheets could be hastened by lubrication of bedrock and collapse of buttressing ice shelves.

4 Oceanic processes

- The acidity of oceans has increased significantly due to greater quantities of dissolved carbon dioxide.
- The freshening of Antarctic Bottom Water from melting ice sheets has increased and is likely to affect ocean circulation.

5 Climate systems

- In the Australian region tropical cyclones may increase in intensity.
- Reduced rainfall in Southern Australia is linked to changes in climate systems patterns over the past 30 years.


1 Greenhouse gas concentrations

2000-2007 trends in greenhouse gas emissions were higher than the worst case Intergovernmental Panel on Climate Change: Special Report on Emissions Scenarios[1].

In 2007 the atmospheric CO_2 concentration was 383 parts per million, 37% above the concentration at the start of the industrial revolution (about 280 parts per million in 1750)[2]. The present concentration is the highest during the last 800,000 years and probably during the last 20 million years[3].

Global emissions from the combustion of fossil fuel and land use change almost reached 10 billion tonnes of carbon in 2007[1]. Australia's fossil-fuel emissions have grown by two per cent per year since 2000[1].

Methane concentrations are influenced by human activity. Atmospheric methane levels started rising in 2006 jumping by more than 25.4 million tonnes from June 2006 to October 2007[4]. Based on the amount of warming it causes and levels in the atmosphere, methane is considered the second worst greenhouse gas.

The amount of frozen organic carbon in the world's permafrost regions is double previous estimates. The release of a small fraction of this vast frozen reservoir of carbon would significantly accelerate climate change[1,5].

2 Carbon sinks and sources

Natural land and ocean carbon dioxide sinks have removed 54% of all carbon dioxide emitted from human activities during 2000-2007[6]. The size of the natural sinks has grown in proportion to increasing atmospheric carbon dioxide. However, the efficiency of these sinks has decreased by 5% over the last 50 years, and will continue to do so in future[1]. Atmospheric carbon dioxide has been outstripping the growth of natural carbon dioxide sinks such as forests and oceans[7].

Oceans and land are taking up 26% and 29% respectively of all anthropogenic carbon emissions[1]. Clearing of tropical forest accounts for 16% of anthropogenic carbon emissions and destroys globally significant carbon sinks[8]. Preventing further decreases of natural carbon sinks will be vital in any mitigation effort.


3 Sea Level

Global atmospheric temperature rise has resulted in warming of the oceans and melting of ice on land. The sea level rose significantly during the 20th century at a rate faster than for the previous several centuries[9].

There has been a global average rise of 0.17m during the 20th century[6]. Ocean warming and thermal expansion trends are about 50% larger than earlier estimates, and account for about 33% of the total sea level rise over the past 50 years[10].

IPCC 2007 projections of a 0.2-0.8m sea-level rise by the end of this century may be underestimated[11]. Larger values can not be excluded[12]. Global sea levels are likely to rise by 0.03 m in the next decade[12].

Stabilisation of atmospheric greenhouse gas concentrations at 550 ppm CO_2 equivalent is likely to result in a high (greater than 78%) likelihood of initiating irreversible melting of the Greenland ice sheet[13]. Although starting this century, this process is likely to occur over at least several hundreds of years[6,13].

Surface ice melt may lubricate the base of ice sheets at the bedrock to increase the flow of ice sheets into the sea. Disintegration of ice shelves also results in faster flow of glaciers to the sea[12]. Our understanding of these processes is limited.

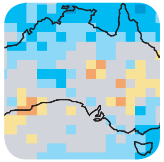
The average rate of sea-level rise from 1961 to 2003 was 1.8mm/year and increased to 3.1 mm/year from 1993 to 2003. Whether this latter rate indicates decadal variability or an increase in the long-term trend over time remains unclear[12].

4 Ocean Processes

Global oceans removed 26% of all carbon dioxide emissions from 2000-2007[1]. Ocean sinks have grown more slowly than expected over the last 20 years.

The increased concentration of carbon dioxide from anthropogenic emissions has increased ocean acidity[14]. Data from the Great Barrier Reef and the Southern ocean is being used to examine effects of increased acidity on marine organisms. Carbonate chemistry drives acidification, with consequences for marine organisms that form calcium carbonate shells, such as molluscs, corals, crustaceans and some plankton species[15]. Changes to species composition and populations at the bottom of the food chain will affect other marine life as well as reducing the capacity of the ocean to store carbon dioxide.

Changes in temperature, salinity and density have been quantified in the Southern Ocean. Salinity of the Southern ocean has decreased since the 1970s resulting in fresher and lighter water above the sea floor[16]. Ocean circulation is driven by different densities of water in the ocean. Fresh water from melting glaciers has increased in polar regions, changing the density of the water, indicating climate change is already having an effect on ocean transport and circulation[17].



5 Climate systems

A number of large-scale climate systems in our region determine rainfall patterns over Australia. In the past 30 years there has been a dramatic shift in the climate, affecting storm tracks in southern Australia, with a 30% reduction in storm growth rate[18]. With the chance of storms dropping significantly, reduced rainfall has occurred across southern Australia.

The sub-tropical pressure ridge, a large belt of high pressure situated about 30°S in latitude, has moved further south over the past 30 years. A poleward movement of the pressure system may be contributing to the reduced winter rainfall over southern Australia[19].

The largest reduction is in the autumn season, in part driven by a lack of La Niña events[20].

The drying trend in south-west Western Australia has been attributed to a combination of natural variability, an increase in greenhouse gas concentrations, and land-use change[21]. The human-induced component accounts for approximately 50% of the reduction[22].

The south-east of Australia is affected by several climate systems including the El Niño – Southern Oscillation and the Southern Annular Mode. There is a consensus that in response to global warming, the IOD[23] and the SAM will contribute to rainfall reduction in the region. The atmospheric response is similar to that of an El Niño state[23] also unfavourable to Australian rainfall.

There is currently no evidence of significant change in the number of tropical cyclones in the Australian region although there is some evidence to suggest that the more intense cyclones will increase in intensity[24].

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This document provides a succinct update of recently published climate change science.

Since these results are 'new', in some cases there has been only limited opportunity for assessment by the wider scientific community. Some findings may change in future in the light of subsequent research. This is, of course, part of the normal development of climate (or any other) science.

Information is aimed at policy makers, government agencies, scientists, science communicators and media. The information presented comes from research within the Australian Climate Change Science Program, Australian universities and international research agencies.

All papers are referenced within the text.

Views expressed are those of the researchers quoted and do not necessarily represent the views of, and should not be attributed to, the Bureau of Meteorology and/or CSIRO.

Recent research has shown that:

- Some measures of climate change are tracking at or above the worst case scenarios considered possible just a couple of years ago.
- Climate extremes are pushing new boundaries, for example the unprecedented heat wave in south-eastern Australia experienced early in 2009.
- Changes to ice sheet dynamics could raise sea levels beyond current IPCC estimates.
- Ocean acidification could lead to permanent changes to marine ecosystems.
- Climate change is likely to be more rapid and severe, and more costly and dangerous than previously thought.

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Summary of recent climate change science

1 Greenhouse gases

- Temperatures do not drop significantly for at least 1,000 years after emissions stop.
- Methane clathrates appear more stable than previously thought.
- The quantity of carbon stored in permafrost has been vastly underestimated.
- Greenhouse gas induced climate change impacts on ozone recovery.

2 Climate extremes

- Australia shows a shift towards temperature extremes.
- It is very likely that climate change has increased the likelihood of extreme fire danger in south-east Australia.
- Fire seasons are likely to be more intense, start earlier and end later.

3 Sea levels and ice sheets

- Current estimates of sea-level rise range from 0.50 m to about 2 m by 2100.
- The Greenland and Antarctic continental ice sheets are losing mass and contributing to sea level rise at rates beyond those projected in the IPCC AR4.
- There are significant regional differences in Antarctic temperatures.
  - i. The West Antarctic Peninsula already shows considerable warming (2.5 °C)
  - ii. Slight cooling has been observed in East Antarctica.

4 Oceanic processes

- The Southern Ocean may become permanently damaging to some calcifying marine organisms, and associated food chains.
- Southern Ocean winds are strengthening, but have not been found to affect ocean circulation .

1 Greenhouse gas concentrations

Greenhouse gas emissions and many aspects of the climate have been changing near the upper boundary of the IPCC range of projections.[1].

Climate change, due to increases in carbon dioxide concentration, is largely irreversible for 1,000 years after emissions stop[2]. Atmospheric carbon dioxide concentrations of 450–600 ppm over the coming century will likely lead to irreversible dry-season rainfall reductions in several regions and inexorable sea-level rise[2].

The level of greenhouse gas emissions that corresponds to 2°C warming (relative to pre-industrial levels) is hard to quantify, given uncertainties in the carbon cycle and the climate response[3]. One estimate finds that halving global greenhouse gas emissions (relative to 1990) by 2050 provides a 12–45% probability of exceeding 2°C global warming[3].

Many 'slow' climate feedback processes such as ice sheet disintegration, vegetation change, and greenhouse gas release from soils, tundra or ocean sediments, are not likely to be well presented in current climate models[4]. A recent study estimates that atmospheric carbon dioxide concentrations will need to be reduced from the current 385 ppm to 350 ppm or less in order to preserve a planet similar to that on which life on Earth is adapted[4].

Achieving peak emissions in 2015 and 3% global emissions cuts annually thereafter, has been estimated to leave an even chance of exceeding 2 °C of warming[5]. To adapt to 90% of the risk implied by delaying mitigation action until 2035, implies planning to adapt to at least 4 °C of warming[5].

Methane

There are three significant methane stores:

1. Methane clathrates, which consist of frozen methane mostly in the deep ocean.
2. Organic matter in permafrost (frozen soil) that can decompose, producing methane.
3. Natural gas.

Methane clathrates appear to be stable in a warming world[6], while permafrost carbon appears increasingly vulnerable[5].

Ice core evidence from the end of the last glacial period suggests that emissions from wetlands were the cause of the then rapid atmospheric methane increase, not methane clathrates as previously suspected[6].

The quantity of carbon in frozen soils in the northern circumpolar region is double previous estimates[7]. These soils have the potential to release vast quantities of carbon dioxide and methane into the atmosphere and subsequently influence carbon-climate feedbacks[8]. Carbon stored in soils at high latitudes is increasingly vulnerable to exposure to the atmosphere[7].

The potential for significant feedbacks from permafrost carbon could be realised with only a small fraction of currently frozen carbon released to the atmosphere. For example, if only 10% of the permafrost melts, the resultant feedback could result in an additional 80 ppm

carbon dioxide equivalent released into the atmosphere, generating about 0.7°C further warming[7].

Stratospheric ozone levels

Increasing levels of atmospheric greenhouse gases have been shown to affect the ozone layer's recovery, hastening recovery in some areas while slowing – or even preventing – it in others[9]. Modelling suggests that stratospheric ozone recovery, at mid latitudes, is enhanced by greenhouse gases[9]. In contrast, ozone recovery in the polar stratosphere is hindered by greenhouse gases.

The ozone hole is currently limiting the effects of climate change on eastern Antarctica[10]. As ozone levels recover by the end of the 21st Century, there is likely to be around one-third less Antarctic sea ice[10].

Equivalent carbon dioxide CO_2[e]

It is important to distinguish between atmospheric carbon dioxide concentrations and equivalent carbon dioxide concentrations CO_2[e].

To calculate the relative concentration of the major greenhouse gases, equivalent carbon dioxide is used. The IPCC used the equivalent carbon dioxide forcing of six greenhouse gases (carbon dioxide, methane, nitrous oxide, HFCs, PFCs and SF6) in the latest assessment report.

Table 1 > Comparison of atmospheric concentrations of carbon dioxide and equivalent carbon dioxide concentrations.

Concentrations of greenhouse gases – parts per million (ppm)	Atmospheric CO_2	CO_2[e] ▲	Radiative forcing
Also referred to as ppmv (parts per million by volume)	The carbon dioxide concentration in the air.	Including carbon dioxide, methane, nitrous oxide, HFCs, PFCs and SF_6	Warming in the entire climate system (oceans, atmosphere and land) compared to preindustrial times
	Very accurate	Best estimate	(Watts per metre^2)
Pre-industrial	280^	280*	0
2005	379#	445#	2.48+
2007	383^	462*	2.68+

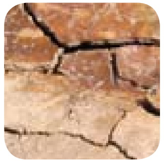
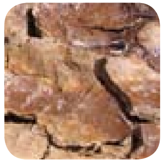
▲ This measure of CO_2(e) includes GHGs only. Anthropogenic aerosol forcing partly offsets this, although the magnitude of this is currently very uncertain. The best estimate for aerosol forcing (2007) is a reduction of CO_2(e) by around 87ppm #

* Pers com: David Karoly (Melbourne University)

IPCC AR4 Synthesis Report, notes to Table 5.1, p.67b

^ Global Carbon Budget: www.globalcarbonproject.org/carbonbudget/07/index.htm

+ Pers com: Paul Fraser (CSIRO)

2 Climate extremes

Australia is experiencing more high temperature extremes, particularly a significant increase in the number of warm nights and heat waves[11].

There was a significant increase in the duration of heat waves in Australia from 1957 to 1999 and increased temperature extremes[11].

The observed trends in extremes are projected to continue into the future. A substantial increase in warm nights and heat wave duration and decrease in frost days are projected by the end of this century under the IPCC-SRES scenarios[11].

Indicators of rainfall extremes are set to more than double within the next 100 years, with longer dry spells interspersed with heavier precipitation events[11]. The magnitude of changes in both temperature and rainfall extremes generally scale with the strength of emissions[11].

Heat waves

An exceptional heat wave affected south-eastern Australia during Jan-Feb 2009. Many records were set for day and night time temperatures and duration of extreme heat[9].

Record high temperatures for February were set over 87% of Victoria on Feb 7[12]. Seven of the eight highest temperatures on record in Tasmania occurred during this heat wave[12]. Adelaide experienced its warmest night on record with a minimum temperature of 33.9ºC on Jan 29[12]. The dry conditions during this heat wave further reinforced very long-term rainfall deficits in much of south-eastern Australia[12].

Severe fire seasons

Climate change is increasing the likelihood of environmental conditions associated with extreme fire danger in south-east Australia and other parts of the world[13]. The pattern of recent extreme fire danger is part of a broader shift towards more severe fire seasons in central Victoria[12]. It is very likely that climate change has increased the likelihood of extreme fire danger in south-east Australia[13].

The climatic conditions experienced in Victoria on February 7 2009 were unprecedented[12,13]. The area north-east of Melbourne had experienced a 12-year drought before the fires, as well as record high temperatures, a record heat wave two weeks earlier, record low rainfall and record low humidity[12]. The area was also experiencing an unprecedented sequence of days without rain[13].

An increase in fire danger in Australia is likely to be associated with a reduced interval between fires, increased fire intensity, a decrease in fire extinguishments and faster fire spread[14]. The number of 'very high' and 'extreme' fire danger days in south-east Australia could increase by 4-25% by 2020 and 15-70% by 2050[15]. Fire seasons are likely to start earlier and end slightly later, while being generally more intense[15].

3 Sea level rise

Several new estimates of projected 21st century sea level rise, including ice dynamic effects, have been made. These vary from an increase of 0.50–1.40 m[18] to up to 2 m by 2100[19]. Contributions from glaciers and ice sheets to future sea level rise are uncertain but may equal or exceed several metres over the next millennium or longer[2].

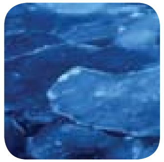
Sea ice and ice sheets are different substances and form through very different processes. Sea ice forms in winter and melts within a few years. The melting and freezing process drives ocean circulation, but does not contribute to sea-level rise. In contrast, ice sheets are thick layers of compacted snow that form over land and move through glacial processes. When they reach the sea, they form ice shelves and eventually ice bergs. Changes in ice sheet dynamics may contribute to sea-level rise[20,21].

Ice sheet dynamics

Both the Greenland and Antarctic ice sheets are losing ice mass and contributing to sea-level rise[20]. There is concern that the contribution of ice sheets to sea level rise over the 21st century could be higher than the IPCC AR4 projections[22]. Rapid changes have been observed over substantial areas of both Greenland and Antarctica[22,23]. However, the error range of estimates of mass change in both Antarctica and Greenland is large[22].

Greenland ice sheets

Greenland was approximately in mass balance during the 1970s and 1980s, but since 1997 the ice sheet has been losing mass at an accelerating rate[24]. However, there can be large variability from year to year in the surface melt in Greenland[25].




Antarctic ice sheets

Large uncertainties remain regarding the current and future contribution to sea level rise from Antarctica[26]. Warming may increase snowfall in the continent's interior but enhance glacier discharge at the coast where warmer air and ocean temperatures erode the buttressing ice shelves[26].

In West Antarctica, ice sheet loss has increased dramatically[26]. In East Antarctica, a combination of small glacier losses and gains combine to a near-zero loss of ice sheets[26].

Antarctic temperatures

Monitoring at three sites in Australia's Antarctic territory and at Macquarie Island indicate minor warming since the mid-1950s. Sparse sites and the short duration of the observations do not provide a complete record for the continent and regional differences are apparent[27].

The West Antarctic Peninsula shows extensive and rapid warming, with an average increase of 2.5ºC already observed[21]. A slight cooling trend observed in East Antarctica in the 1980s-1990s is attributed to the interaction of the stratospheric ozone hole with regional climate[10]. As the ozone hole recovers, more rapid warming is expected in this region[9].

Antarctic sea ice

Sea ice distribution, averaged across Antarctica, shows a slight increase in maximum extent[21]. Regional changes have been much larger. The Weddell and Ross Seas in East Antarctica have slightly increased sea ice mass[21]. The West Antarctic Peninsula has shown a decline in sea ice extent coincident with an increase in average winter air temperature of 5.8ºC from 1950-2005[21].

Climate models predict that by 2100 Antarctic sea ice will reduce by around 24% in total extent and 34% in total volume, with possible delays in observed reduction until stratospheric ozone recovers[21].


4 Ocean processes

Ocean acidification

Oceans are becoming more acidic as they absorb carbon dioxide[28,29]. Ocean acidification is decreasing the ability of many marine organisms to build shells and skeletal structure[28,29].

By the time that atmospheric carbon dioxide reaches 450 ppm, large parts of the ocean system may become corrosive to key marine species, with possible negative flow-on impacts for wider marine ecosystems[28,30].

Changes to the oceanic uptake of atmospheric carbon dioxide may also occur[29].

Reef-building corals are under increasing physiological stress from a changing climate and increasing uptake of carbon dioxide by the oceans[31]. Skeletal records of corals in the Great Barrier Reef show that calcification has declined by 14.2% since 1990[31]. The data suggest that such a severe and sudden decline in calcification is unprecedented in at least the past 400 years.

Ocean winds

Winds in the southern hemisphere have a vital role in climate, causing the movement of millions of cubic metres of ocean water every second[32]. Winds can influence the rate at which oceans take up carbon dioxide, along with exchanges of other entities such as heat and trace gases[32]. Changes in the Southern Annular Mode (a mode of climate variability between the sub-Antarctic and mid latitudes that leads to changes in wind and storm activity) are currently causing winds to increase in strength. There are predictions that this will continue in the coming decades[32].

Strengthening westerly winds in the Southern Ocean do not appear to have affected the Antarctic Circumpolar Current or the overturning circulation. Small-scale eddies may be counteracting the wind changes, stabilising the ocean circulation[32].

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APPENDIX 4 – DERM AND QUEENSLAND CLIMATE CHANGE CENTRE OF EXCELLENCE –

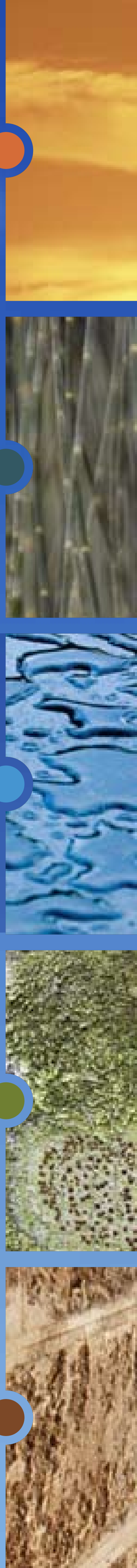
CLIMATE CHANGE: WHAT THE SCIENCE IS TELLING US

OFFICE OF climate change

Climate Change in Queensland

What the Science is Telling Us

2010



Toward Q2 Tomorrow's Queensland

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Minister's foreword

A sound understanding of our climate and the impacts of climate change underpin the policies and initiatives that I have introduced to address climate change. Climate change poses very real risks to Queensland. The very climate that makes Queensland so attractive to residents and international tourists alike is changing with potentially major consequences.

The land-ocean temperature record indicates that 14 of the past 15 years have been the warmest since 1880. Last year was the fifth warmest year in the 160 years of global instrumental temperature records, with 1998 being the warmest.

Queensland is particularly vulnerable to climate change impacts such as sea level rise, more frequent heatwaves, more intense rainfall events in some regions and drought in others.

Without practical action informed by the latest science, priceless natural assets such as the Great Barrier Reef and the industries that rely on our natural environment such as agriculture, mining and tourism are at risk.

Climate science may be complex but a basic understanding of how the climate is changing and what the impacts mean will ultimately help each and every one of us to make more informed decisions about what we can do to deal with it. In 2008 the Queensland Government released the first edition of the *Climate Change in Queensland: What the science is telling us* report. It provided general information on climate change, the projected impacts across Queensland, and potential impacts on key sectors.

This 2010 edition offers a detailed review and update on the latest climate science and what it means for Queensland. It provides a more in-depth analysis drawing on a review of more than 200 peer-reviewed scientific papers published in the last three years. It highlights the fact that we now have multiple lines of evidence to show that Queensland's climate is changing.

This report presents the differences between weather and climate, the causes of climate change and the indicators which provide support for these changes. It highlights the latest developments in international, national and Queensland research and discusses the latest observations and projections on temperature, rainfall, sea level rise and extreme events. Importantly, it outlines how the climate is likely to alter in the future for regional Queensland.

By investing in our climate science capability, the Government is seeking to ensure that Queensland is well positioned to better understand and respond to the challenges posed by climate change. That is why the Queensland Government established the Queensland Climate Change Centre of Excellence, the only state-based climate science research centre in Australia. I commend the scientists for their expertise and commitment to world class climate change research.

Clearly, there is plenty of new data showing we have some serious issues ahead of us but there is simply no benefit in shying away from these 'inconvenient truths'. Climate literacy in our community will become increasingly important as regional and national governments around the world work towards global agreement on collective action to reduce our greenhouse gas emissions.

In reading this report, I am sure you will be left in no doubt that successful mitigation and adaptation actions will depend on effective communication of climate science. Preparing communities for the impacts of climate change on human health, water security, industries, our built environment, emergency services and ecosystems is uppermost in my mind.

A better understanding of the science of climate change will ensure that we can all engage in informed debate on the implications for Queensland communities. This report is another step along that path.

The Honourable Kate Jones MP
Minister for Climate Change and Sustainability

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Executive summary

This report updates the science in the previous report, *Climate Change in Queensland: What the science is telling us*, released in June 2008. It discusses the science on which the Queensland Government based its climate change mitigation and adaptation strategy, *ClimateQ: toward a greener Queensland*, released in August 2009, and additional scientific information released since then.

Key findings for Queensland

- The last decade (2000–2009) was the hottest on record with temperatures 0.58 °C higher than the 1961–1990 average.
- Queensland regions can expect increased temperatures of between 1.0 °C and 2.2 °C by 2050.
- Rainfall is expected to change, with a potential decrease by up to seven per cent in central Queensland by 2050.
- A three to five per cent decrease in rainfall in the south-east Queensland region is projected.
- More frequent hot days and warm nights.
- Less frequent cold days and cold nights.
- Sea levels are rising faster than expected and the 2007 Intergovernmental Panel on Climate Change estimate of a 0.26–0.79 metre rise by 2100 may be a significant underestimate.

As a result of climate change, Queensland is likely to experience impacts including:

- increased flooding, erosion and damage in coastal areas due to increased numbers of severe tropical cyclones and sea level rise
- cyclones occurring further south
- increased numbers of hot days and warm nights, placing increased stress on the population and infrastructure
- reduced rainfall across most of Queensland. Cape York, the Gulf Region and Far North Queensland are projected to be less affected than the rest of the state
- longer dryer periods interrupted by more intense rainfall events (especially in the Gulf and Cape York)
- difficulty in supplying water to meet urban and agricultural demand due to decreasing rainfall and runoff, and increasing temperature and evaporation

- changes to terrestrial biodiversity with a potential loss of half the existing high-altitude Wet Tropics rainforest from a 1 °C increase in temperature
- changes to marine biodiversity particularly in the Great Barrier Reef due to increased acidification of oceans
- annual bleaching of up to 97 per cent of the Great Barrier Reef and associated large-scale mortality, if the average sea-surface temperature increases by 2 °C
- changes to marine species distribution, with potential impact on the fishing industry, due to changes in currents
- reduced breeding habitat of seabirds and turtles due to sea level rise
- increased spread of disease due to changed conditions for vectors
- increased heat-related illnesses.

The impacts of climate change will affect society as well as the environment. Both mitigation and adaptation will be necessary across all sectors of society to help limit and reduce the extent of greenhouse gas emissions and to avoid and adapt to expected impacts.

Adaptation mechanisms could include:

- changing agricultural practices, including the use of different crops or stock that are more resilient to changed climatic conditions
- changing water management practices to more efficient use of scarcer water supplies
- increasing reservation of high-conservation areas to help retain at-risk species
- increasing planning and land allocation for habitat connectivity to allow species to move as climate zones change
- improving planning for, and management of, coastal impacts of sea level rise and storm surges.

ClimateQ: toward a greener Queensland contains policies and initiatives that aim to reduce greenhouse gas emissions and adapt to the impacts of climate change. Details of these initiatives can be found at ‹http://www.climatechange.qld.gov.au›.

Australian climate changes

A number of recent reports have consolidated climate science information to provide an overview of climate change and expected impacts on Australia.

Climate Change in Australia is a joint Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Australian Bureau of Meteorology (BoM) publication, released in 2007 (CSIRO & BoM 2007). It builds on a large body of Australian climate research to provide a comprehensive assessment of Australia's climate. It outlines the latest information on observed and projected climate change over Australia and its likely causes.

The Garnaut Climate Change Review (2008) examined the impacts of climate change on Australia. It found that even at current emissions levels, the world is already committed to a level of warming that could lead to damaging climate change. The report noted that the business-as-usual approach to climate change increases the risk of serious and irreversible impacts. It found that the benefits of strong, early action on climate change would outweigh the costs.

Climate Change 2009 (Steffen 2009) reviewed the science of climate change since the publication of the Intergovernmental Panel on Climate Change's (IPCC) *Fourth Assessment Report, Climate Change 2007* (AR4) (IPCC 2007a–c). Steffen suggests that the AR4 was conservative in its range of projections and that many aspects of the climate system are changing at the upper level of the IPCC range of projections—towards more rapid and severe climate change with dangerous impacts.

The Science of Climate Change: Questions and Answers published in August 2010 by the Australian Academy of Sciences outlines changes in Australian climate including:

- an increase of about 0.7 °C in average surface temperature since 1960, with some areas having warmed faster and others showing little evidence of warming
- an increase in the frequency of extremely hot days
- a decrease in the frequency of cold days
- significant increase in rainfall over north-western Australia
- decrease in rainfall over south-eastern Australia
- sea level rise of about 1.2 millimetres per year since 1920.

Future impacts of climate change on Australia are likely to include:

- projected increases in average surface temperature of 0.6–1.5 °C by 2030 and 2.2–5.0 °C by 2070
- decreased average annual rainfall over much of Australia
- more intense rainfall on days with heavy rainfall over many areas
- an increase in the proportion of severe tropical cyclones, with a possible decrease in the total number of cyclones
- more frequent heatwaves
- more frequent droughts.

These findings (Australian Academy of Sciences 2010) indicate stronger than expected and sooner than expected climate changes.

Global climate changes

The IPCC has indicated that climate changes are linked to increased emissions of greenhouse gases caused by human activity.

Concentrations of atmospheric CO_2 are increasing rapidly, with the 2009 concentration level at 387 parts per million (ppm). Levels of atmospheric CO_2 are now at their highest concentration, much higher than the natural range over the last 800 000 years of 172–300 ppm. There is now 38 per cent more CO_2 in the atmosphere than at the start of the Industrial Revolution.

Recent research has indicated that the IPCC is likely to have been conservative in its projections and that the observed increase in the concentration of greenhouse gases has likely committed the world to an average warming of 2.4 °C (1.4–4.3 °C) above pre-industrial surface temperatures. The land–ocean temperature record indicates that 14 of the past 15 years are the warmest since 1880. Average global temperatures have increased by about 0.75 °C since 1900. Enhancement of the natural greenhouse effect due to the increased concentration of greenhouse gases is leading to global warming and long-term climate changes.

Over the past few decades, the Arctic has warmed at about twice the rate of the rest of the Earth. Arctic temperatures are currently higher than at any time in the last 2000 years, with the period 1999–2008 being the warmest.

At the current high levels of greenhouse gases in the atmosphere, warming of the climate will continue even if emissions are reduced. This is due to the long lifetimes of some greenhouse gases, especially CO_2. Even if emissions were to cease, slower heat loss from the ocean means that temperatures would not drop significantly for at least 1000 years.

Over the past 50 years the effectiveness of the Earth's carbon sinks has reduced. The fraction of total CO_2 emissions taken up by the land and oceans is decreasing, while the fraction that remains in the atmosphere has increased. The absorption of CO_2 into sea water is making the oceans increasingly acidic, with the potential to have negative impacts on marine organisms.

Data from tide gauges around the world shows that global sea level has risen by almost 0.2 metres since 1870. Since 1993, sea level has been more accurately measured by satellites. Both sets of measurements show that the rate of sea level rise has accelerated. Sea levels have been projected to rise by 0.8 metres, but indications are that the rise could be significantly greater.

Introduction

The 2008 publication *Climate Change in Queensland: What the science is telling us*, was principally based on the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007a–c) and *Climate Change in Australia—Technical report 2007* (CSIRO & BoM 2007).

In August 2009, the Queensland Government released *ClimateQ: toward a greener Queensland*, which includes climate change mitigation and adaptation policies and programs informed by the IPCC AR4. The AR4 remains the authoritative reference for Queensland policy development.

However, considerable scientific research has been published since that time, contributing further to our knowledge of climate change and its potential impacts. For example, in May 2009 the Australian Government released the report, *Climate Change 2009: Faster change and more serious risks* (Steffen 2009), which reviewed and synthesised scientific papers published since the release of IPCC AR4. This was followed by a similar report released by the United Nations Environment Programme in September 2009 (McMullen & Jabbour 2009).

Climate change is a complex issue that will affect each of us in our everyday lives and we need to understand the issues better.

This document draws on a comprehensive list of peer-reviewed reports and articles published up to August 2010, to provide up-to-date climate science research and to indicate projected changes in climate.

The effects of climate change are being felt across the globe. This report provides an overview of basic climate science and information on expected global climate change. More importantly, it focuses on the outcomes and expected impacts on Queensland and its key sectors.

It describes the projected changes in temperature, rainfall and extreme events for Queensland's various regions. It also outlines the key issues relevant to Queensland and shows how climate change is affecting the key sectors including human settlements and infrastructure, primary industries, water supplies, health, emergency management, and marine and terrestrial biodiversity.

Finally, the report outlines the current and proposed research actions and priorities needed to fully determine the social, environmental and economic implications for Queensland.

Chapter 1: Climate and weather

The climate system is complex. The Earth's climate is controlled by the exchange and storage of heat through the ocean, land, atmosphere and snow/ice. It is influenced by interactions between the sun, ocean, atmosphere, aerosols, clouds, ice and land (Figure 1).

The climate system is also finely balanced. Small changes in any of these variables can lead to significant changes in global and regional climate. For example, Soden *et al*. (2002) found that aerosols from the eruption of the Mt Pinatubo volcano in 1991 caused lower than average global temperature for approximately 2–4 years.

In contrast to the weather, 'climate' is how the atmosphere behaves over long periods of time. Climate is about changes, trends and averages over years, decades and centuries.

'Weather' is the day-to-day changes in temperature, precipitation, cloudiness, humidity, air pressure and wind. Synoptic maps show global weather systems, particularly high- and low-pressure systems and tropical cyclones, over three-hour or six-hour time periods (as specified by the World Meteorological Organization).

The United Nations Framework Convention on Climate Change (UNFCCC) makes a distinction between 'climate change' attributable to human activities, and 'climate variability' due to natural causes. The UNFCCC defines climate change as 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods' (United Nations 1992).

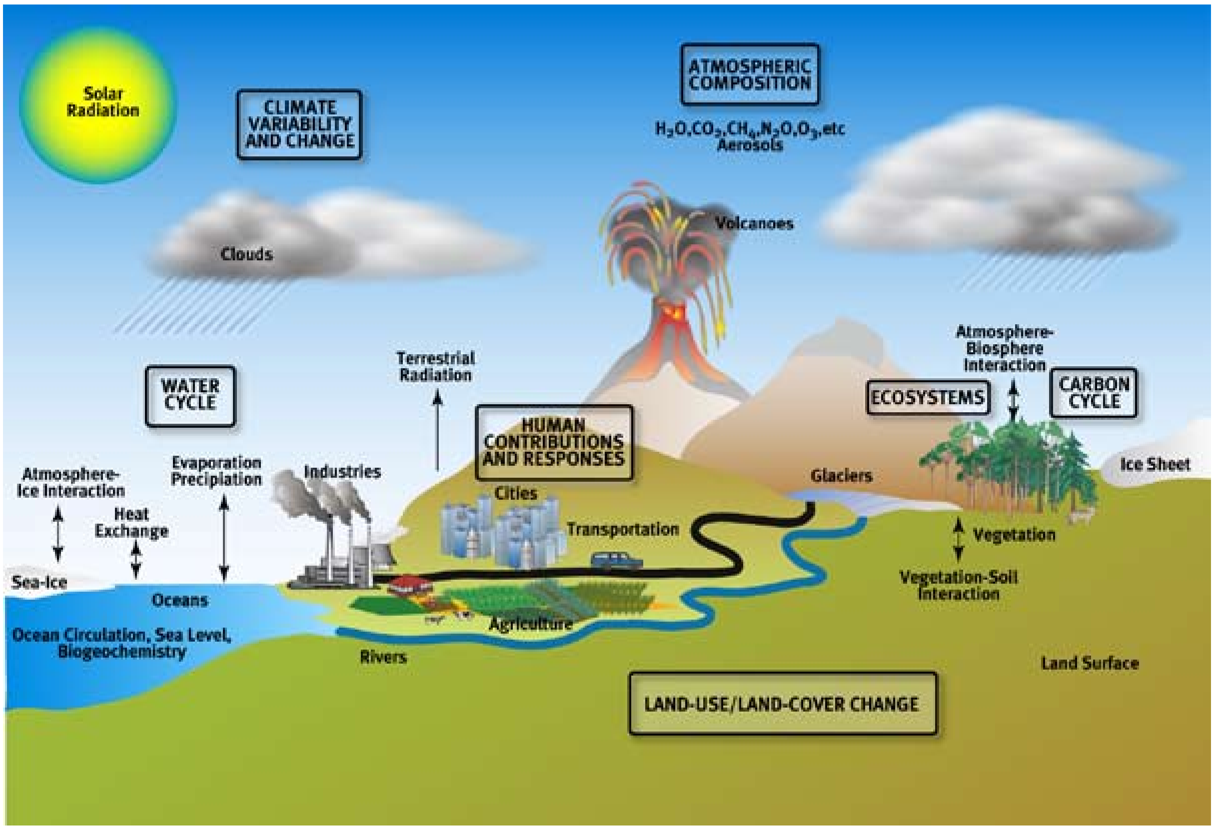


Figure 1: The climate system and climate change (Source: United States Global Change Research Program 2003; IAN 2010)

Two primary global atmospheric circulation patterns that have an impact on Australia's climate, in particular rainfall, are the Hadley cell and the Walker circulation.

The Hadley cell is a circulation pattern that transports excess heat from the equator towards lower temperate latitudes. It can be thought of as a conveyor belt, with warm moist air rising into the atmosphere in the tropics and moving southward (in the southern hemisphere) to the mid-latitudes where it cools and descends. The air is then returned to the tropics along the surface. The descending arm of the Hadley cell results in a band of high pressure known as the Sub-Tropical Ridge (STR). The Hadley cell also impacts on the easterly trade winds.

The Walker circulation is driven by the easterly trade winds (in the southern hemisphere) which carry warm moist air across the large ocean basins (Pacific, Indian and Atlantic) and is strongly linked to the El Niño Southern Oscillation (ENSO) in the Pacific Ocean. For example, during El Niño episodes the Walker circulation weakens, seas around Australia cool, and the trade winds feed less moisture into the Australian/Asian region.

Seasonal variations, for example the summer monsoon, affect synoptic weather patterns. Year-to-year fluctuations in the climate system and in particular the ENSO have a strong impact on the year-to-year fluctuations in Queensland's rainfall. There is also a multi-year cycle known as the Inter-decadal Pacific Oscillation (IPO) which contributes to extended dry or wet periods in Queensland. These fluctuations do not represent climate change but understanding these natural variations will improve our understanding of climate change impacts.

Australia's climate is among the most variable in the world. Figure 2 shows the main influences on Australian climate. Although there are many climatic features that affect Queensland's climate

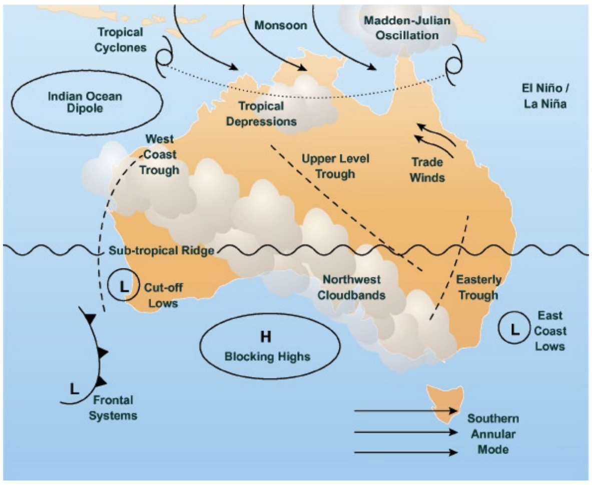


Figure 2: Climate signals which influence Australia's weather (Source: modified BoM 2010a)

the major climate drivers affecting the amount and pattern of rainfall across Queensland are the:

- El Niño Southern Oscillation (ENSO)
- Inter-decadal Pacific Oscillation (IPO)
- Madden-Julian Oscillation (MJO)
- Sub-Tropical Ridge (STR).

The ENSO has a significant effect on the annual fluctuations in seasonal conditions over eastern Australia. The ENSO is the oscillation between El Niño, La Niña and neutral conditions and is the result of variations in sea-surface temperatures and atmospheric patterns across the Pacific Ocean. The ENSO exerts a major influence on Queensland's climate, especially rainfall in northern and eastern Australia (Murphy & Ribbe 2004). Below-average seasonal rainfall in eastern Australia has long been linked to the El Niño phase of the ENSO and above-average seasonal rainfall with the La Niña phase (Murphy & Ribbe 2004).

There is also a link between major Queensland droughts and El Niño events, which occur when the sea-surface temperature rises in the eastern Pacific Ocean and cools in the west around Indonesia (DPI 2009).

El Niño and La Niña events typically last 9–12 months when equatorial sea-surface temperatures in the Pacific Ocean are well above (El Niño) or below (La Niña) average. The Southern Oscillation Index (SOI) is an indicator of ENSO conditions. It is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. SOI values are normally negative during an El Niño and positive during a La Niña.

Braganza *et al.* (2009) reconstructed the behaviour of ENSO from 1525 to 1982. They found that the variability of ENSO from the 16th to early 18th centuries was relatively low, but that high-frequency variability (at approximately 2–4 year intervals) has increased over the last 200 years (Braganza *et al.* 2009).

The IPO, like ENSO, is a change in the sea-surface temperatures in the Pacific Ocean. However, unlike ENSO, the IPO has an irregular interdecadal cycle. The positive phase of the IPO is characterised by warm sea-surface temperatures in the east, and central equatorial Pacific and cool sea-surface temperatures in the west Pacific. When the IPO is in this positive phase there is a weakening of the relationship between ENSO and Australian rainfall (Power *et al.* 1999).

The MJO is associated with a belt of low pressure that moves eastward across the equatorial Indian and Pacific Oceans. This 'pulse' of cloudiness has been observed to repeat roughly every 30–60 days. The passage of the MJO also influences the development of tropical cyclones. The MJO has its greatest effect on the tropical areas of Australia, increasing the intensity and duration of summer rainfall (Wheeler *et al.* 2009).

The STR is a large climatic feature that influences seasonal variations in weather across Australia. It is an area of high pressure to the south of Australia that moves north in winter, resulting in drier conditions over Queensland.

Recent warming appears to have increased the intensity of the STR (Timbal *et al.* 2010). The penetration of rain-bearing systems is impeded by the dry descending air of the STR which leads to a drier southern half of the Murray-Darling Basin. The influence of the STR was evident during the La Niña event in 2008, where storms and flooding affected Queensland and New South Wales, but had little impact on the Murray Valley or its headwater catchments (SEACI 2009).

Other climate drivers that affect rainfall include the East Coast Lows. These large-scale storm systems are one of a family of low-pressure systems which most often develop during the winter months along the east coast of Australia. East Coast Lows have the most impact on the New South Wales coast, with impacts off southern Queensland occurring occasionally. They are very intense and localised events which are difficult to predict. As with cyclones, they contribute to flooding and wind damage and beach erosion (BoM 2010a).

The Southern Annular Mode (SAM) also affects rainfall; however its impacts are felt primarily in southern Australia. The SAM is the north–south movement of the strong westerly winds that dominate the middle to higher latitudes of the Southern Hemisphere (BoM 2010a). Trends in SAM can account for 70 per cent of observed rainfall declines across southern Australia (Nicholls 2009). Although the relationship between the SAM and Australian rainfall is felt primarily in Southern Australia, the SAM is thought to have an impact on Queensland's rainfall through its effect on the STR (Williams & Stone 2009).

More research is needed to understand the relationship between rising global temperature and the STR intensification, and also the relationships among the various climate drivers, including the Hadley cell, ENSO and SAM.

The greenhouse effect

The natural greenhouse effect is a well-documented physical process which keeps the Earth at a stable temperature and makes it habitable. When energy from the sun (visible and ultraviolet radiation) reaches the Earth, it is either reflected back into space or absorbed by the land and oceans. The absorbed energy warms the Earth, which then emits heat (infra-red radiation). Some of this heat is captured by greenhouse gases, warming the atmosphere. Without the natural greenhouse effect, the average temperature on Earth would be about –19 °C, about 34 °C colder than it is today (Richardson *et al.* 2009).

Higher concentrations of greenhouse gases in the atmosphere increase the amount of outgoing heat absorbed, resulting in an 'enhanced' greenhouse effect. The increased level of greenhouse gases in the atmosphere, are contributing to changes in the climate.

The carbon cycle and carbon dioxide

Carbon dioxide or CO_2 is the major greenhouse gas responsible for human-induced (anthropogenic) climate change. Carbon in various forms circulates continuously between the atmosphere, oceans and land. Figure 3 shows the processes of release and storage of carbon, referred to as the carbon cycle. Carbon 'sources' (shown in Figure 3 as arrows) are activities such as burning fossil fuels, deforestation or fires that release CO_2 into the atmosphere. Carbon 'sinks' (shown in Figure 3 as asterisks) remove CO_2 from the atmosphere by sequestering (storing) it in the oceans, soil and vegetation. For example, the carbon from CO_2 absorbed by a tree may be stored as wood for hundreds of years. However, if the carbon becomes part of a leaf that dies and decomposes, the carbon is returned to the atmosphere relatively quickly.

It takes only a small change in the amount of CO_2 and other greenhouse gases in the atmosphere to upset the balance between the amount of carbon released and the amount sequestered.

Accelerated use of fossil fuels has increased emissions of greenhouse gases. Changes in land use also alter the amount of carbon in the atmosphere. For example it can increase through deforestation or be reduced through reforestation.

The continued and increasing release of CO_2 is altering the Earth's carbon cycle.

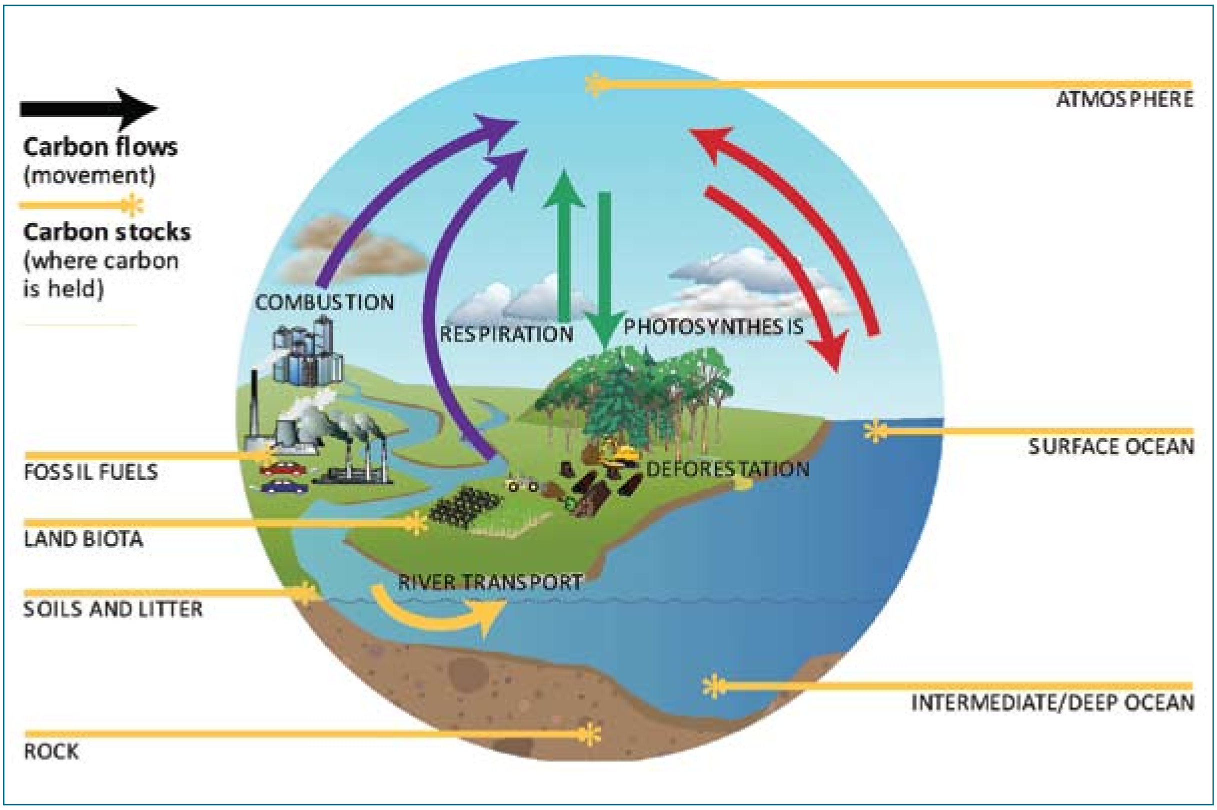


Figure 3: The carbon cycle (Source: DCC 2008; IAN 2010)

Contribution of human and natural factors to global warming

The term 'global warming' is often used with reference to climate change. Global warming describes the trend of increasing average global temperatures across the world, over decadal timeframes. It does not mean that every year is warmer than the previous year everywhere on Earth.

Both natural and human-caused (anthropogenic) climate forcings that can result in a changing climate include:

- greenhouse gases—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons
- ozone (O_3)
- changing surface reflectivity (albedo)
- solar variability
- aerosols.

Radiative forcing

Radiative forcing is a measure of the change in the energy balance of the atmosphere and is used to compare the contribution of different factors to global warming or cooling.

The IPCC (2007a) explains radiative forcing as a measure of the influence that a climatic factor (e.g. ice, clouds or greenhouse gases) has in altering the balance of incoming and outgoing energy in the Earth–atmosphere system.

A positive radiative forcing increases the energy of the Earth–atmosphere system, thereby warming it. In contrast, a negative radiative forcing decreases the energy cooling the Earth–atmosphere system. There are both natural and human causes of positive and negative radiative forcing (Figure 4).

Increases in solar activity provide a natural positive forcing, whereas volcanic eruptions may result in a negative forcing. Negative forcings from volcanic eruptions can cause a drop in mean global surface temperature of about half a degree Celsius that can last for months or even years (IPCC 2007b).

Human activities that produce CO_2, such as the use of fossil fuel for energy generation and clearing land, cause positive forcing and significantly contribute to global warming.

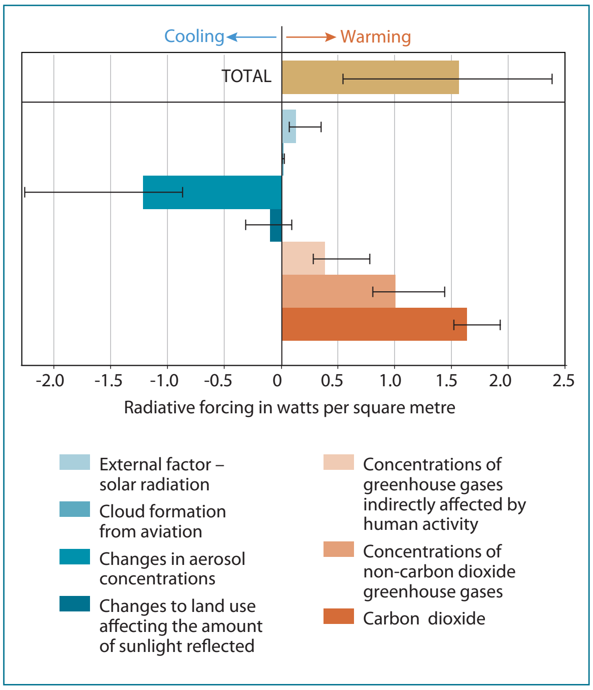


Figure 4: Contribution of human and natural factors to warming since 1750. The black error bars show the amount of uncertainty associated with each factor (Source: IPCC 2007a; updated Garnaut 2008)

The IPCC (2007a) compared the differences in natural variation and human activities between the present day and the start of the industrial era. It concluded that human activities caused a much greater difference in radiative forcing than natural variations (IPCC 2007a). Therefore, the radiative forcing from human activities has important implications for our current and future climate change.

Greenhouse gases

The four major human-generated greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (better known as CFCs or chlorofluorocarbons). CFCs are chemicals used largely as refrigerants and cleaning agents.

Ozone (O_3) can also be either a warming gas or a cooling gas depending on where it is found in the atmosphere. Concentrations of O_3 have risen by around 30 per cent since the pre-industrial era and it is now considered to be the third most important greenhouse gas after CO_2 and methane (NOAA 2010).

Water vapour has the greatest influence on climate because of its abundance in the atmosphere. However, unlike CO_2, water vapour is not influenced by anthropogenic activities.

Not all greenhouse gases are alike, either in terms of their concentration, their 'warming potential' or the length of time they stay in the atmosphere. For example, each greenhouse gas has a different average lifetime and effectiveness at trapping infra-red radiation (heat). Methane lasts about five to twelve years. CO_2 is less powerful as a warming agent (molecule for molecule) than CH_4; however, it can last for hundreds of years in the atmosphere (IPCC 2007b).

In order to compare greenhouse gases against one another, a unit called carbon dioxide equivalent (CO_2-e) is used. CO_2 equivalency enables the comparison of global warming potential (GWP) over a specified time frame (generally 100 years). Methane has a GWP of 25 (i.e. it is 25 times stronger than CO_2 over 100 years) (IPCC 2007b).

Greenhouse gases in the atmosphere are measured either as emissions or concentrations. An emission is the amount of a substance released into the atmosphere from a specific source and in a specific time frame. It is expressed by the mass per time period, for example, million tonnes (Mt) per year. A concentration is the relative amount of a substance in the atmosphere and is usually expressed as parts per million (ppm).

Figure 5 shows the concentration of three greenhouse gases which have increased significantly over recent decades. This contributes to the enhanced greenhouse effect and thus impacts on anthropogenic climate change.

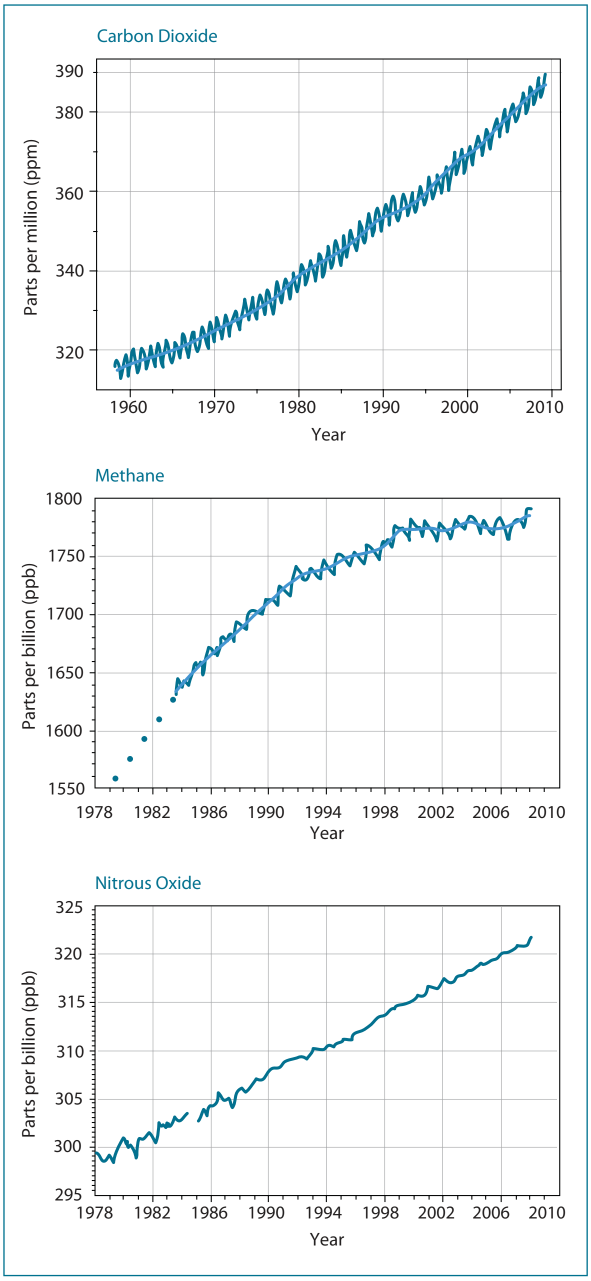


Figure 5: Atmospheric concentrations of carbon dioxide in ppm; methane in ppb (parts per billion); and nitrous oxide in ppb (Source: Richardson *et al.* 2009; Tans 2010; Hoffman 2009; Dlugokencky *et al.* 2005)

Since the start of the Industrial Revolution around 1750, the global CO_2 concentration has risen 38 per cent, CH_4 has risen 150 per cent and N_2O has risen 18 per cent (Le Quéré *et al*. 2009; IPCC 2007a).

The atmospheric CO_2 concentration in 2009 of 387 ppm (Tans 2010) is much higher than the natural range of 172–300 ppm that has existed over the last 800 000 years (Lüthi *et al*. 2008). The increase in CO_2 is due to the use of fossil fuels and land clearing. Increases in atmospheric concentrations of CH_4 and N_2O are primarily due to agricultural activities. Global carbon emissions from the combustion of fossil fuel and land-use change reached 10 billion tonnes in 2008, up from about two billion tonnes in 1950 (Le Quéré *et al*. 2009).

Denman and Brasseur (2007) report that over 60 per cent of atmospheric methane emissions are now related to human activities. Methane is responsible for almost a fifth of the enhanced greenhouse effect, second in importance only to CO_2 (IPCC 2007b).

Ozone

Ozone (O_3) absorbs long-wave infra-red radiation emitted from the Earth's surface, contributing to the greenhouse effect. Ozone makes a significant contribution to the radiative balance. Changes in the distribution of O_3 in the upper troposphere and lower stratosphere affect the radiative forcing of climate. During the 20th century, tropospheric ozone has been supplemented by anthropogenic ozone. Tropospheric ozone increases have contributed to warming, while stratospheric ozone decreases have contributed to cooling (IPCC 2007b).

Changing surface reflectivity (albedo)

Warming of the Earth is also affected by changing the fraction of solar radiation that is reflected (called 'albedo'). Albedo is affected by changes in cloud cover, atmospheric particles or land cover. About 30 per cent of the sunlight that reaches the top of the atmosphere is reflected back to space. Roughly two-thirds of this reflectivity is due to clouds and small particles in the atmosphere known as 'aerosols'. Light-coloured areas of Earth's surface (mainly snow, ice and deserts) account for the remaining one-third of the reflected sunlight. The energy that is not reflected back to space is absorbed by the Earth's surface and atmosphere (IPCC 2007b).

There is growing scientific evidence that the clearing of vegetation can have an impact on regional climate. Deo *et al*. (2009) found that the clearing of approximately 15 per cent of Australia for agriculture is likely to have contributed to a hotter and drier climate, and also exacerbated the El Niño effect by reducing evaporation and transpiration. Results for modified land-cover conditions show an increase in the number of dry and hot days, a decrease in wet-day rainfall (the amount of rain that falls on a wet day) and increases in the duration of droughts (Deo *et al*. 2009). These changes were statistically significant for all years and were especially pronounced during strong El Niño events. Therefore it appears that land-cover change has exacerbated climate extremes in eastern Australia, resulting in longer-lasting and more severe droughts (Deo *et al*. 2009).

Solar variability

Solar energy directly heats the climate system and can also affect the atmospheric abundance of some greenhouse gases such as stratospheric ozone. Solar output has increased gradually in the industrial era, causing a small positive radiative forcing. This is in addition to the changes in solar radiation that occur over the known 11-year cycle of solar activity (IPCC 2007b).

Aerosols

Aerosols (airborne particles) can also influence climate. Aerosols result both from natural sources and human activities. Natural sources include forest fires, sea spray, desert winds and volcanic eruptions. Human activities such as the burning of fossil fuels, deforestation and smoke from grass and bushfires also produce aerosols. Aerosols can cause both negative forcing (cooling) and positive forcing (warming) on the atmosphere (IPCC 2007b).

Aerosols, such as sulphates and nitrates, reflect visible solar radiation resulting in hazy skies and a cooling effect. Aerosols also cause an indirect negative radiative forcing through the changes they cause in cloud properties (IPCC 2007b). However, black carbon aerosols (soot) absorb visible solar radiation, warming the Earth (IPCC 2007b).

The direct radiative forcing summed over all aerosol types is negative. Currently the indirect effect of aerosols is not well quantified and the associated uncertainty is large (Figure 4).

Climate feedbacks

A change in a component of the climate, causing an impact which further changes the climate, is called a 'feedback'. A feedback can be either positive or negative.

A positive feedback increases the rate of global warming. For example, as the atmosphere heats up it has a greater capacity to hold water vapour, which will enhance the greenhouse effect leading to further warming. Another example of a positive feedback is when snow and ice melt to reveal darker land and water surfaces. These darker surfaces absorb more of the sun's heat, increasing the rate of warming, which causes more melting, and so on in a self-reinforcing cycle. This positive feedback loop is known as the 'ice-albedo feedback'.

A negative feedback slows the rate of global warming and has a cooling effect on the atmosphere. For example, as the ocean cools, its capacity to absorb CO_2 increases. The removal of CO_2 from the atmosphere dampens the greenhouse effect, resulting in further cooling.

Research into the Earth's climatic changes has focused on detecting, understanding and accurately quantifying climate feedbacks.

Climate modelling

Dynamical models and emissions or concentration scenarios are used to project changes in our climate and the relative impacts of these changes.

Climate models are numerical representations of various parts of the Earth's climate system. The models simulate the current climate system and use different emissions scenarios to project how the climate system might respond to natural and anthropogenic changes, such as increased greenhouse gas emissions or reduced land cover.

Models have a three-dimensional grid of points which extends horizontally and vertically on land, the sea and the atmosphere. Most global climate models use a grid spacing of approximately 200 kilometres. The latest UK Met Office Hadley Centre model, HadGEM1, uses a 135 kilometre horizontal grid.

Regional models operate at a finer resolution, for example using a 50 kilometre grid. Depending on the quality of the input data, these models can provide more detailed projections over a smaller area and take into account local effects.

The validity of a model is tested against the historical climate record. Once the ability of the model to accurately represent past climate has been established, the model can be refined to project future trends.

There is greater confidence in the model projections for temperature and pressure than there is for rainfall. Rainfall projections show stronger spatial and temporal variations which produce large variations between model outputs.

Simulation of large-scale climatic variability has improved, but local effects and small-scale extreme events are harder to simulate.

Queensland's climate change strategy, *ClimateQ: toward a greener Queensland*, released in August 2009, provides climate change projections for 13 Queensland regions. These indicate the projected changes (up to 2070) for temperature and rainfall. A summary of the climate projections and potential impacts for the 13 regions is presented in Chapter 3 and Table 1 (page 29).

Emissions scenarios

There is a distinction between climate change 'projections' and 'predictions'. Even with the best climate models, it is impossible to accurately predict the future climate. Climate change models take into account a range of climate variables on the physical environment and project the likely impact of greenhouse gases and other forcings on future climate.

There are various 'scenarios' developed by the IPCC (2007a) which reflect different assumptions about emissions of greenhouse gases, changes in population, rate of adoption of new technologies, economic growth and other factors.

These scenarios based on four 'storylines' (A1, A2, B1 and B2) are sets of assumptions about possible alternative futures. Each storyline yields a family of scenarios, 40 in total. The three IPCC scenarios most often used in climate modelling are:

- **B1 lower** emissions growth scenario—assumes a rapid shift to less fossil-fuel intensive industries and projects a global temperature increase relative to 1990 of 1.8 °C (1.1–2.9 °C) by 2100
- **A1B medium** emissions growth scenario—uses a diversity of energy sources and projects a global temperature increase of 2.8 °C (1.7–4.4 °C) by 2100
- **A1FI higher** emissions growth scenario—assumes a continued dependence on fossil fuels. The scenario projects a tripling of CO_2 concentrations (relative to pre-industrial levels) and a global temperature increase of 4.0 °C (2.4–6.4 °C) by 2100. Recent observations indicate that CO_2 emissions have been tracking above the A1FI level (Le Quéré *et al*. 2009).

The A2 emissions scenario is also used in climate modelling. The A2 scenario displays a continuously increasing population with a more fragmented and slower uptake of technology than the other storylines. Emissions for the A2 scenario are between those of the A1B and the A1FI scenarios for most of the century (from approximately 2030 to 2090) but by 2100, A2 emissions are greater than those of the A1FI scenario (IPCC 2007b).

The *IPCC Fourth Assessment Report* (AR4) also considers emissions reduction scenarios that would stabilise greenhouse gas concentrations at 445–490 ppm CO_2-e and global average temperature increases of 2.0–2.4 °C. The AR4 concluded that to stabilise greenhouse gas concentrations at this level, developed countries would need to reduce emissions by 25–40 per cent by 2020 relative to 1990 levels, and by 80–95 per cent by 2050 (IPCC 2007a).

A new area of climate science study—decadal projection—is emerging. This focuses on the links between seasonal forecasting and longer-term climate change projections. Decadal projections explore the evolution of regional climate conditions over the next 10 to 30 years. Projections on this timescale are very important to infrastructure planners, water resource managers and other land managers (McMullen & Jabbour 2009).

Improved modelling capability and increased knowledge of the climate system is enhancing the certainty of global climate change projections on a global scale. However, more local data and accurate regional modelling is needed for accurate projections of climate change on a regional scale.

Chapter 2: Global climate change

The Intergovernmental Panel on Climate Change (IPCC) is the authoritative international scientific body on climate change. The IPCC produces reports that assess climate change science which are based on published, peer-reviewed research. The most recent report, the *IPCC Fourth Assessment Report* (AR4) released in 2007, summarises the scientific research up to 2006 (IPCC 2007a).

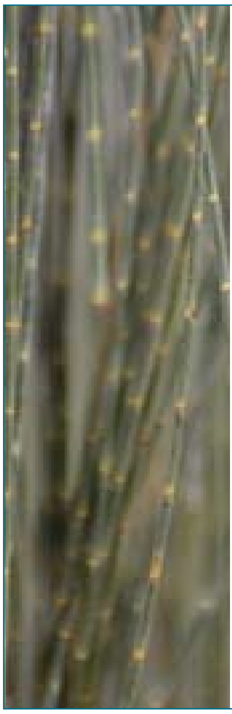
The AR4 concluded that warming of the climate system is unequivocal and that there is a more than 90 per cent probability that the warming is due to human activities, predominantly the burning of fossil fuels and clearing of natural vegetation.

The next report, the Fifth Assessment Report (AR5) is expected to be released in 2014.

Since 2006, a number of significant reports and papers have been published supporting the human influence on the climate and underlining the need for urgent action to mitigate the effects of climate change and to adapt to a changing climate.

In particular, the *2009 State of the Climate* report by the US National Oceanic and Atmospheric Administration (NOAA) released in July 2010 (Arndt *et al*. 2010) documents significant weather events from around the world that occurred in 2009, examines current climate anomalies, analyses 37 key climate indicators and provides a detailed review of 10 of these indicators. The 10 indicators were selected because of their clear and direct link with global temperatures. All 10 of these indicators were based on multiple global sets of observed data and all are consistent with a warming trend.

The Science of Climate Change: Questions and answers published in August 2010 by the Australian Academy of Sciences, unambiguously supports the conclusion that a continued reliance on fossil fuels would lead to a warmer world. The report addresses the current confusion about climate change created by contradictory information in the public domain and sets out to explain the current climate science, including areas of consensus or uncertainty.



Key messages

CO_2 emissions grew 3.4 per cent per year between 2000 and 2008, a growth more than triple that experienced during the 1990s. Increases in CO_2 in the atmosphere and oceans have resulted in:

- 14 of the past 15 years being the warmest since records began in 1880
- 2009 was the fifth warmest year (1998 was the warmest) in the 160 years of global instrumental temperature records
- global average temperature increasing by about 0.75 °C since 1900
- increased melting of permafrost releasing greenhouse gases into the atmosphere
- increased frequency of temperature extremes such as hot days and hot nights
- more frequent heatwaves
- extreme rainfall events with a greater number of severe tropical cyclones
- increased flooding associated with sea level rise and storm surges
- more severe droughts and bushfires
- increased ocean acidification disrupting marine ecosystems.

Observed climate change

Greenhouse gas emissions have increased rapidly over the last decade; if this continues it will result in increased impacts on human society and on ecosystems.

Observations of increasing global land and ocean temperatures, ocean heat content, rising sea levels and the retreat of glaciers and ice sheets all indicate the world is warming. Strengthening the certainty in this warming is the number of observations of each of these climate change indicators. There are four sets of global land and ocean temperature data, seven sets of global ocean heat content data and three sets of Arctic sea ice extent data. All of this data indicates that the world has warmed (Arndt *et al.* 2010). Increases in the number and severity of extreme weather events, which are expected in a warming world, are starting to be observed.

Greenhouse gases

Global emissions of CO_2 from fossil fuel combustion are currently at high levels. Le Quéré *et al.* (2009) found that CO_2 emissions grew 3.4 per cent per year between 2000 and 2008, more than triple the growth experienced during the 1990s. The concentration of CO_2 in the atmosphere is also increasing rapidly, rising to 387 ppm in 2009 (Tans 2010).

Figure 6 shows that observed emissions of CO_2 from fossil fuel combustion and cement production (a CO_2 intensive industry) align with the most carbon-intense emissions scenario (A1FI) of the IPCC.

The observed global CO_2 emissions up to 2006 are shown in Figure 6 from the US Department of Energy Carbon Dioxide Information Analysis Center, with 2007 and 2008 figures based on British Petroleum economic data.

The shaded area covers all the scenarios used by the IPCC to project climate change. Global CO_2 emissions in 2009 are expected to be approximately 3 per cent below 2008 levels, close to the level of emissions in 2007 (Le Quéré *et al.* 2009).

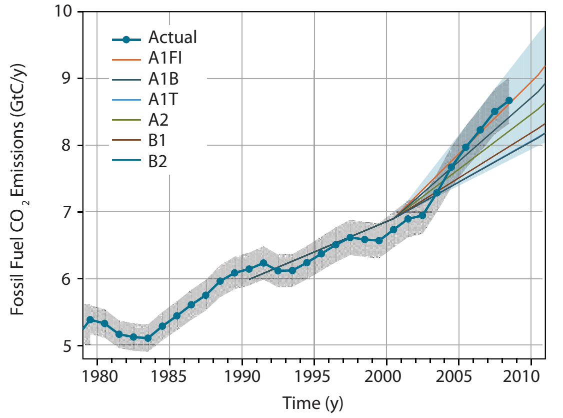


Figure 6: Observed global CO_2 emissions from fossil fuel burning and cement production compared with IPCC emissions scenarios between 1980 and 2010 (Source: Le Quéré *et al.* 2009)

Natural land and ocean carbon sinks absorb over half of all anthropogenic emissions. However, increased CO_2 emissions over the last 50 years have reduced the effectiveness of these sinks, increasing the amount of CO_2 retained in the atmosphere (Canadell *et al.* 2007).

Even if anthropogenic CO_2 emissions are reduced, the impacts will persist for centuries. Archer and Brovkin (2008) found that between 20 and 60 per cent of released CO_2 will remain in the atmosphere for a thousand years or longer (Archer & Brovkin 2008).

Temperature

The IPCC AR4 has increased our understanding of the causes of the recent century-scale warming and concluded that over 90 per cent of the observed warming is due to human factors (IPCC 2007a).

Lean and Rind (2008) compared the role of natural factors, such as solar variability and volcanoes, with human influences on temperatures since 1889. They found that over the last century, the sun contributed about 10 per cent of combined land- and sea-surface warming. Over the last 25 years, the sun's contribution to this warming was negligible (Lean & Rind 2008).

Ramanathan and Feng (2008) argue that the observed increases in the concentration of greenhouse gases has already committed the world to an average warming of 2.4 °C (1.4–4.3 °C) above pre-industrial surface temperatures.

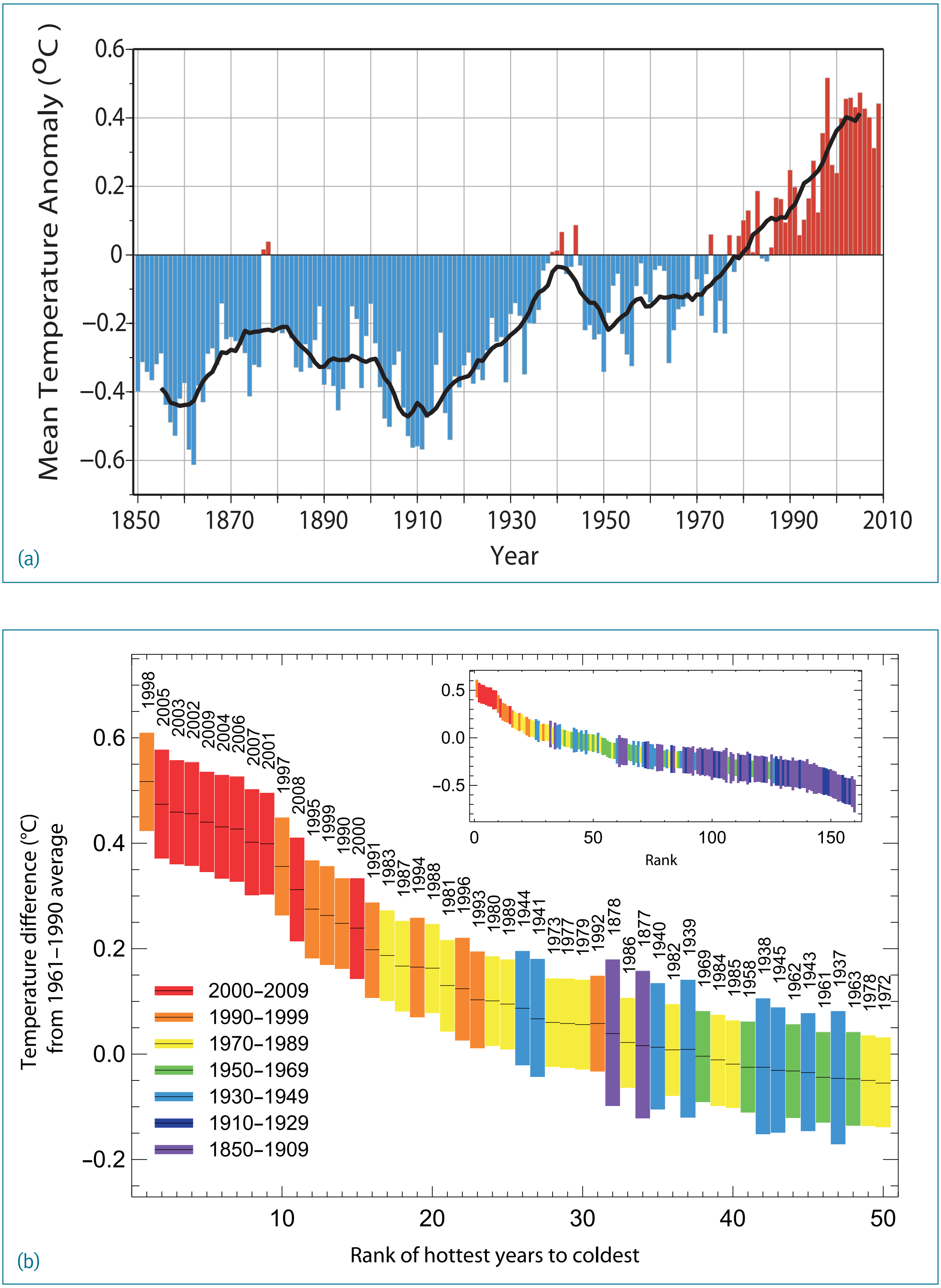


Figure 7: The global land–ocean temperature record from UK Met Office Hadley Centre (HadCRUT3) between 1850 and 2009 (temperature anomaly is relative to the average temperature from 1961 to 1990), (a) time series and (b) ranked by temperature (Source: Met Office 2010; Brohan *et al*. 2006)

Globally, the land–ocean temperature record indicates that 14 of the past 15 years are the warmest since records began in 1850 (Met Office 2010).

Figure 7(a) shows the strong warming trend in the global temperature record since the early 20th century. Figure 7(b) shows the individual years in the record ranked according to their average temperature, the year ranked as number one (1998) being the warmest year on record. This figure highlights the increasing trend in global temperatures, with recent decades dominating as the warmest years.

January 2000 to December 2009 was the warmest decade on record, with the last three decades displaying an upward trend. In total, average global temperatures have increased by about 0.75 °C since 1900 (Met Office 2010). The UK Met Office Hadley Centre (2010) data set shows that 2009 was the fifth warmest year in the almost 160 years of global instrumental temperature records.

There has also been a consistent and upward warming trend in ocean surface temperatures over the past 50 years. Satellite measurements of ocean surface temperature showed 2007 to be the warmest year ever recorded, despite the extremely strong El Niño event in 1997–98. Overall, ocean surface temperatures for 2009 were the second warmest on record (Allison *et al.* 2009; Met Office 2010).

Ocean heat content

Observations indicate that the world's oceans are warming. This is because they absorb most of the heat being added to the atmosphere by greenhouse gases. It is estimated that approximately 90 per cent of the heat added to the atmosphere from 1963 to 2003 was absorbed by the ocean (IPCC 2007b).

Arndt *et al.* (2010) and Palmer *et al.* (2010) summarise the recent observations of ocean heat content and compare eight separate studies examining the heat content of the upper 700 metres of the ocean. Although there are differences between the various datasets, they all show an increase in ocean heat content and a rapid increase over the last two decades. One of the most important consequences of increasing ocean heat content is sea level rise.

Sea level rise

Sea level rise is caused by increases in ocean thermal expansion and ocean mass due to increasing global temperatures. Water expands when it heats up, increasing the level of the ocean. Melting mountain glaciers, ice caps and the ice sheets of Greenland and Antarctica add new water to the ocean also increasing its level.

Domingues *et al.* (2008) found that the Earth's oceans have warmed 50 per cent more than previous estimates, which has direct implications for rising sea levels.

Data from tide gauges around the world shows that global sea level has risen by almost 0.2 metres since 1870 (Church & White 2006). Since 1993, satellites have been used to measure sea level more accurately. Both sets of measurements show that the rate of sea level rise has accelerated.

Coastal observations confirm that sea level rise has been occurring around Australia since at least 1920. Eastern Australia has experienced extreme sea level events three times as often in the last half of the 20th century compared with the first half (Church *et al.* 2006).

Figure 8 shows that the current rate of global average sea level rise is following the highest level (A1FI) of the IPCC projections. The sea level measurements using tide gauge data are indicated in red and satellite data is in blue. The shaded band shows the projections of the IPCC Third Assessment Report (IPCC 2001).

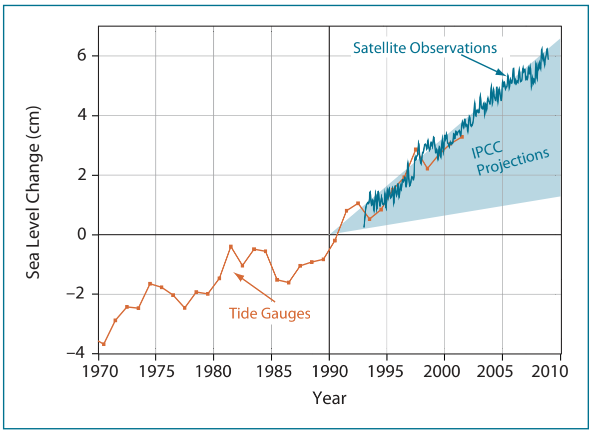


Figure 8: Sea level change compared with IPCC projections between 1970 and 2010 (Source: modified Allison *et al.* 2009)

Arctic sea ice

Over the past few decades, the Arctic has also warmed at twice the rate of the rest of the Earth. Kaufman *et al.* (2009) found that present Arctic temperatures are higher than at any time in the last 2000 years. The period from 1999 to 2008 was the warmest of the past 2000 years.

Since the early 1970s, Arctic sea ice extent at the end of the melt season in September has declined sharply and more rapidly than predicted by the IPCC AR4 (Stroeve *et al.* 2007).

Data from the National Snow and Ice Data Center (NSIDC) (Figure 9) indicates that at the end of the 2007 melt season, sea ice was 39 per cent below the long-term average and that 2005 to 2009 had the five lowest annual sea ice extents on record (NSIDC 2010). The observed September Arctic sea ice extent in millions of square kilometres is indicated by the orange line. The average sea ice extent from IPCC modelling is indicated by the solid blue line, while the dashed blue lines represent their range. The 2009 observed extent has been calculated at 5.1 million square kilometres, the third lowest year on record (NSIDC 2009).

A recent study by Wang and Overland (2009) found that by 2040, the Arctic Ocean could be nearly ice-free in the summer. Previous projections had this happening 60 years later—at the end of the century.

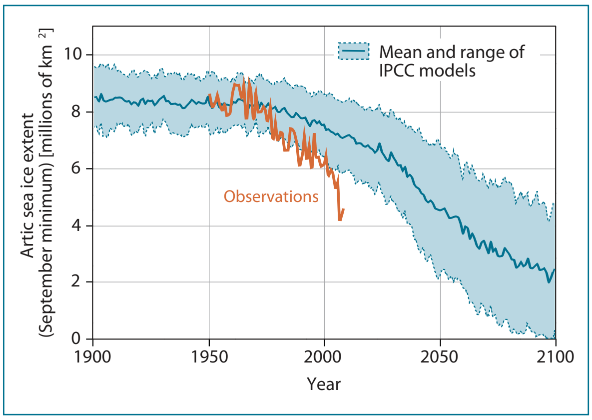
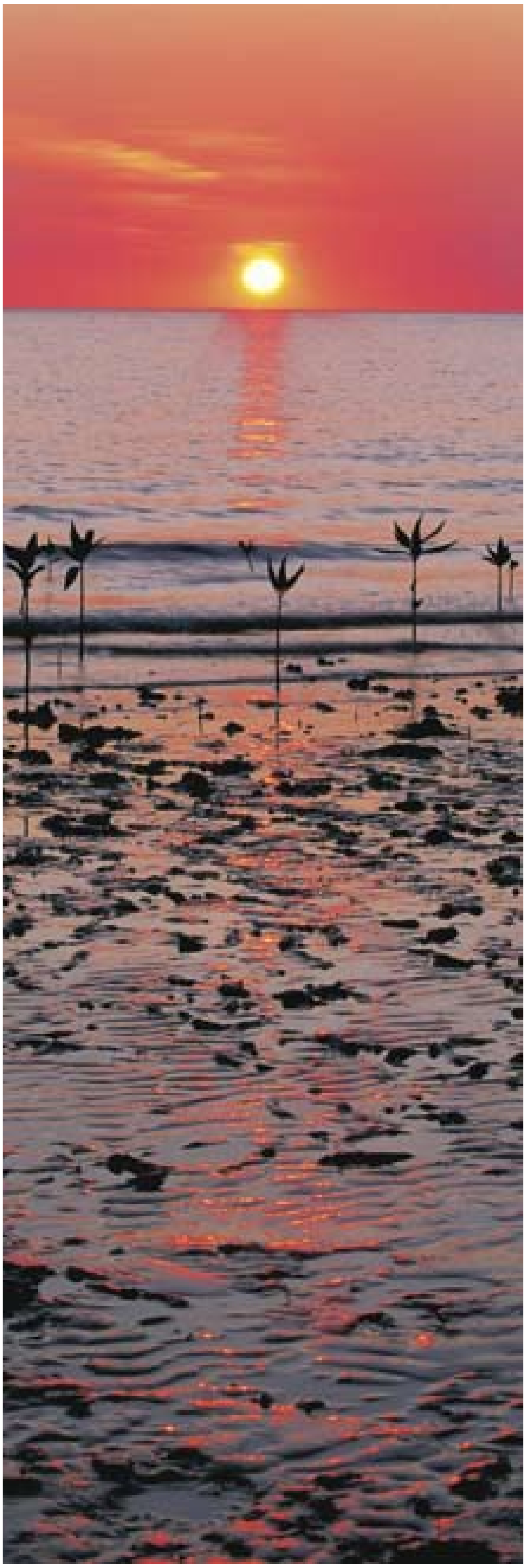


Figure 9: September minimum Arctic sea ice extent between 1953 and 2008 compared with IPCC AR4 projections between 1900 and 2100 (Source: Stroeve *et al.* 2007 updated; NSIDC 2009; Allison *et al.* 2009)



Ocean acidification

When CO_2 dissolves in sea water it forms carbonic acid, lowering the pH of the ocean and making the water more acidic. Hoegh-Guldberg *et al.* (2007) found that the increasing emissions of CO_2 have made the oceans more acidic than at any time in the last 420 000 years.

Ocean acidification affects all marine ecosystems in addition to reducing the capacity of oceans to store carbon. It is projected that once atmospheric CO_2 levels reach 450 ppm, large areas of the Southern Ocean and other polar oceans will have become so acidic that the shells and skeletons of key marine organisms will dissolve (Orr *et al.* 2009).

Figure 10 shows the changes that are projected to occur at different CO_2 concentrations. Changes in aragonite saturation are shown by the colour range, while the number at the top left of each panel is the atmospheric CO_2 concentration in ppm (Hoegh-Guldberg *et al.* 2007).

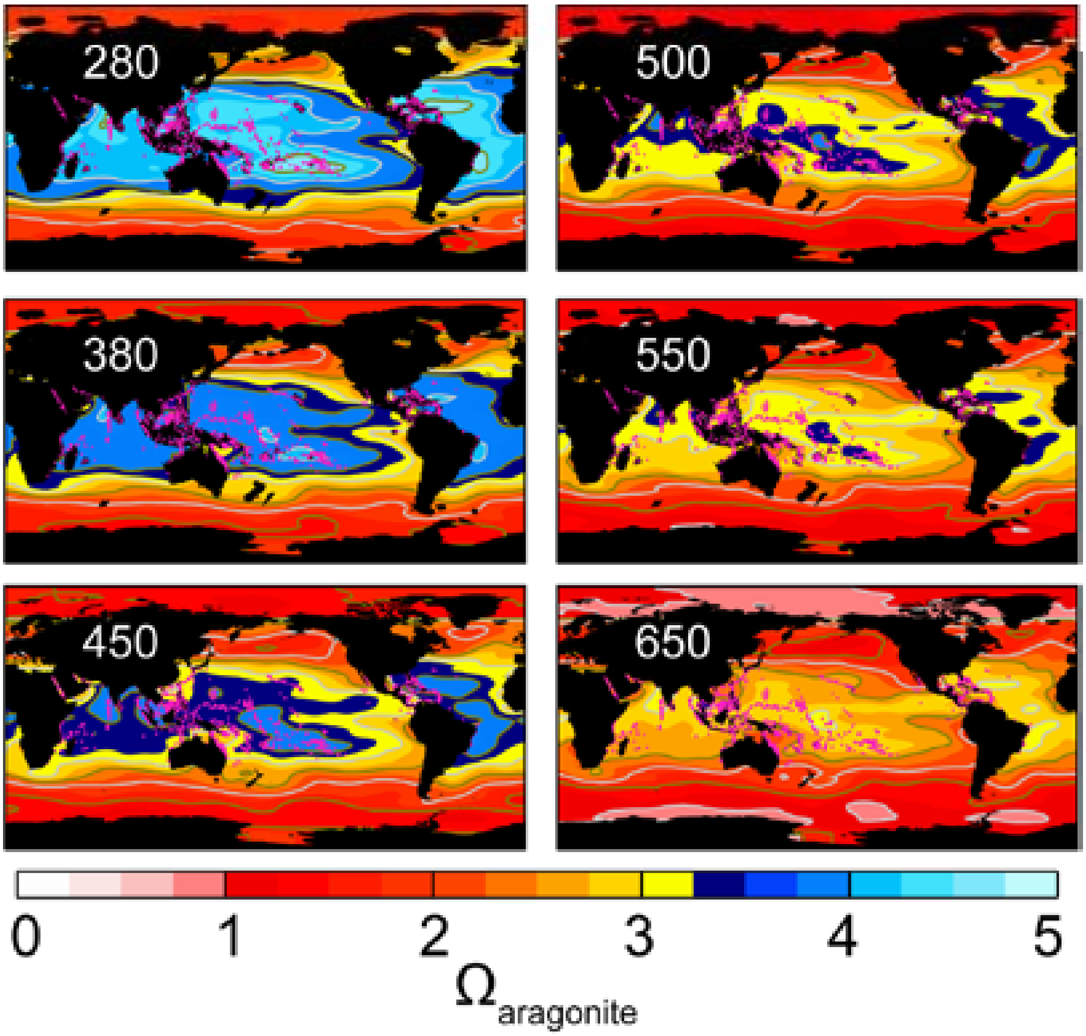


Figure 10: Changes in aragonite saturation as atmospheric CO_2 concentrations (ppm) increases (Source: Hoegh-Guldberg *et al.* 2007)

Aragonite is a mineral form of calcium carbonate used by organisms to form their shells and skeletons. If its concentration falls below about 3 ppm, marine organisms find it difficult to produce these shells and skeletons.

Increasing ocean acidification is likely to endanger many of the world's unique reef ecosystems including the Great Barrier Reef. Coral reefs now face a double threat of rising sea-surface temperature causing coral bleaching and acidification reducing some marine organisms' ability to grow (Hoegh-Guldberg *et al.* 2007). Moy *et al.* (2009) and De'ath *et al.* (2009) have already observed a decline in shell weights for several marine species since the Industrial Revolution.

Climate extremes

Extreme weather events occur within the climate's natural variability. However, recent observations show that an increasing number of extreme weather events can be attributed to human-induced changes in the climate system.

Steffen (2009) noted that during the last 50 years, hot days and hot nights have become more frequent, while cold days and cold nights are less frequent. He also found that over the same period, heatwaves have become more frequent and longer (Steffen 2009).

A comparison of satellite observations with model simulations of tropical rainfall events has also shown a clear link between temperature and rainfall extremes (Allan & Soden 2008). Allan and Soden (2008) found that heavy rain events increase during warm periods and decrease during cold periods.

Extreme weather events from climate change have the greatest potential impact on human and natural systems. Therefore accurate projections of such events are important for future climate change planning.

Future climate change

The long lifetimes of some greenhouse gases means that the climate will continue to warm into the future even if emissions are reduced. An analysis by Solomon *et al.* (2009) suggests that even if emissions were to stop completely, slower heat loss from the ocean would cause temperatures to remain high for at least 1000 years.

Sea level rise

For the high (A1FI) emissions scenario, the IPCC projected a sea level rise of 0.26–0.59 metres by 2100 (IPCC 2007a). A possible addition of 0.1–0.2 metres from melting ice sheets was also suggested but not included in the projections (IPCC 2007b). However, sea level has risen much faster than expected and current observations suggest that the projections of the IPCC AR4 may be significant underestimates (Rahmstorf *et al.* 2007; Vermeer & Rahmstorf 2009). The biggest uncertainty in current sea level rise projections is the response of the Greenland and Antarctic ice sheets to global warming.

Release of methane from permafrost

Permafrost (frozen soil) is found mostly in Siberia, Alaska, Canada and Scandinavia and acts as a large land-based carbon sink. An estimated 1670 billion tonnes of carbon is stored in permafrost—more than twice the amount of carbon in the atmosphere (Tarnocai *et al.* 2009).

Increasing land temperature could trigger rapid thawing of permafrost. As the soils defrost, the greenhouse gases (primarily CH_4) previously locked in the frozen soils are released into the atmosphere, further contributing to global warming (Lawrence *et al.* 2008).

Risk assessments estimate that if permafrost thawing continues, 0.5–1 billion tonnes of carbon per year would be released into the atmosphere, a figure similar in magnitude to current emissions from large-scale land-use change (Schuur *et al.* 2008).

Tipping points

Processes within the climate system appear to be unresponsive to change until a specific threshold is crossed. These thresholds or climatic 'tipping points' are regional-scale features that could result in abrupt or irreversible changes in the Earth's natural and climate systems (Lenton *et al.* 2008). Figure 11, shows some of the changes in systems which could trigger severe and long-term consequences for the climate system.

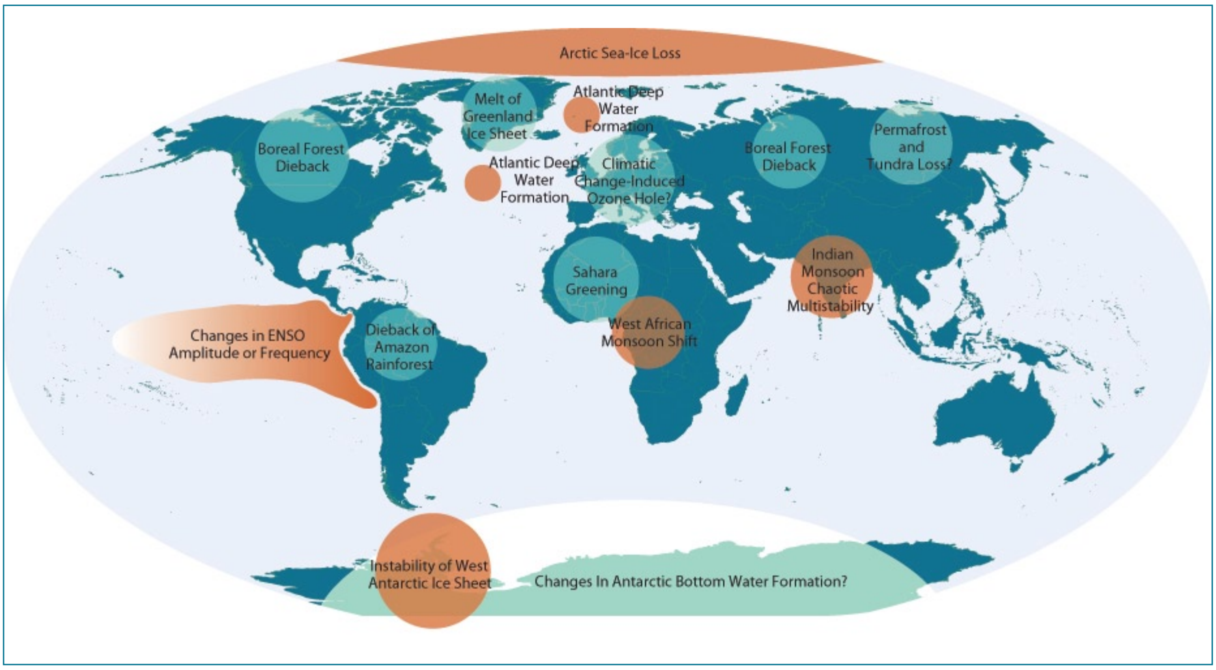


Figure 11: Map of some of the potential tipping points in the Earth's climate system (Source: Lenton *et al.* 2008; updated Richardson *et al.* 2009)

The question marks in Figure 11 indicate systems whose status as potential tipping points is particularly uncertain. Other potential thresholds include shallow-water coral reefs threatened in part by ocean acidification (Veron *et al.* 2009).

To minimise the risk of reaching these tipping points, Lenton *et al.* (2008) suggest that warming of the climate system must not exceed 2 °C above pre-industrial temperatures.

Meinshausen *et al.* (2009) showed that projected emissions from 2000 to 2050 are a good indicator of whether or not 21st century warming will exceed 2 °C. Limiting total 2000–2050 emissions to 1000 billion tonnes of CO_2 yields a 25 per cent chance of exceeding 2 °C. However, the likelihood of exceeding 2 °C of warming increases to 50 per cent if emissions total 1440 billion tonnes (Meinshausen *et al.* 2009).

While there is no global consensus on the definition of 'dangerous climate change', considerable support has developed for containing the rise in global temperature to a maximum of 2 °C above pre-industrial levels. However, research has shown that even with a temperature rise of less than 2 °C, impacts can be significant.

Beyond 2 °C, major societal and environmental disruptions may occur and the possibilities for adaptation of society and ecosystems may rapidly decline.

Many policy mechanisms focus on stabilising the level of greenhouse gas emissions at 450 ppm. This level reflects the need for continued economic growth and development, particularly in less developed countries. However stabilisation at 450 ppm will still result in significant impacts on society and the environment.

These impacts will require us to adapt to changes in how we live and work within our environment. Queensland's climate change strategy, *ClimateQ: toward a greener Queensland*, provides a range of mitigation and adaptation initiatives to help Queenslanders reduce emissions and adapt to a changing climate.

Chapter 3: Climate change in Queensland

Queensland has one of the highest per capita greenhouse gas emissions in the world and they have continued to grow over the last decade. Queensland is responsible for 30 per cent of Australia's carbon emissions despite having only 20 per cent of the national population (OCC 2009). Queensland's net greenhouse gas emissions are projected to rise from 175 million tonnes of CO_2-e in 2007, to nearly 250 million tonnes of CO_2-e by 2050 under a business-as-usual scenario (Nous Group & SKM 2008). Queensland is the Australian state that is most vulnerable to climate change.

All areas of Australia have experienced warming over the past 50 years. The geographic distribution of rainfall has also changed significantly over the same period.

Since 1960 the mean temperature in Australia has increased by about 0.7 °C. Some areas have experienced warming of up to 0.4 °C per decade resulting in total warming over the five decades of 1.5–2 °C. The number of days with record hot temperatures has also increased each decade over the past 50 years. While the total amount of rainfall has been relatively consistent, the distribution of rainfall over Australia has changed. Parts of northern and central Australia have experienced increasing rainfall while rainfall has decreased across much of southern and eastern Australia (CSIRO & BoM 2010).

The *State of the Climate* report (CSIRO & BoM 2010) indicates that in the future much of Australia will be drier; however, it is likely that the occurrence of intense rainfall events will increase in many areas. Australian average temperatures are projected to rise by 0.6–1.5 °C by 2030. If global greenhouse gas emissions continue to grow at rates consistent with past trends, warming is projected to be between 2.2 °C and 5.0 °C by 2070 (CSIRO & BoM 2010).

The effects of climate change will be superimposed on natural climate variability, leading to changes in the frequency and intensity of extreme weather events. For example, there is likely to be an increase in the proportion of severe tropical cyclones but a possible decrease in the total number of cyclones (CSIRO & BoM 2007). A strong increase in the frequency of hot days and warm nights is also projected (Garnaut 2008).

Key messages

The regional projections released in *ClimateQ*, Queensland's climate change strategy, indicate the key climatic changes expected in each of the 13 regions.

Regional changes in temperature, rainfall and evaporation are expected to impact on Queensland's biodiversity, infrastructure, water supplies, primary industries, human health and emergency management. To reflect projected changes in temperature and rainfall across Queensland, policy and planning should be based on:

- increased temperature, more hot days and warm nights
- increased frequency of heatwave events
- reduced rainfall across most of Queensland, with Cape York, the Gulf Region and Far North Queensland projected to be less affected than the rest of the state
- longer dry periods interrupted by more intense rainfall events, especially in the Gulf and Cape York
- rising sea levels of at least 0.8 metres by 2100
- increased number of severe tropical cyclones
- cyclones occurring further south
- increased hail days in south-east Queensland
- increased intensity of extreme rainfall events in some locations.

Observed climate changes

Observed global climate changes such as rising sea level and the retreat of Arctic ice have been examined in Chapter 2. Observed changes in Queensland climate, including trends in temperature, rainfall and evaporation are discussed below.

Temperature

Figure 12 shows the warming trend for Queensland, which is slightly stronger than the global trend (Figure 7a). The average surface temperature in Queensland has risen by almost 0.9 °C since early last century (Figure 12).

The warming trend over the whole of Queensland from 1950 to 2007 (Figure 13) shows that the greatest change in mean temperature occurs in southern Queensland, especially the south-western corner.

In the two decades to 2009, Queensland experienced just one year with an annual mean temperature below the 1961–1990 average (Figure 12). The decade 2000–2009 was the hottest on record for Queensland, 0.58 °C higher than the 1961–1990 average (BoM 2009a).

Throughout most of Queensland (especially central Queensland) the daily temperature range has decreased over the period 1950 to 2007. This is due to a greater increase in minimum temperatures than in maximum temperatures (Figure 13) (BoM 2009a).

Hennessy *et al.* 2008 define exceptionally hot years as those in which the annual mean temperature is in the highest 5 per cent of those on record. From 1968 to 2007, 11 per cent of Queensland experienced exceptionally hot years. This is

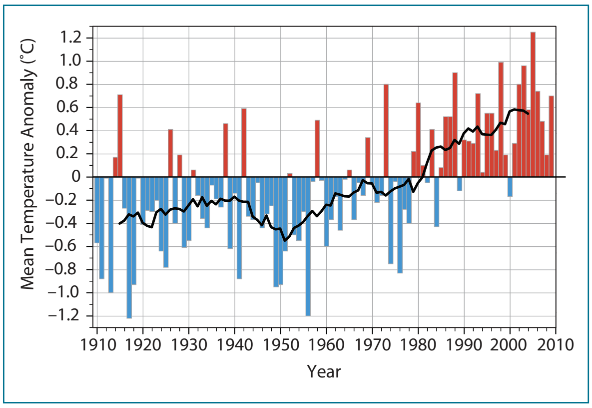


Figure 12: Time-series (1910–2009) of Queensland's annual mean surface temperature anomalies. The black line indicates the running 11-year average (Source: BoM 2009a)

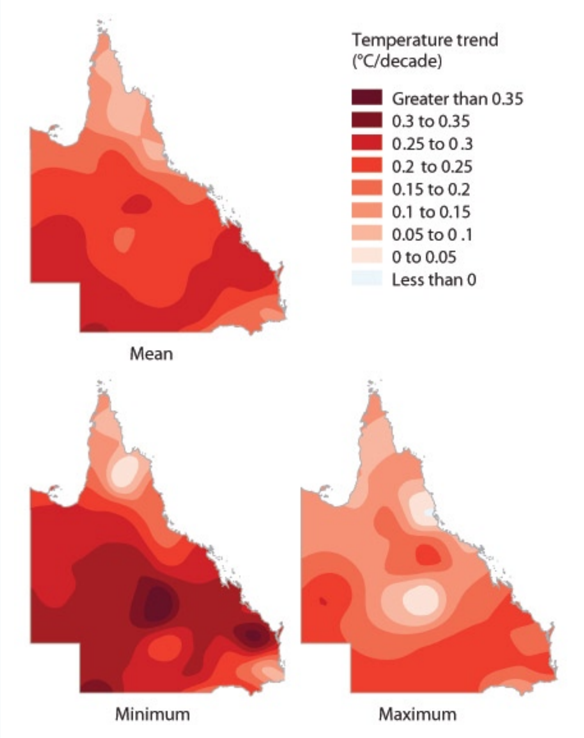


Figure 13: Trend in Queensland annual average temperature 1950–2007 (expressed as °C per 10 years) (Source: adapted by Department of Environment and Resource Management from BoM 2009a)

more than twice the 20th century average of approximately 4.6 per cent (Hennessy *et al.* 2008).

Rainfall

Figure 14(a) shows the annual rainfall trend for the last century, with increased rainfall predominantly in north Australia. Since 1950 the western part of Australia, particularly north-west Australia, has experienced increases in total annual rainfall whereas eastern Australia; including Queensland (except Cape York), New South Wales, Victoria and Tasmania has experienced significantly reduced rainfall (Figure 14(b)).

The reduction in annual rainfall across eastern Australia since 1950 is reflected by decreases in the:

- total number of wet days per year (days with at least one millimetre rainfall) (BoM 2009a)
- number of very heavy precipitation days (at least 30 millimetres rainfall) (BoM 2009a)
- amount of precipitation falling on extremely wet days (those days with precipitation greater than 99 per cent of the days on record) (BoM 2009a; Gallant *et al.* 2007; Alexander *et al.* 2007).

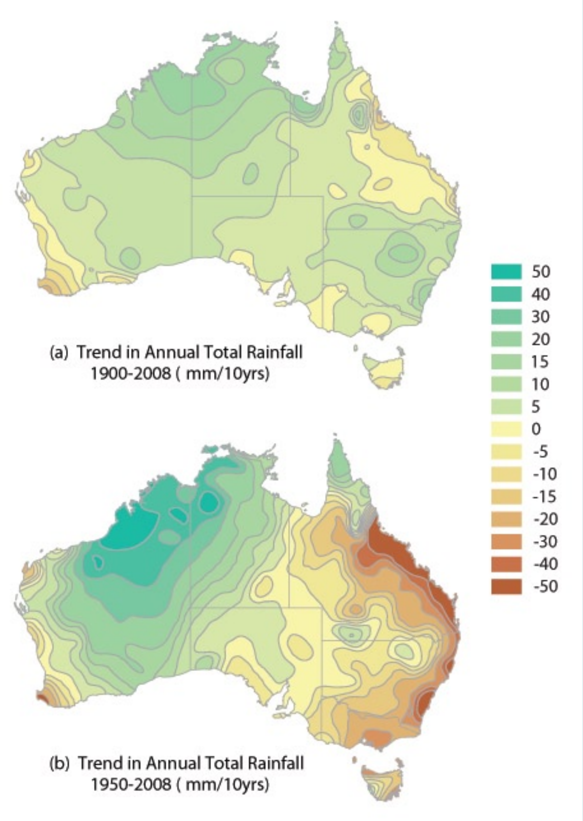


Figure 14: Trends in annual rainfall (expressed as millimetres per 10 years) for (a) 1900–2007 and (b) 1950–2007 (Source: adapted by Department of Environment and Resource Managment from BoM 2009a)

Queensland rainfall varies greatly from year to year. However, there has been a sustained decrease in rainfall along the east coast of Queensland since the 1950s (Figure 14).

This trend is partly due to natural variability in the global climate system. For example, changes in the Sub-Tropical Ridge and the Southern Annular Mode have been linked to recent reductions in south-east Australian rainfall. These changes may be linked to enhanced greenhouse gas concentrations; however, this needs to be clarified through further research (Murphy & Timbal 2008).

Drought

The recent drought in south-east Queensland (2001–2008) was the most severe on record. Previously the worst recorded drought was the Federation Drought from 1898 to 1903.

Figure 15 compares the cumulative rainfall deficiencies for south-east Queensland for the Federation and 2001–2008 droughts. The severe rainfall deficit and extended length of the recent drought (2001–2008) was magnified by higher temperatures and evaporation than had been experienced in previous decades (Nicholls 2004).

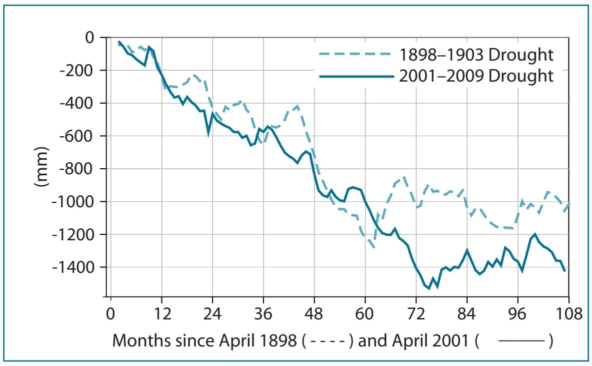


Figure 15: Comparison of the accumulated rainfall deficit in the catchment area west of Brisbane during the recent south-east Queensland drought (2001–2008) and the Federation Drought (1898–1903) (Source: DNRW 2007)

Tropical cyclones

Tropical cyclones are a common part of the Queensland climate and on average 4.7 tropical cyclones per year affect the Queensland area. However, not all of these cross the coast and cause damage (BoM 2010b). Those that make landfall can cause coastal erosion, property damage, flooding and inundation in coastal communities.

In January–February 2009, Category 1 tropical cyclones Charlotte and Ellie resulted in widespread flooding across north and west Queensland (BoM 2009b). The rainfall coincided with king tides along the Queensland coast, exacerbating flooding and inundation of coastal properties in Cairns, Townsville and Ingham.

Evaporation

Evaporation is measured as the amount of water that evaporates from an open pan called a 'Class A evaporation pan' (OCC 2009). Evaporation values range from 2–3 millimetres per day in south-east Queensland in winter, to over 10 millimetres per day in south-west Queensland in summer. While there is a strong link between evaporation and temperature, evaporation is also influenced by other factors such season, location, humidity, wind and cloud cover. Evaporation generally increases inland and is greatest in summer and spring.

Most of Queensland has experienced significant increases in evaporation. This has amplified the impacts of rainfall decreases, except in Cape York and the Gulf regions (BoM 2009a). Evaporation, unlike rainfall, is a constant process. Therefore during high evaporation conditions, small decreases in rainfall have a substantial impact on soil moisture and water storages. This affects water supplies available for people and agriculture.

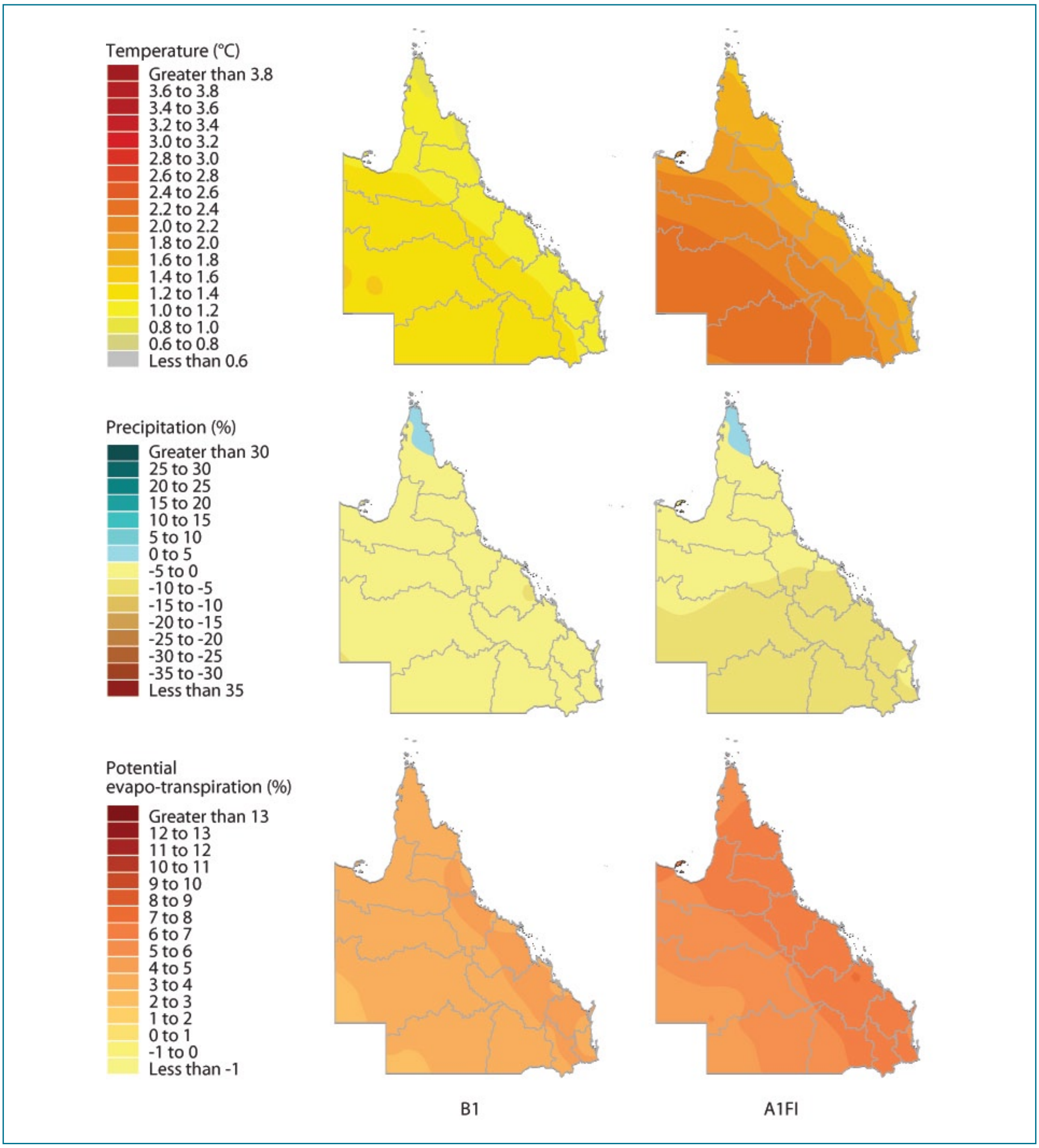


Figure 16: Best estimate (50th percentile) of projected change in annual temperature (°C), rainfall (%) and potential evapo-transpiration (%) by 2050 for low (B1) and high (A1FI) emissions scenarios (Source: OCC 2009, based on CSIRO data set)

Projected climate changes

ClimateQ contains detailed information on projected changes in temperature, rainfall and evaporation for each of the 13 regions of Queensland. These projections, based on climate modelling undertaken by the CSIRO for the Queensland Climate Change Centre of Excellence (QCCCE), are shown graphically in Figure 16 and summarised in Table 1. Figure 17 names the regions.

Figure 16 shows the expected changes in annual temperature, rainfall and potential evapo-transpiration (the amount of water that could evaporate and transpire from plants if sufficient water was available) for climate projections for Queensland in 2050 under low (B1) and high (A1FI) emissions scenarios. Temperature and evapo-transpiration are projected to increase across all of Queensland. Projections for rainfall are less clear.

The values in Figure 16 and Table 1 are the median (best estimate) projections resulting from 23 global climate models in the case of temperature and rainfall and 14 climate models for potential evapo-transpiration. Potential evapo-transpiration is calculated from projected values of surface air temperature, relative humidity and downward solar radiation (CSIRO & BoM 2007).

Table 1 lists the best estimates of the projected change in mean temperature (°C), rainfall (per cent) and evaporation (per cent) by 2050 under low (B1) and high (A1FI) greenhouse gas emissions scenarios for the 13 regions shown in Figure 17. A positive (+) figure indicates an increase in the variable. A negative(–) figure indicates a decrease in the variable. An historical (baseline) mean (1971–2000) is included for comparison.

Projections are the changes relative to the model base period of 1980–1999. The projections are expressed as changes in average climate for the 30-year period centred on 2050.

Table 1 also indicates the climate change impacts that can be expected in each of the 13 regions. In general, Queensland can expect to experience: increases in heat-related illnesses, difficulty in supplying urban and agricultural water needs due to decreasing rainfall; and increasing temperature and evaporation. Greater numbers of severe tropical cyclones, combined with storm surges, will increase erosion and coastal flooding and cause more damage.

Temperature

Projected temperature increases for Queensland regions by 2050 are in the range 1–1.4 °C for the low emissions scenario and 1.7–2.2 °C for the high emissions scenario (Table 1). Inland regions that already experience high temperatures will have the greatest increases.

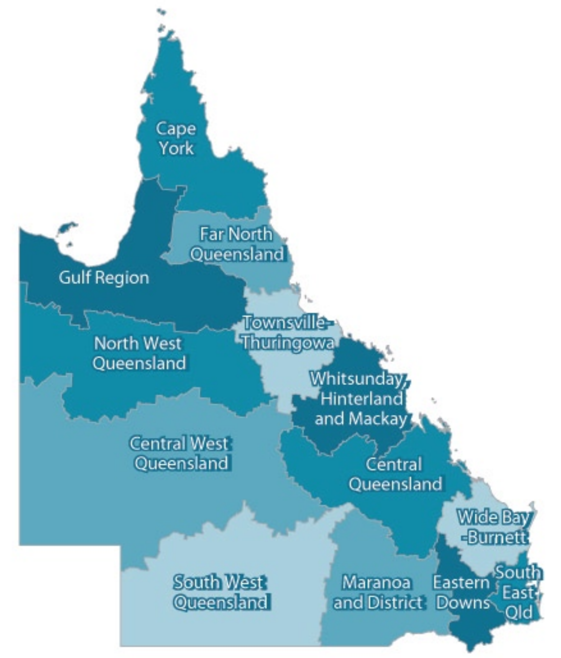


Figure 17: Queensland regions—land-use planning regions as at October 2007 (Source: OCC 2009)

Rainfall

Although the confidence in projections for Queensland's rainfall is lower than that for temperature, the best estimates (of both low and high emissions scenarios for 2050) are for decreasing or stable rainfall across each of the regions.

The low emissions scenario projections range from no change to a decline of four per cent in rainfall across Queensland. The high emissions scenario projects a decline of one to seven per cent. Cape York, the Gulf Region and Far North Queensland are projected to experience smaller declines in rainfall than the rest of the state.

Daily rainfall intensity is the average amount of rainfall occurring on 'wet days', that is, for days when daily rainfall exceeds one millimetre. Increases in rainfall intensity are projected for large areas of Queensland, especially in Cape York and the Gulf Region (CSIRO & BoM 2007).

These changes in rainfall intensity are due to an increase in rainfall on 'wet days', which may be accompanied by a reduction in the annual number of 'wet days'. In the areas where rainfall intensity increases, it could be expected that within the year there will be longer dry periods interrupted by more intense rainfall (CSIRO & BoM 2007).

Evaporation

Potential evaporation is strongly linked to temperature. By 2050 evaporation is projected to increase in Queensland regions by two to four per cent under the low emissions scenario and by five to seven per cent under the high emissions scenario (Table 1).

Sea level rise

Regional sea level rise will be influenced by localised effects. Modelling using the A1B (medium) emissions scenario shows a localised sea level rise along the east coast of Queensland and the Gulf Region of up to 0.05 metres by 2070, due to the strengthening of the East Australian Current. This is in addition to the IPCC's projected global sea level rise of up to 0.79 metres (CSIRO & BoM 2007), giving a total of 0.84 metres. For planning purposes, Queensland is currently using 0.8 metres as the projected sea level rise by 2100 (DERM 2009).

Future sea level rise will have dramatic consequences for many coastal communities. Relatively moderate levels of sea level rise are projected to cause large increases in the frequency of extreme sea level events. For example, an event that currently occurs once every 100 years could occur two or three times per year with a 0.5 metre sea level rise (Steffen 2009).

This multiplying effect of sea level rise is likely to impact on major population centres and have the greatest effect on eastern Australia (ACE CRC 2008).

Figure 18 shows the effect of a 0.5 metre sea level rise on high sea level events. The size of the circles shows the estimated multiplying factor for the increase in frequency of occurrence of high sea level events. For example, if the sea level was to rise 0.5 metres, high sea level events in Cairns could be a thousand times more frequent.

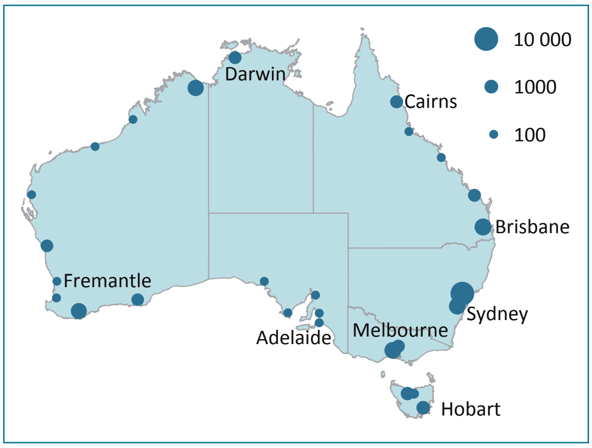


Figure 18: The multiplying effect of sea level rise on high sea level events in Australia (Source: ACE CRC 2008)

Extreme weather events

Extreme weather events can be classified as infrequent events at the high or low end of the range of values of a particular variable. For example, the number of hot days (those with a maximum temperature greater than 35 °C) is a measure of the high end of temperature values. Extreme weather events can also be classified by their impacts on the community, the economy and the environment. In this way any weather event that has a severe impact would be labelled an extreme event (Nicholls 2008). Potential changes in some extreme weather events are considered below.

Drought

Temperature, rainfall and soil moisture contribute to drought conditions. An 'exceptional' year is defined by Hennessy *et al*. (2008) as one in which a variable, such as mean temperature, rainfall or soil moisture, falls in the highest or lowest five per cent of years for that variable. Projections of changes in the number of exceptional years provide an indication of future drought conditions.

Projections for Queensland indicate a significant increase in the number of 'exceptionally hot' years. These are also projected to increase in frequency from an average of approximately one every 22 years to an average of one every 1.7 years by the period 2010–2040. Historically, 4.6 per cent of Queensland has been affected by these exceptionally hot years. Hennessy *et al*. (2008) have estimated that this will increase to 62.2 per cent over the period 2010–2040.

There is expected to be little change in the frequency and extent of exceptionally low rainfall years. However, slight increases in the frequency of exceptionally low soil moisture years, from an average of one every 16.5 years (1900–2007) to an average of one every 12.6 years (2010–2040), are projected.

The extent of Queensland affected by these exceptionally low soil moisture years is also expected to increase from 6.5 per cent in 1900–2007 to 7.4 per cent from 2010 to 2040. Hennessy *et al.* (2008) calculated these projections for soil moisture from a rainfall-runoff model using projected values of rainfall and potential evaporation.

Hot days

Figure 19 shows the average number of hot days (days with a maximum temperature greater than 35 °C) projected to 2050 for a selection of Queensland locations. The current number of hot days is calculated using a base period of 1971–2000 and the values in brackets are an indication of the range of projections from the different climate models (10th and 90th percentiles). Not surprisingly, inland sites are expected to have the greatest number of hot days.

The IPCC (2007b) states that, in the future, warmer and more frequent hot days over most land areas are virtually certain and that more frequent warm spells/heatwaves over most land areas are very likely. The projections for Queensland show increases in the number of hot days across the entire state (Figure 19).

Station Name	Number of days per year over 35°C			
	Current	2030 Mid	2050 Low	2050 High
Barcaldine	87	110 (100-121)	115 (103-129)	134 (116-156)
Birdsville	125	141 (135-149)	144 (137-154)	158 (145-173)
Brisbane Aero	1	2 (1-2)	2 (2-3)	3 (2-5)
Cairns	4	6 (5-8)	7 (5-11)	13 (8-26)
Camooweal	156	180 (168-190)	183 (171-195)	204 (185-224)
Longreach	112	133 (126-144)	138 (129-152)	156 (140-179)
Mackay	1	1 (1-2)	1 (1-3)	3 (2-8)
Rockhampton	16	26 (22-33)	29 (24-36)	40 (31-58)
Townsville	4	7 (6-9)	8 (6-13)	16 (9-31)
Weipa	55	82 (74-92)	86 (76-105)	118 (91-162)

Figure 19: Number of projected days per year above 35 °C for a range of emissions scenarios in regional centres (Source: OCC 2009, using CSIRO high-quality data set 2009)

Warm nights

Warm nights, defined as those with a minimum temperature higher than that of the temperature of 90 per cent of the nights between 1961 and 1990, are projected to increase across all of Queensland (and Australia). Northern Queensland is projected to experience up to a 50 per cent increase in warm nights by 2080–2099 under a medium emissions (A1B) scenario (CSIRO & BoM 2007).

Throughout most of Queensland, minimum temperatures are projected to increase more than mean temperatures (except for the tip of Cape York). This suggests that minimum temperatures will continue to increase more rapidly than maximum temperatures, as has occurred over the period 1950–2007 (Figure 13).

Extreme rainfall

Extreme rainfall is defined as the amount of rain falling in the top one per cent of rainfall days. Projections based on 15 climate models and a medium emissions (A1B) scenario indicated that Cape York can expect up to a four per cent increase in extreme rainfall across all seasons, and that western Queensland and the Gulf Region can expect up to a four per cent increase in summer and autumn (CSIRO & BoM 2007).

Climate change is also likely to affect extreme rainfall in south-east Queensland (Abbs *et al*. 2007). Projections indicate an increase in two-hour, 24-hour and 72-hour extreme rainfall events for large areas of south-east Queensland, especially in the McPherson and Great Dividing ranges, west of Brisbane and the Gold Coast. For example, Abbs *et al*. (2007) found that under the A2 emissions scenario, extreme rainfall intensity averaged over the Gold Coast sub-region is projected to increase by 48 per cent for a two-hour event, 16 per cent for a 24-hour event and 14 per cent for a 72-hour event by 2070. Therefore despite a projected decrease in rainfall across most of Queensland, the projected increase in rainfall intensity could result in more flooding events.

Fire danger

The Forest Fire Danger Index provides a measure of the bushfire risk. The index is based on the amount of moisture in the air, temperature, wind speed and the drought factor—a measure of the influence of recent rainfall and temperatures on fuel availability.

The most dangerous fire conditions occur with low relative humidity and high temperature and wind speed after periods of low rainfall (which raises the drought factor). The Forest Fire Danger Index is commonly lower for Queensland, with fewer high-risk days than in other states, due to higher levels of relative humidity.

By 2070 under a high emissions scenario, projections indicate up to a two per cent decrease in relative humidity across the majority of Queensland (except for a band along the east coast and the tip of Cape York where no change is projected) (CSIRO & BoM 2007).

Decreases in relative humidity, combined with projections of increased temperature, an increase in the number of hot days and less frequent rainfall events, are likely to increase the number of high Forest Fire Danger Index days.

Tropical cyclones

As reliable satellite observations of tropical cyclones only began in 1969, there is limited data on the long-term variations of tropical cyclones (Donnelly & Woodruff 2007; Nyberg *et al*. 2007). Therefore it is very difficult to distinguish between natural variability and human-induced climate change as the cause of changes in cyclone behaviour (Hunt & Watterson 2009).

Abbs *et al*. (2006) projected a nine per cent decrease in tropical cyclone frequency off the east coast of Australia by 2070, but an increase in the number of long-lived and severe (Category 3–5) tropical cyclones.

Two different studies have projected that the number of severe tropical cyclones will increase by 56 per cent by 2050 (Walsh *et al*. 2004) and 22 per cent by 2050 (Leslie *et al*. 2007). The variation in these projections is due to a lack of good observational data and the limited ability of global climate models to represent cyclone behaviour (Hunt & Watterson 2009). Leslie *et al*. (2007) projected an approximately 200 kilometre southward shift in cyclone source areas.

Severe thunderstorms

For a thunderstorm to be classified as severe by the Bureau of Meteorology, it needs to produce any of the following:

- hailstones with a diameter of two centimetres or more at the ground
- wind gusts of 90 kilometres per hour or greater at 10 metres above the ground
- flash flooding
- a tornado.

Current climate models do not have fine enough resolution to project small-scale events such as thunderstorms. Therefore it is difficult to attribute changes in thunderstorm frequency, intensity and location to human-induced factors. The likelihood of a thunderstorm event is determined on the basis of more widespread meteorological conditions. Projections obtained in this way demonstrate an increase in hail risk (hail days per year) associated with thunderstorms of up to four hail days per year by 2070 in south-east Queensland (CSIRO & BoM 2007).

Table 1: Summary of climate projections for 2050 and key impacts for 13 Queensland regions (Source: CSIRO & BoM 2007).

Region	Temperature			Rainfall			Evaporation			Impacts
	Baseline mean (°C)	2050 Low (°C)	2050 High (°C)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Examples of climate change impacts for the given region
Cape York	26.5	+1.0	+1.7	1431	0	-1	2216	+3	+6	• flooding, erosion and damage to infrastructure associated with sea level rise/increased storm surge • increased spread of disease (e.g. malaria, dengue) due to more favourable conditions for vectors • ecosystem changes and extinctions in the Wet Tropics rainforests • increased heat-related illness • increase in amount of rain falling on extremely wet days is likely to increase the severity of flooding
Central Queensland	21.6	+1.2	+2.0	692	-4	-7	1997	+4	+7	• more regular bleaching and mortality of corals of the Great Barrier Reef due to increased temperature • increased acidification of sea water and resultant decrease in coral growth and coral reef maintenance • increased spread of disease (e.g. malaria, dengue) due to more favourable conditions for vectors • increased pressure on water supplies • increased heat-related illness • increased risk and intensity of bushfires
Central West Queensland	23.6	+1.4	+2.2	362	-4	-6	2914	+3	+5	• declining pasture quality and quantity due to increased evaporation and decreased rainfall • increased pressure on water supplies • increased heat-related illness • increase in amount of rain falling on extremely wet days is likely to increase the severity of flooding • increased risk and intensity of bushfires • increased pressure on water supplies

Region	Temperature			Rainfall			Evaporation			Impacts
	Baseline mean (°C)	2050 Low (°C)	2050 High (°C)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Examples of climate change impacts for the given region
Eastern Downs	18.3	+1.2	+2.0	694	-3	-6	1737	+3	+7	• increased pressure on water supplies • reduction in grain quality due to increased temperature, evaporation and decreased rainfall • increased heat-related illness • increased risk and intensity of bushfires
Far North Queensland	24.4	+1.1	+1.8	1250	-1	-2	1999	+3	+6	• more regular bleaching and mortality of corals of the Great Barrier Reef due to increased temperature • increased acidification of sea water and resultant decrease in coral growth and coral reef maintenance • ecosystem changes and extinctions in the Wet Tropics rainforests • increased spread of disease (e.g. malaria, dengue) due to more favourable conditions for vectors • flooding, erosion and damage to infrastructure associated with sea level rise/increased storm surge • increased heat-related illness
Gulf	26.6	+1.2	+2.0	855	-1	-1	2549	+3	+6	• flooding and erosion associated with sea level rise/increased storm surge • increased spread of disease (e.g. malaria, dengue) due to more favourable conditions for vectors • increase in amount of rain falling on extremely wet days is likely to increase the severity of flooding
Maranoa and Districts	20.2	+1.3	2.2	582	-4	-6	1985	+3	+6	• reduction in grain quality due to increased temperature, evaporation and decreased rainfall • increased pressure on water supplies • increased risk of heat-related illness • increased risk and intensity of bushfires

Region	Temperature			Rainfall			Evaporation			Impacts
	Baseline mean (°C)	2050		Baseline mean (mm)	2050		Baseline mean (mm)	2050		Examples of climate change impacts for the given region
		Low (°C)	High (°C)		Low (%)	High (%)		Low (%)	High (%)	
North West Queensland	25.2	+1.3	+2.1	534	-2	-3	2775	+3	+6	• increased pressure on water supplies • increased risk of heat-related illness • increase in amount of rain falling on extremely wet days is likely to increase the severity of flooding • increased risk and intensity of bushfires
South East Queensland	19.4	+1.1	+1.8	1135	-3	-5	1553	+3	+6	• declining pasture quality and quantity due to increased evaporation and decreased rainfall • increased pressure on water supplies • conditions may become more favourable for plant diseases, weeds and pests • flooding, erosion and damage to infrastructure associated with sea level rise/increased storm surge • increased risk of heat-related illness • increased risk of tropical cyclone impact due to southward shift in genesis region
South West Queensland	21.6	+1.4	+2.2	383	-4	-6	2588	+2	+5	• declining pasture quality and quantity due to increased evaporation and decreased rainfall • increased pressure on water supplies • increased risk of heat-related illness • increase in amount of rain falling on extremely wet days is likely to increase the severity of flooding (especially in summer and autumn) • increased risk and intensity of bushfires

Region	Temperature			Rainfall			Evaporation			Impacts
	Baseline mean (°C)	2050 Low (°C)	2050 High (°C)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Examples of climate change impacts for the given region
Townsville Thuringowa	23.3	+1.1	+1.9	813	-3	-5	2025	+4	+7	• more regular bleaching and mortality of corals of the Great Barrier Reef due to increased temperature • increased acidification of sea water and resultant decrease in coral growth and coral reef maintenance • flooding, erosion and damage to infrastructure associated with sea level rise/increased storm surge • increased spread of disease (e.g. malaria, dengue) due to more favourable conditions for vectors • declining pasture quality from increased temperatures • ecosystem changes and extinctions in the Wet Tropics rainforests • increased risk of heat-related illness • increased risk and intensity of bushfires
Whitsunday Hinterland and Mackay	22.7	+1.1	+1.9	837	-4	-7	1964	+4	+7	• more regular bleaching and mortality of corals of the Great Barrier Reef due to increased temperature • increased acidification of sea water and resultant decrease in coral growth and coral reef maintenance • flooding, erosion and damage to infrastructure associated with sea level rise/increased storm surge • increased risk of tropical cyclone impact due to possible southward shift in genesis region • increased risk of heat-related illness • Increased spread of disease (e.g. malaria, dengue) due to more favourable conditions for vectors • increased risk and intensity of bushfires

Region	Temperature			Rainfall			Evaporation			Impacts
	Baseline mean (°C)	2050 Low (°C)	2050 High (°C)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Baseline mean (mm)	2050 Low (%)	2050 High (%)	Examples of climate change impacts for the given region
Wide Bay Burnett	20.5	+1.1	+1.8	862	-4	-6	1715	+4	+7	• increased pressure on water supplies • flooding, erosion and damage to infrastructure associated with sea level rise/increased storm surge • variable and declining rainfall, combined with rising temperatures and increased evaporation could have a significant impact on primary production • increased risk of tropical cyclone impact due to possible southward shift in genesis region • increased risk of heat-related illness • increased risk and intensity of bushfires

Storm surge

Storm surge is a local rise in sea level caused by the combined action of severe surface winds and decreased atmospheric pressure (Hardy *et al.* 2004). When storm surge is combined with normal astronomical tide variations and wave setup this is referred to as storm tide. It is the storm-tide level which must be accurately predicted to determine the likely extent of inundation from a storm event (Hardy *et al.* 2004).

The height of storm surge on the Queensland east coast is expected to increase with rising sea level and changes in tropical cyclone behaviour. The most recent Queensland study by Hardy *et al.* (2004) assesses the risk to coastal communities of changes in storm surge and wind speed from tropical cyclones. Figures 20 and 21 summarise the key results.

Figure 20 shows the height of the one-in-100-year storm surge added to the expected highest tide at some key Queensland coastal locations. The dark blue line indicates current conditions while the light blue line represents projected conditions to 2050.

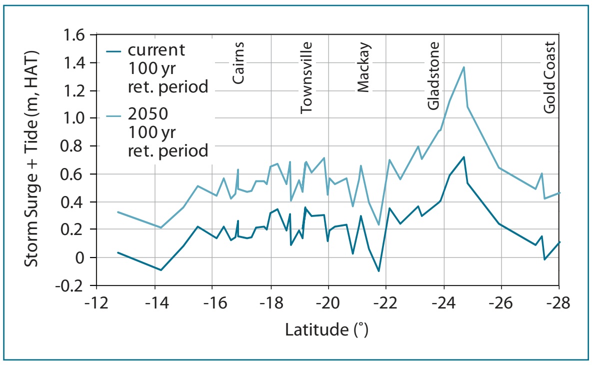


Figure 20: Height above highest astronomical tide (HAT) of storm surge plus tide for current and 2050 100-year return periods (Source: Hardy *et al.* 2004)

In assessing the risk to coastal communities Hardy *et al.* 2004 used the following values:

- a 0.3 metre mean sea level rise (IPCC 2001)
- a 10 per cent increase in the frequency of cyclone occurrence (Harper 2001)
- the combined effects of a:
  - » 10 per cent increase in maximum intensity
  - » southward shift of tropical cyclone tracks of approximately 120 kilometres (Henderson-Sellers *et al.* 1998; Walsh & Katzfey 2000).

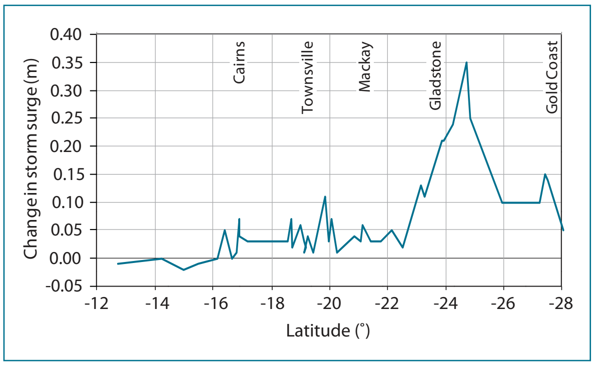


Figure 21: Changes in storm surge between 2050 and current 100-year return period events, not including the contribution from sea level rise (Source: Hardy *et al.* 2004)

Figure 21 shows the projected change in storm surge to 2050 after the 0.3 metre sea level rise is removed. It represents changes in storm surge associated with increases in frequency and intensity, as well as a southward shift in tropical cyclones (as for Figure 20). It shows significant rises in storm surge independent of the mean sea level rise, especially for the south-east Queensland coast.

The storm surge shown in Figures 20 and 21 is not a true indication of the actual potential level of inundation (storm tide) as it does not include wave setup.

Most of the south-east Queensland coastline is projected to experience an increase of over 0.1 metres in storm surge from changes in tropical cyclone behaviour alone (Hardy *et al.* 2004). The complexity of the coastline and the proximity of the Great Barrier Reef create various responses to storm surge along the Queensland coast. Storm surge is magnified in open coast locations, where a wide continental shelf creates a 'pile up' of water; as well as in embayments, where the water is funnelled into a concentrated area.

Chapter 4: Impacts of climate change on key sectors

Projected changes to temperature, rainfall, evaporation and extreme events, such as cyclones and sea level rise have been discussed in Chapter 3. This chapter provides information on the impacts of these changes on key sectors of the Queensland economy and indicates some adaptation options.

Human settlements and infrastructure

Human settlements refer to cities and towns right down to much smaller communities. Infrastructure is the essential physical structures that exist to support these settlements, including transport and service facilities such as water, sewerage and power.

As Queensland's population and settlement densities continue to grow, so do the potential impacts of climate change on Queensland settlements and infrastructure.

Greater urbanisation in vulnerable areas increases risks from climate change to both existing and future infrastructure.

Key messages

In Queensland the major risks to communities and their supporting infrastructure are cyclones and flooding. In addition, poor building design will place an increasing load on mechanical cooling to manage the effects of higher temperatures, increasing the need for fossil-fuelled electricity generation and thereby increasing greenhouse gas emissions.

Climate change will affect settlements through direct and indirect impacts resulting in damage to buildings and other infrastructure. These climate changes include:

- increased intensity of rainfall events
- increased temperatures
- more frequent extreme weather events
- increased extent and frequency of coastal flooding due to sea level rise and storm surges.

There will be a need for:

- changes to building codes to strengthen buildings in areas that may be at greater risk of cyclones due to the projected southward shift of cyclone source areas
- planning decisions and building standards reflective of the life span of the built environment, which can be up to 200 years
- design and loading codes to be based on a risk assessment process to ensure that the potential impacts of climate change are considered and factored into design of buildings and infrastructure
- consideration of the impact of changes in land use driven by climate change on supporting infrastructure services including transport.

The current accuracy of topographic data constrains planning for the impacts of sea level rise, storm surge and flooding. Digital elevation modelling being undertaken by the Queensland Government will provide more accurate topographic information to inform planning and emergency management decisions.

Policy and legislative mechanisms will help to reduce the impacts of climate change and the level of adaptation required. However, these will need to be regularly reviewed and revised to reflect the changing science.

Climate risks

Climate projections for Queensland point to higher temperatures, rising sea levels and an increased intensity of extreme events. The resilience of building and infrastructure to climate change will depend on building stock characteristics such as design, structure, size, age and condition.

Extreme heat events and higher temperatures, particularly in inland regions, will generate greater demand for well-designed new buildings and retrofitting of existing buildings.

Climate change may increase the risk of structural damage to buildings, especially damage resulting from strong winds associated with more intense tropical cyclones or damage resulting from more intense storms and associated flooding. Cracking may also occur as soils dry out from higher temperatures and reduced rainfall. Residential buildings are likely to be more vulnerable to such damage than commercial buildings, with older buildings more vulnerable than newer ones.

The structures that support our energy, telecommunication and transportation requirements (e.g. transmission lines, roads, railways, ports and bridges) have been identified in a number of studies as vulnerable to climate change impacts (IPCC 2007c; PMSEIC 2007; ATSE 2008).

Poorly designed buildings with increased reliance on mechanical air-conditioning to manage effects of higher temperatures will place additional loads on supporting energy infrastructure, with associated increases in greenhouse gas emissions. Through more frequent extreme daily rainfall events there is also a risk of exceeding the capacity of stormwater, drainage and sewerage infrastructure (NCCARF 2009).

Climate change impacts

Variations in temperature and rainfall across Queensland will produce a wide range of climatic impacts which will affect the planning and management of infrastructure requirements. These are discussed below.

Cyclones

Tropical cyclones are the main hazard for low-lying lands along the Queensland coast due to very high winds, heavy rain and storm surges (DCC 2009a). For example, Tropical Cyclone Larry crossed the far north Queensland coast on 20 March 2006 near Innisfail, with wind gusts of up to 240 kilometres per hour. This resulted in more than $1 billion damage to coastal townships, infrastructure and crops, as well as flooding coastal rivers (DCC 2009a).

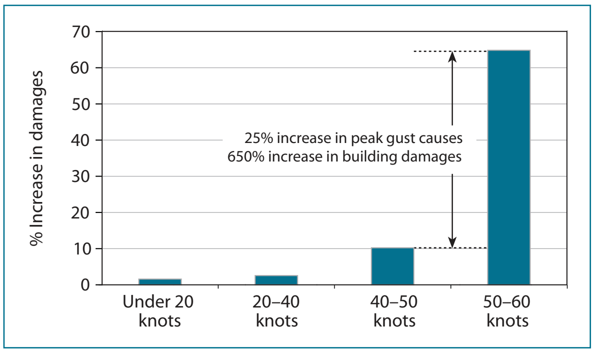


Figure 22: Increase in building damage due to wind gust speed (Source: Coleman 2002, in DCC 2009a)

The impacts of cyclones on the built environment are from winds, heavy rainfall, flooding and storm-tide events. Damage to buildings includes weakening of structural loadings of buildings, uplifting of roofs, collapse of buildings, impacts from flying debris, and internal damage from rain and moisture penetration. Extreme rainfall events are expected to affect the stormwater and sewerage infrastructure, while roads and bridges are vulnerable to changes in moisture content.

Vulnerability of buildings and infrastructure varies widely and depends on the location, topography, construction materials, age, features and standards applicable at the time of construction and subsequent levels of maintenance.

Coastal areas are subject to greater impacts from extreme wind events than inland areas, and climate change could increase the intensity of wind gusts.

The Australian Government's report on risks to Australia's coasts (DCC 2009a) suggests that this could lead to a significant increase in damage to buildings. Figure 22 shows that a 25 per cent increase in wind gust speed could generate a 650 per cent increase in building damage.

A preliminary study by Wang and Wang (2009) of the risk to buildings in Australia from extreme wind gust speeds found that the building standard specifications for Brisbane may not be adequate when the combined hazard of cyclonic and non-cyclonic winds is considered.

Models are being developed to help understand what makes residential buildings vulnerable. These consider how buildings resist and transmit wind loading forces and include the impact of windborne debris. This engineering modelling approach has been applied to north Queensland structures to help define the range of damage for a given wind gust speed (Henderson & Harper 2003).

Ensuring good quality construction of wind-resistant buildings, the securing of elements that can blow away (e.g. metal sheeting, roofing, fences and signs) and engineering to withstand wind forces and water damage can help reduce impacts.

A quantitative assessment of the impacts of climate change on Australia's physical infrastructure by the Australian Academy of Technological Sciences and Engineering (ATSE 2008) identified that comprehensive risk assessment techniques should be applied to support the design of critical infrastructure. This would require the review of existing design codes, particularly loading codes.

Options for better building performance with respect to cyclones, winds and intense storms include the development of:

- impact-resistant building materials, especially external claddings and glazing
- enhanced external finishes and claddings that prevent water access
- better window designs (e.g. increased thickness of glazing or reduced panel sizes to reduce wind forces)
- improved 'fixing' systems (roof to walls, walls to floors)
- aerodynamic building designs
- better foundation design
- better planning guidance to avoid a 'wind tunnel' effect.

Sea level rise, coastal and inland flooding

Flooding occurs most commonly from heavy rainfall when natural watercourses do not have the capacity to convey excess water. La Niña years experience more floods on average than El Niño years.

Riverine flooding occurs in relatively low-lying areas adjacent to streams and rivers in the extensive flat inland regions. Such floods may spread over thousands of square kilometres and last several weeks. Flash floods can occur when there is a relatively short intense burst of rainfall such as during a thunderstorm and where the drainage system has insufficient capacity or time to cope with the downpour.

However, floods are not always caused by heavy rainfall. In coastal areas inundation can be caused by a storm surge associated with a tropical cyclone. East coast lows (intense, short-lived low-pressure systems) can also bring widespread rain, gale force winds, rough seas and prolonged heavy swells over coastal and ocean waters in south-east Queensland, resulting in damage to the coastline, buildings and infrastructure.

The IPCC AR4 (IPCC 2007b) projected an increase in the severity of storms and coastal flooding by 2050. Sea level rise will also have an impact on extensive coastal housing and tourism development. Low-lying coastal areas such as the Gold Coast and the Torres Strait islands will potentially be adversely affected by rising sea levels.

Floods are the most expensive natural disaster in Australia (BTE 2001), estimated to contribute 29 per cent of the average annual natural hazard damage in Australia and costing around $314 million each year. Some of the largest floods in Australia have been caused by decaying tropical cyclones; for example, the 1974 Brisbane flood was caused by the decaying Tropical Cyclone Wanda. This flood resulted in 16 deaths, 300 injuries and made 9000 people homeless (EMA 2006).

The decay of cyclone systems can bring significant rain which can affect areas that are some distance from the coast. Under such circumstances, the risk of localised flooding is high in urban or rural areas where drainage is poor. For example, while having little direct effect on the inland Eastern Downs region, tropical cyclone systems have been associated with flooding in the region through the weakening of such systems into significant rain-bearing depressions.

In 2006, peak flood levels were recorded in the Leichhardt River after Tropical Cyclone Larry travelled almost 450 kilometres inland to around Croydon before being downgraded to a rain depression. The anticipated greater intensity of rainfall in certain regions of Queensland will also have implications for flooding risks.

Crompton and McAneney (2008) reviewed the insurance losses from the ten major events in Australia since 1973. Wang *et al.* (2010) provided estimates of flood damage in Queensland. Table 2 shows a number of weather-related events resulting in significant financial losses. For example, the 1974 Brisbane flood resulting from Tropical Cyclone Wanda resulted in losses of $2090 million at current prices.

Event	Year	Location	State	Current Loss as at 2006 (AUD$ million)
Earthquake	1989	Newcastle	NSW	4300
Tropical Cyclone Tracy	1974	Darwin	NT	3650
Hailstorm	1999	Sydney	NSW	3300
Flood (Tropical Cyclone Wanda)	1974	Brisbane	QLD	2090
Hailstorm	1985	Brisbane	QLD	1710
Ash Wednesday Bushfires	1983	Multiple	VIC/SA	1630
Hailstorm	1990	Sydney	NSW	1470
Tropical Cyclone Madge	1973	Multiple	QLD/NT/WA	1150
Hailstorm	1976	Sydney	NSW	730
Hailstorm	1986	Sydney	NSW	710
Flood	2008	Mackay	QLD	342
Flood	1981	Dalby	QLD	200
Flood	1998	Townsville	QLD	154
Flood	2008	Emerald	QLD	104

Table 2: Normalised losses from insured events (Source: Wang *et al.* 2010; Crompton & McAneney 2008)

Coastal and inland floods cause direct damage by inundation, erosion or 'washing away' of facilities. Damage to infrastructure can include damage or disruption to power and communication services, sewerage, water supply and transportation links. Bridges and many major airports are vulnerable to sea level rise and storm surge.

An Australian Government Department of Transport and Regional Services report (Amitrano *et al.* 2007) found that there is a greater chance of flooding events in areas with the potential for increased rainfall and storm events, including Cairns, Brisbane and the Gold Coast.

Building code requirements for flooding are generally limited, with most residential buildings not specifically designed to cope with flooding. Flood modelling to determine the likelihood of flooding for a given area is undertaken by estimating flood potential or probable flood flows (hydrologic analysis), and evaluating the flow of water through the specific area (hydraulic analysis) (Amitrano *et al.* 2007).

The accuracy of the topographic data is often the greatest constraint for flood risk modelling. While many factors contribute to flood damage of buildings, knowledge of the depth of flooding is a key data requirement. The velocity and duration of inundation is also required for a more rigorous analysis of flood risk.

Engineers Australia is currently revising the Australian rainfall and runoff guideline for assessment of rainfall, runoff, water resources and flooding to include issues related to climate change (NCCARF 2009). The Australian Bureau of Meteorology in conjunction with CSIRO has embarked on a major program to collect, manage and interpret Australia's water information (BoM 2009c).

Severe storms, including cyclones, can cause damaging storm tides. The resultant storm tide (a combination of storm surge, normal tidal variations and wave setup) can cause severe coastal flooding. This can undermine, erode or destroy structural foundations; material durability can be affected by salt spray; and building contents can be damaged from water, sewage and mud (Amitrano *et al.* 2007).

An Australian Government report assessing the risks of climate change to the coast found that the delivery of essential services such as electricity generation and wastewater management will be increasingly impacted by climate change (DCC 2009a). The report suggests that under a worst case sea level rise scenario of 1.1 metres, between 157 000 and 247 600 existing residential buildings are at risk of inundation, with a replacement cost of approximately $63 billion (DCC 2009a). Figure 23 shows the distribution of these properties in Australia and indicates that Queensland has the second-highest susceptibility to inundation from sea level rise.

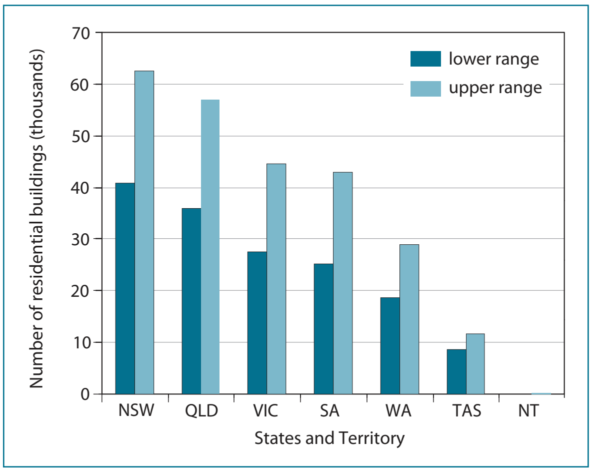


Figure 23: Estimated numbers of residential buildings at risk from sea level rise of 1.1 metre by 2100 (Source: DCC 2009a)

Wang *et al.* (2010) assessed the effects to infrastructure in south-east Queensland of a 1-in-100-year inundation event under different adaptation scenarios in 2030 and 2070. The study found that although about 227 000 people are at risk, this could increase with rising sea levels to 245 100 by 2030 and 273 000 by 2070. This is based on current population alone and does not consider the potential increase in population in south-east Queensland from the current 2.69 million to a projected 4.4 million by 2030.

Options for better building performance with respect to flooding include:

- more sophisticated rainwater collection and re-use technology
- water-resistant building materials
- roofing materials and design to cope with increased drainage loads, including drainage systems, gutters and downpipes
- better land-use management and site analysis
- better foundation design to cope with subsidence, cracking and heave.

Better planning and development guidance is most important if Queensland is to build resilience against coastal flooding. The *Draft Queensland Coastal Plan* requires that redevelopment in built-up urban areas and in high hazard and medium hazard zones consider the inundation impacts associated with a one-in-100-year defined storm-tide event with a sea level rise of 0.8 metres above 1990 levels by 2100. High hazard areas are those subject to inundation levels greater than one metre, while medium hazard areas are subject to inundation levels less than one metre. New permanent structures will be required to mitigate hazard impacts for example, by ensuring that habitable rooms remain above the anticipated storm-tide inundation levels (DERM 2009).

Adaptation

Buildings and other infrastructure can have a life expectancy of 30–200 years; therefore planning and construction decisions made now can have long-term consequences (Hallegatte 2009). Adaptation to climate change through the planning process and building standards is therefore crucial to ensure that these effects are managed.

The Queensland Government requires all state government investment in buildings and infrastructure to conduct a climate change impact assessment to identify the impacts on the project and mitigation and adaptation actions to be taken (OCC 2009).

A number of common approaches lead to good adaptation. Avoiding and reducing future risk is the most cost-effective adaptation response in most cases (DCC 2009a). Upgrading of building and engineering codes and standards for building, plumbing and construction could ensure that future buildings and infrastructure are adapted to climate change impacts.

Land-use plans and development codes need to identify where climate change risks can be accommodated, where protection is required, how planned retreat could be undertaken and the costs and benefits of early or delayed action.

In addition, many opportunities exist for new technologies and construction techniques to assist buildings to cope with inland or coastal flooding. Most of these relate either to keeping water out or the capture and use of the water.

Improving planning and building regulations is likely to considerably reduce the future costs of managing climate change impacts. CSIRO has developed a preliminary estimate of the costs and benefits of the uptake of strengthened planning and building regulation on inundation of residential buildings for a 1-in-100-year storm surge event in south-east Queensland (DCC 2009a). Table 3 shows the expected number of people and buildings impacted by climate change in 2030 under varying adaptation options and the cost of those options in today's dollars (DCC 2009a).

Adaptation Option	People affected 2030	Buildings affected 2030	Total costs 2030
Business as usual (same planning and building regulation as today)	616 000	124 800	$4 billion
Planning regulations tightened to allow no further risky development, building stock under same regulation	378 000	83 200	$2.6 billion
In addition to planning regulation tightened as above, retrofit/reclaim to maintain existing level of risk	270 000	47 900	$1.5 billion

Table 3: Estimated costs and benefits of residential adaptation in south-east Queensland for 2030 (Source: DCC 2009a).

Accurate modelling of storm tides and other sources of flooding will lead to a better understanding of the impacts of sea level rise, storm surge and coastal erosion along Queensland's coastline.

The Queensland Government is investing $8 million to develop a digital elevation model that will allow more accurate modelling and subsequent planning decisions. Improved planning taking into account regional variations (e.g. risk-based vulnerability zoning such as coastal zone and hazard mapping) and restrictions on development will also help increase resilience to the impacts of climate change.

Water supplies

On average, 40 per cent of Australia's total stream discharge or approximately 160 million megalitres (ML) per year occurs in Queensland (DEEDI 2009). About 94 per cent of the water in Queensland's river systems drains to the coast, with only six per cent draining inland (Cox 2008).

Inland regional communities obtain more water from groundwater and/or overland flow storages than coastal areas. Thirty-six per cent of all water used in Queensland, about 1.4 million megalitres per year, comes from underground water, principally the Great Artesian Basin and associated sub-artesian water. This is significantly higher than the national average of approximately 20 per cent and it is thought that underground water is being extracted faster than it is being replenished in some systems (Cox 2008; DEEDI 2009).

Queensland relies heavily on surface water storages with almost 200 major reservoirs providing approximately 64 per cent of the state's total water supply (Cox 2008).

Annual water usage in Queensland varies from 4–5 million megalitres, with agriculture accounting for approximately 70 per cent (DEEDI 2009). The amount of irrigation water used by Australia's 40 000 irrigating agricultural businesses increased 3 per cent to 6501 gigalitres in 2008–09. Queensland continued to be the largest irrigating state, using 2058 gigalitres of water for irrigation, an increase of 12 per cent from 2008–09 (ABS 2010).

In 2007–08 the south-east Queensland residential and business sectors together used 80 per cent of available water supplies. Of this 80 per cent, households used 71 per cent and businesses used 29 per cent (QWC 2009).

The Millennium Drought (2001–08) was the worst drought in the history of south-east Queensland. In 2008, the combined levels of south-east Queensland's major dams (Wivenhoe, North Pine and Somerset) fell to 16.7 per cent (QWC 2009). Although dam levels have since risen substantially and south-east Queensland is no longer officially in drought, securing water supplies is still a concern given Queensland's highly variable rainfall.

Key messages

Water security is a key factor in the development of Queensland communities and industries. Climate change is projected to have impact on rainfall, evaporation and runoff and hence on the amount of water that is available for use as well as the frequency and intensity of rainfall events. In particular:

- the amount of rainfall will change depending on the region of Queensland
- Queensland is more likely to experience reduced rainfall across most regions
- the number of severe tropical cyclones is projected to increase
- projected increases in temperature and evaporation and reduction in rainfall are expected to significantly impact water availability and security
- groundwater is being extracted faster than it can be recharged in some important systems
- higher temperatures, increased evaporation and lower rainfall associated with climate change are expected to adversely affect water runoff
- 75 per cent of Queensland's rain falls in the less populous north of the state
- demand for water is increasing and long-term average inflows into rivers and dams as well as end-of-system flows are expected to decrease
- without additional supplies, the gap between supply and demand of water in south-east Queensland would be between 97 000 and 308 000 megalitres per year by 2056, depending on population growth, water savings achieved and the impacts of climate change.

Policy makers and planners must therefore take into account these changing rainfall regimes and diversify water supply mechanisms to optimise the capture and use of rainfall.

The Queensland Government is focusing on developing regional water supply strategies as a means of managing water supply changes expected as a result of climate change impacts.

These strategies provide information and guidance for the management of water supply issues to meet predicted changes and meet urban, industrial, agricultural and environmental water demands.

Climate risks

Climate change has emerged as an important issue in water resource management. Rainfall in Queensland is seasonal, falling mostly during summer, with 75 per cent of all Queensland rain falling in the less developed and sparsely populated northern catchments that drain into the Gulf of Carpentaria and the Coral Sea (Cox 2008).

Projected increases in temperature and evaporation, reductions in rainfall and a higher variability in weather conditions and extreme events are expected to significantly impact water availability and security.

Challenges for managing water resources in Queensland are compounded by the fact that Queensland's rivers are characterised by alternating severe droughts and major floods and that Australian stream flow is more variable than anywhere else in the world (CSIRO 2007).

Climate change impacts

The impacts associated with climate change are also related to changes in climate variability. Although Queensland's landscape has adapted to a variable climate, changes in both the magnitude and frequency of rainfall may have unknown impacts on the water cycle. Seasonal shifts in rainfall, temperature changes and evaporation can affect agricultural and residential water demand and put pressure on major industrial water users such as power stations. In addition, coastal communities may be faced with saline intrusion or sea level rise, which will put additional pressure on water infrastructure and supply.

Rainfall, temperature and evaporation

Future climate trends in Queensland include changes to the frequency and magnitude of rainfall and increases in minimum and maximum temperatures leading to increased evaporation. Coastal zones are particularly at risk due to increasing population placing pressure on water supplies.

While mean temperature is projected to increase across Queensland regions by 1.7–2.4 °C by 2050 under the high emissions scenario, there is greater uncertainty regarding rainfall projections. By 2050, the increase in annual average evaporation (defined as potential evapo-transpiration) is projected to be 5–7 per cent for the high emissions scenario across Queensland regions (Table 1).

Factors are applied to values of evaporation to estimate potential evaporation over various surfaces; for example rivers, dams and crops. An Urban Water Security Research Alliance study (UWSRA 2009) estimated that the loss of water through natural evaporation from dams, rivers and other water storages in south-east Queensland could be 300 000 megalitres per year, while losses through degraded or damaged infrastructure could be as high as 40 000 megalitres per year.

Runoff

Runoff is the amount of rainfall that is not evaporated, stored as soil moisture or filtered down to groundwater and which therefore runs into streams and rivers and other surface water storages.

While runoff generally tracks rainfall, increases and decreases in precipitation do not necessarily lead to equal increases and decreases in runoff. Droughts cause soil moisture reductions that can reduce expected runoff until soil moisture is replenished. Conversely, water-saturated soils can generate floods with only moderate additional rain (Karl *et al.* 2009).

Higher temperatures, increased evaporation and lower rainfall associated with climate change are expected to adversely affect water runoff. Rural landscapes may need 50–100 millimetres of rain before runoff can occur and they usually produce runoff only a few times each year (DNRW 2008a). Estimating short- and long-term future runoff patterns is important for managing potential climate change impacts on water supply sources.

Rainfall–runoff modelling that includes climate change projections from global climate models (GCMs) is progressively being done for all major catchments in Queensland as part of the Regional Water Supply Strategies' development and implementation. Results indicate that future runoff is more likely to decrease than increase in most catchments (Preston & Jones 2006).

Groundwater

Groundwater accounts for over 30 per cent of Australia's total water consumption (NWC 2009a). Groundwater is the water that has seeped from the surface into porous sands, silts and fractured rocks, to be stored in underground aquifers.

Surface water in many rivers, dams, lakes and wetlands is connected to aquifers. Groundwater is a finite resource and is only replenished when surface water seeps into and recharges aquifers. Changes in rainfall may have positive or negative impacts on the recharge of groundwater.

Queensland has extensive underground water resources. The Great Artesian Basin is the largest known artesian basin in the world, underlying 20 per cent of continental Australia, including most of Queensland (Cox 2008).

Groundwater in the south-east Queensland region is considered to be almost fully utilised (QWC 2008). Historically south-east Queensland has relied on rainfall over dam catchments and the recharging of groundwater aquifers to meet urban and rural water needs. A key challenge facing south-east Queensland includes planning for the impact of climate variability and climate change on the region's surface and groundwater supplies.

How climate change will affect groundwater is not well known. Increased water demands of regional communities already reliant on groundwater may further stress this resource, which can often be drawn down faster than it can be recharged (IPCC 2007c).

Reduced precipitation or increased evaporation and runoff would reduce the amount of water available for recharge. Changes in vegetation and soils that occur due to temperature changes, fire or pest outbreaks are also likely to affect recharge by altering evaporation and infiltration rates (Bates *et al*. 2008).

Groundwater has become a national research priority. An $82 million National Groundwater Action Plan is investing in projects to improve our knowledge and understanding of groundwater (NWC 2009b). The National Water Commission is also assisting the states and territories to improve knowledge of the expected effects of climate change on these resources.

Climate change impacts on regional water flow systems

Climate change will impact on the quantity, distribution and flow of water in Queensland's regions through changes to rainfall frequency and intensity, and through higher temperatures leading to increased evaporation. Potential impacts of climate change on system flows for a number of Queensland regions are discussed below.

South-east Queensland

By 2050 under a high emissions scenario annual rainfall in south-east Queensland is projected to decrease by five per cent (about 55 millimetres) combined with a six per cent (about 90 millimetres) increase in potential evaporation (Table 1).

The Urban Water Security Research Alliance is conducting a climate and water project which aims to increase the accuracy of climate modelling and provide the best projections on south-east Queensland rainfall and inflow to storage reservoirs.

The Burdekin catchment

In the 129 500 km^2 Burdekin River catchment, the channel floodplain configuration combines with rapid runoff to create very fast flood-wave speeds (Alexander *et al*. 1999). Current climate change predictions indicate that the region is increasingly likely to be subject to more extreme flooding due to more severe cyclones, higher summer rainfall intensity and increased flooding of low-lying coastal areas by rising sea levels (DIP 2008; OCC 2009).

Central Queensland and the Fitzroy catchment

Current average annual rainfall varies from 500 to 1700 millimetres and evaporation averages 2000 millimetres. The stream flow is highly variable with an average annual discharge from the Fitzroy catchment of around 5 million megalitres. The minimum recorded discharge was 96 000 megalitres in 1969. Over the period 2000–2005, the annual discharge ranged from 581 000 to 2 450 000 megalitres (DNRW 2008b).

It is likely that changes to rainfall, temperature and evaporation in the region will translate into reductions to inflows and water storage in coming decades.

Wide Bay–Burnett

Higher temperatures, lower rainfall and increased evaporation are expected under a changing climate. By 2050 the region can expect decreases in supply from existing storages and decreased end-of-system flows. In the same time period, an increase in urban and rural water demand is expected, largely due to a growing population (OESR 2010).

Cape York Peninsula and the Gulf

Strongly seasonal rainfall in north Queensland causes extremely variable water discharge. Tropical cyclones commonly produce high-magnitude, short-duration floods resulting in increased runoff. Possible increases in rainfall in the Gulf and Cape York catchments may contribute to stronger recharge of the Great Artesian Basin.

Condamine–Balonne

The Condamine–Balonne region of the Murray–Darling Basin (MDB) represents 12.8 per cent of the total area of the MDB (CSIRO 2008). Increasing temperatures and evaporation and more prolonged drought, combined with periodic extreme flow events, are projected to be the main climate change impacts (OCC 2009).

Rainfall–runoff modelling with climate change projections from global climate models indicate that future runoff in the region is more likely to decrease than increase, with a nine per cent reduction by 2030. The extreme estimates (which come from a high global warming scenario) range from a 20 per cent reduction to a 26 per cent increase in average annual runoff (CSIRO 2008).

Adaptation

It is estimated that in 2056, without additional supplies, the gap between supply and demand of water in south-east Queensland would be between 97 000 and 308 000 megalitres per year, depending on population growth and water savings achieved and the impacts of climate change (QWC 2008). The $9 billion South East Queensland Water Grid, has been designed to optimise water storage and supply infrastructure to maintain water supplies for an increasing population. It includes dams, recycled water and desalination water facilities.

Filling the supply gap is an important challenge that the Queensland Government is addressing through regional water supply strategies (RWSS). Under the RWSS, the available water supplies and projected demands are examined to determine the water balance for any given strategy area. Water resource plans and resource operations plans provide a structure for the allocation of water, while also maintaining environmental flows.

Better management of artesian bores and dams through leakage reduction and implementing best-practice systems will help reduce water loss. The development of new technologies and farm management techniques is an important challenge for the rural sector.

Terrestrial biodiversity

Australia supports such a rich diversity of life that it has been named one of 17 'mega-diverse' countries—a group of countries that are home to more than 70 per cent of the Earth's species (Steffen *et al*. 2009).

Queensland also has a wide range of unique and diverse terrestrial ecosystems, from the well-known Wet Tropics and Fraser Island World Heritage rainforests, to the desert floodplains of the Channel Country.

Queensland is Australia's most naturally diverse state. Around 1350 ecosystems support 70 per cent of Australia's mammals, 80 per cent of its native birds and more than 50 per cent of its native reptiles, frogs and plant species. Queensland's plants are unique, with 45 per cent of all plant species found nowhere else on earth (EPA 2008).

Despite the intrinsic and environmental value of this diversity of animals and plants, the world is currently losing species at the rate of about one per day and more mammals are threatened with extinction in Australia than anywhere else in the world. Of Queensland's diverse ecosystems, some 222 are currently listed as endangered and 561 as vulnerable (DERM 2010).

Key messages

Significant and adverse effects on terrestrial ecosystems are projected if global mean surface temperatures rise more than 2 °C above pre-industrial levels including:

- declining native biodiversity
- increase in weeds and pests
- loss of high-altitude species due to lack of suitable habitat
- potential loss of half the existing high-altitude Wet Tropics rainforest from a 1 °C increase in temperature
- landscape-level tree mortality due to climate-induced water stress contributing to greenhouse gas emissions and reducing carbon sequestration
- reduced extent and diversity of ecosystems having potentially adverse impacts on tourism income and regional economies
- loss of the benefits of ecosystem services which contribute directly and indirectly to Queensland's economy and lifestyles.

The consequences of a business-as-usual scenario for Australia's biodiversity are severe. Without rapid and effective mitigation of climate change, there is a high risk of an accelerating wave of extinctions throughout the 21st century and beyond (Steffen *et al*. 2009).

Climate risks

The Millennium Ecosystem Assessment (MEA 2005), a four-year study involving more than 1300 scientists worldwide, found that by the end of this century climate change and its impacts may be the dominant direct drivers of biodiversity loss and changes in ecosystem services globally.

The study found that earlier predictions of climate change impacts are too conservative and that future climate conditions can be expected to be hotter and drier than predicted. Also sea levels may rise faster than projected. This suggests that impacts on ecosystems, supporting biodiversity, ecosystem services and dependent human systems, could be even more severe than first predicted.

Figure 24 shows that the current trends of several non-climate factors on terrestrial ecosystems are now being exacerbated by the increasing impact of climate change on ecosystem and species loss.

We benefit from a multitude of resources and processes that are supplied by natural ecosystems and collectively these benefits are known as ecosystem services. The MEA (2005) identified four broad categories of services:

- provisioning—the production of food and water
- regulating—the control of climate and disease
- supporting—nutrient cycles and crop pollination
- cultural—spiritual and recreational benefits.

MEA (2005) found that the degradation of ecosystem services could increase during the first half of this century as climate change impacts intensify. There may be a significant and harmful impact on ecosystem services worldwide if global mean surface temperature increases more than 2 °C above pre-industrial levels.

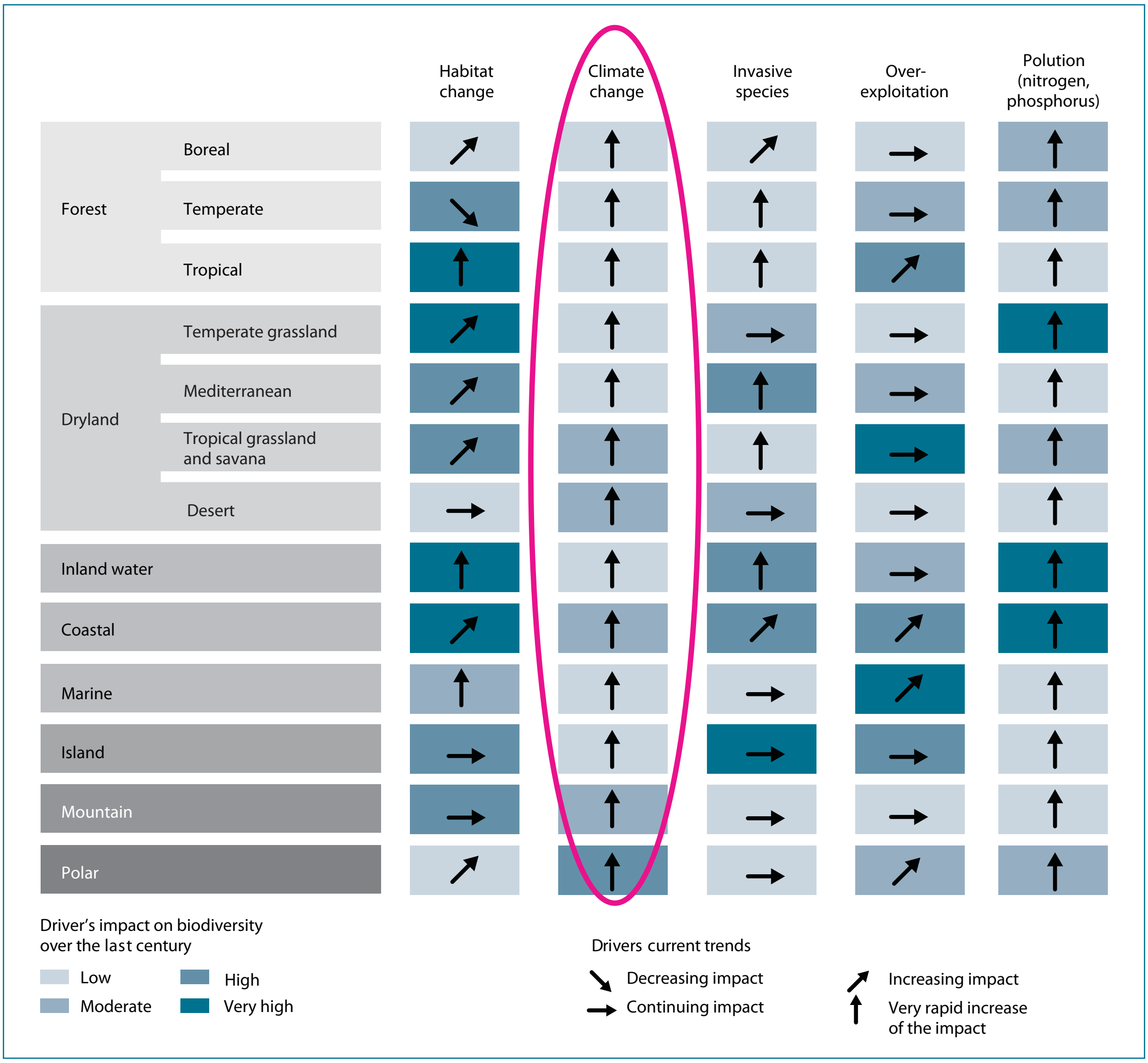


Figure 24: Impact of climate change on biodiversity (Source: MEA 2005 updated; Richardson *et al*. 2009)

Changes in temperature, precipitation patterns and levels of atmospheric carbon dioxide all impact on biodiversity. In biological terms, the contemporary rate of climate change is unprecedented since the last mass species extinction event that took place 60 million years ago (Steffen *et al.* 2009).

Many of Queensland's ecosystems and native wildlife are also threatened by a range of non-climate factors. Clearing for agriculture and urban development, construction of water supply infrastructure, poor land management and invasive species all contribute to ecosystem degradation (EPA 2008).

Managing these non-climate threats is critical to building the resilience of ecosystems to withstand future climate change impacts. Climate change is likely to exacerbate these existing stressors through declining water availability, changed fire regimes and more frequent heatwaves and extreme heat events.

The *Australia's biodiversity and climate change* report (Steffen *et al.* 2009) identifies the key climate change impacts as:

- increases in temperature
- sea level rise
- altered rainfall and runoff patterns
- changed frequency of weather events.

Secondary impacts associated with these key impacts include:

- changes in species distribution
- changes in ecosystem and community composition
- changes in the ranges of invasive species
- a reduced capacity to recover from fires
- a reduced capacity to recover from other extreme events.

The currently high rates of species extinction are also likely to increase as the global average temperature rises by just 1.0 or 1.5 °C above pre-industrial levels, and are likely to accelerate sharply as temperature rises beyond 2 °C (Steffen *et al.* 2009).

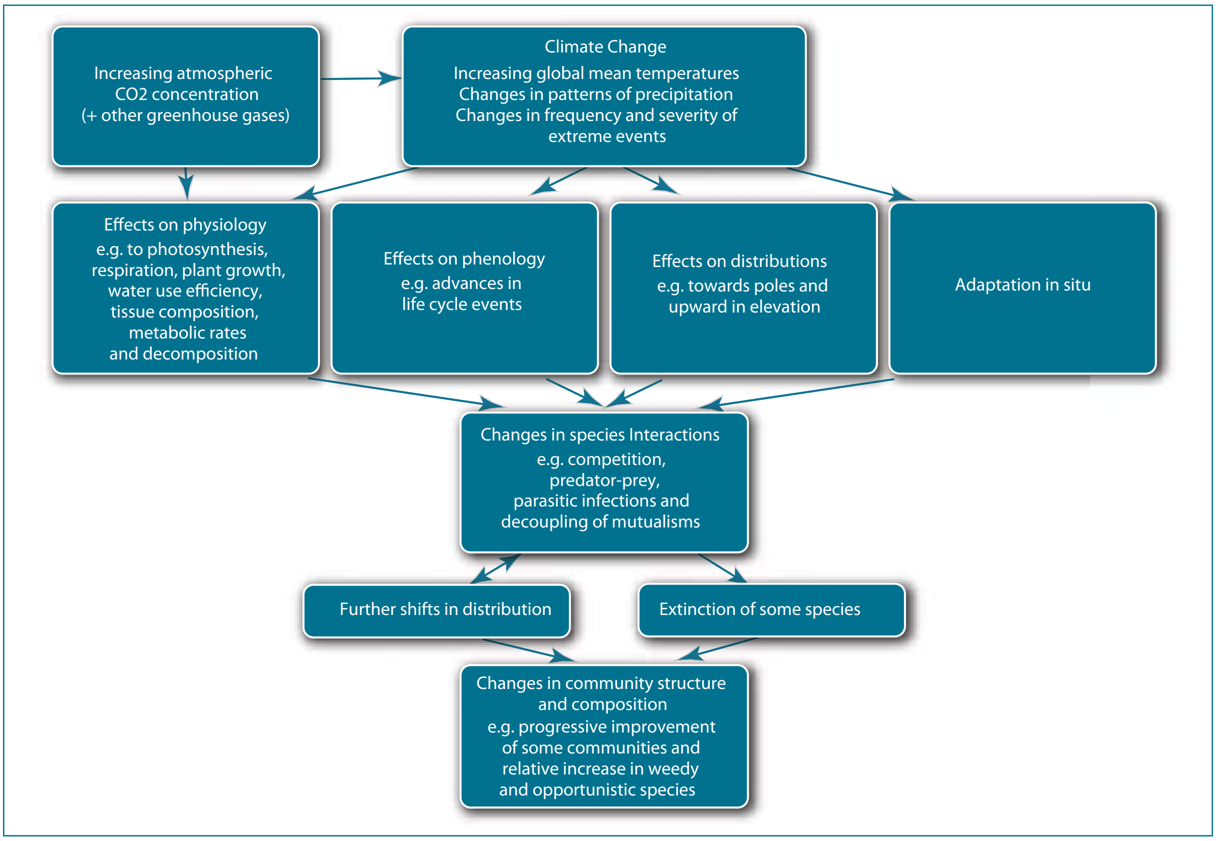


Figure 25: Impacts and pathways of changes due to climate change (Source: Hughes 2000)

Thomas *et al*. (2004) found that for a mid-range climate change scenario, 15–37 per cent of known plant and animal species become 'committed to extinction' by 2050.

The unique responses of different species to climate change mean that many ecosystems and communities might change in ways that we currently cannot predict.

Climate change is expected to cause local extinctions in some areas and the establishment of new species from other areas thereby changing community composition and species distribution. Figure 25 shows the process of climate change impacts on biodiversity.

For the majority of biological systems, climate change may affect:

- individual organisms (physiology)
- timing of life cycles (phenology)
- population processes (birth and death rates)
- shifts and changes in distribution (dispersal and shifts in geographic range)
- potential for adaptation (rapid evolutionary change).

These effects on individual organisms and populations cascade into changes in interactions among species due to the interconnection of ecosystems, especially rainforest ecosystems. Changes in interactions further heighten extinction rates and shifts in geographic range, reducing biodiversity and favouring pest species at the expense of native species.

Many plant and animal species depend on the wide dispersal of individuals for both demographic processes and interchange of genes to avoid inbreeding effects.

Over large areas and long periods, many species have already responded to climate change by moving their geographic range. However, some species now lack a suitable habitat into which to move, have limited or impeded mobility or do not possess the necessary genetic diversity to adapt. The geographic ranges for these species are expected to contract, increasing the risk of extinction.

High-altitude ecosystems

Queensland's high-altitude species are especially vulnerable to climate change. These species are already at their range limits and lack any suitable, higher-altitude habitat. The potential for their extinction is therefore high, even under moderate levels of warming.

Wet Tropics rainforest

The Wet Tropics rainforests and vertebrates of northern Queensland are also likely to face high levels of extinction.

Montane rainforest's endemic vertebrates are projected to decrease by 50 per cent with only a 1 °C rise in average temperatures (Williams & Hilbert 2006). These animal species are found only in the high-altitude rainforests of the Queensland Wet Tropics.

An Australian Centre for Biodiversity study (2008) found that an average temperature rise of 2 °C would eventually force all endemic Australian tropical rainforest vertebrates to extinction.

An assessment by Meynecke (2004) of the potential changes in the distribution of 12 endemic Wet Tropics rainforest vertebrates in response to global warming suggested that even species with currently wide climatic ranges may become vulnerable.

Figure 26 shows the distribution of habitat in the Wet Tropics with mean annual temperature less than 22 °C, which is approximately the upper temperature limit for many Wet Tropics leaf-eating species. A 2 °C rise would reduce the range of this Wet Tropics habitat to small areas of Mt Windsor, Mt Lewis, Mt Bartle Frere and the Atherton Tablelands (Figure 26).

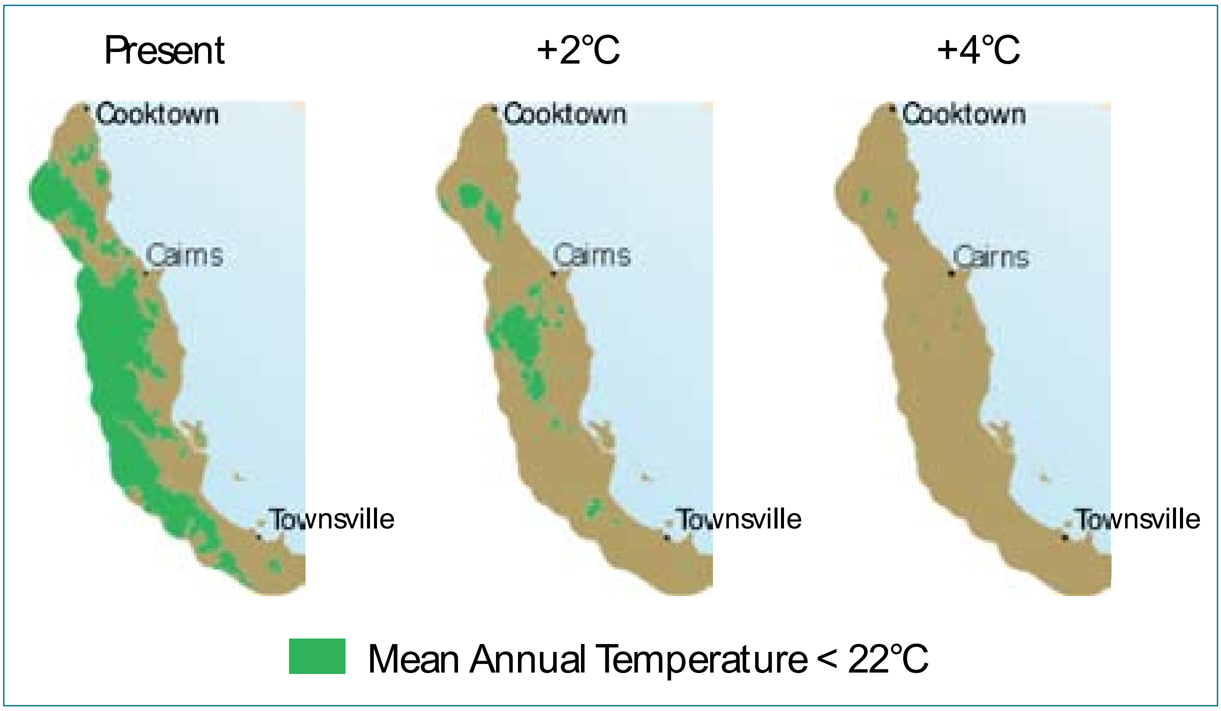


Figure 26: Projected changes to Wet Tropics habitat with increased warming (Source: VanDerWal & Williams 2010)

It has been estimated that by 2050 large areas of the Wet Tropics rainforest habitat could be lost (Garnaut 2008; IPCC 2007b). Hilbert *et al.* (2001) estimated that a 1 °C rise in temperature could result in a 50 per cent decrease in the area of the cool–wet rainforest environment occurring at the highest elevations. As well as loss of biodiversity, reductions in rainforest area also have implications for the tourism industry and for regional economic development.

Tropical savannas, grasslands and dry eucalypt forests

These ecosystems are home to a wide diversity of wildlife in Queensland. They also contain a great deal of Australia's stored terrestrial carbon and are some of our most fire-prone ecosystems.

Fires in these ecosystems contribute significantly to Australia's greenhouse gas emissions and strongly influence the rate of carbon sequestration. Appropriate restoration of these lands to support carbon sequestration may help protect biodiversity and build ecosystem resilience.

Climate-induced water stress over extended periods can force plants to shut down photosynthesis to conserve water, triggering landscape-level tree death (Allen & Breshears 2007). Even larger-scale events can occur when combined with other stressors such as insect outbreaks (Kurz *et al.* 2008). Beckage *et al.* (2008) found that these changes are expected to be most rapid and prominent at the boundaries of ecosystem types.

Adaptation

Australia's Biodiversity and Climate Change (Steffen *et al.* 2009) suggests the following potential adaptation mechanisms to maintain biodiversity:

- reducing existing threats to species
- including information on climate change in biodiversity management tools
- maintaining well-functioning ecosystems
- improving management of areas of high conservation value
- building appropriate types of landscape connectivity to give space for nature to self adapt
- eco-engineering to allow ecological systems to self organise for anticipated climatic conditions
- preservation of genetic stocks, for example in zoos and seed banks
- increased monitoring and research into the impacts of climate change and adaptation options for threatened species and ecosystems.

The Queensland Government has recognised the value of maintaining and enhancing biodiversity. *ClimateQ* includes an initiative to create biodiversity corridors that link parcels of remnant habitat across the landscape, increasing the capacity of species to adapt to climate change impacts.

Several potential corridor projects have already been identified in Queensland, such as the Great Eastern Ranges Corridor project. It aims to link and protect ecosystems along the Great Dividing Range from the Victorian Highlands to the Atherton Tableland in Queensland, and the Coastal Ranges and Great Artesian Basin corridors.

Steffen *et al.* (2009) proposed the following integrated actions to provide effective policy and management responses to the threat of biodiversity from climate change:

- reform management of biodiversity—adapt the way we manage biodiversity to meet existing and new threats and develop new approaches to enhance the resilience of our ecosystems
- strengthen the national commitment to conserve Australia's biodiversity—develop a new national vision for Australia's biodiversity
- invest in our life-support system—create public and private investment in this capital
- build innovative and flexible governance systems—build agile and innovative structures and approaches
- meet the mitigation challenge—establish strong emissions mitigation actions.

Marine biodiversity

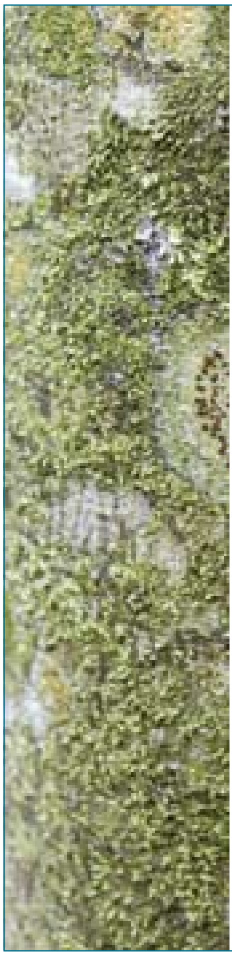
Queensland's mainland coastline encompasses a variety of habitat types including beaches, dunes, rocky reefs, mangroves, seagrass, sand flats and islands. These coastal habitats support a wide range of organisms and are important for tourism, fisheries (i.e. commercial, recreational and Indigenous), aquaculture and maintaining high ecological diversity. Substantial sections of the coastline are also heavily urbanised and industrialised, although large sections in the north and far north remain free from dense development.

Two key marine parks in Queensland are the Great Barrier Reef Marine Park and Moreton Bay Marine Park.

The Great Barrier Reef (GBR) extends for over 2100 kilometres along the Queensland coastline, with an area of 348 000 km^2.

The GBR comprises more than 2900 coral reefs and a diverse range of marine life. It includes about 1500 species of fish, 350 species of hard coral, more than 4000 species of mollusc, 500 species of algae, 24 species of seabird, more than 30 species of whale and dolphin, the dugong and six of the world's seven species of marine turtle (GBRMPA 2009a).

Moreton Bay in south-east Queensland is one of the largest estuarine bays in Australia, covering 3400 km^2 between Caloundra and the Gold Coast. Now a marine park, it contains a wide variety of habitats including coral reefs, sandy beaches, mangroves, rocky shores, mudflats, sandbanks and seagrass beds. It is home to more than 1000 species of fish, six of the world's seven marine turtle species, and threatened species including dugong and grey nurse sharks. Migratory whales and birds add to the bay's biodiversity.



Key messages

The impacts of climate change on marine ecosystems and biodiversity are expected to be considerable, affecting organisms at all life stages as well as their habitat. In particular:

- sea level rise will adversely impact on the nesting grounds of turtles and seabirds, reducing the available breeding habitat of many species
- continued ocean acidification will negatively affect calcification and early development in many important reef species, such as corals and crustose coralline algae (reef cementers)
- the expected increase in the strength of the East Australian Current will influence larval dispersal patterns and durations, and nutrient supply, and may extend the southward distribution of tropical species
- changes in breeding cycles and productivity of fisheries could lead to a range of positive and negative impacts on commercial, recreational and Indigenous fisheries
- an increase in average sea-surface temperature of 2 °C is predicted to lead to annual bleaching of up to 97 per cent of the Great Barrier Reef and associated large-scale mortality, shifts in species' distribution and abundance, changes in the timing and success of reproductive events, and changes to food availability, resulting in serious changes to many marine ecosystems. All these will in turn have a negative impact on tourism and the regional economy.

Some species may be able to adapt better than others but more research is required to model and predict the impacts of climate change and to understand species interactions.

Climate risks

The GBR is vitally important for Australia's tourism and fisheries industries. In 2009, the GBR's contribution to the economy was estimated to be $6 billion. As a World Heritage Area, it attracts two million tourists each year (Access Economics 2008).

The GBR also acts as a natural barrier protecting coastal communities, which has an additional economic value in terms of avoided loss of productive land and infrastructure. While it is difficult to put a value on this coastal protection function, Oxford Economics (2009) estimated that the cost of constructing and maintaining coastal defences equivalent to the length of the GBR could be at least $10 billion in present value terms.

Key environmental variables that affect marine ecosystems include water temperature, circulation patterns, water chemistry (e.g. pH, salinity, nutrient supply), sea level, tropical cyclones and sources of climatic anomalies such as ENSO events (Munday *et al*. 2009). All of these variables are likely to be affected by climate change, potentially resulting in changes to:

- the distribution of organisms—due to shifts in species' ranges or changes in larval dispersal and habitat availability
- phenology—shifts in the timing of reproduction (spawning and nesting) and migrations
- population biology—due to changes in survival rates or physiological effects on biological processes such as metabolism, growth and reproductive output
- breeding cycles and productivity of fisheries—leading to a range of positive and negative impacts on commercial, recreational and Indigenous fisheries
- community structure and species interactions—due to uneven sensitivities of species to climate change impacts, which may result in changes to species interactions and community dynamics.

A recent Great Barrier Reef Marine Park Authority (GBRMPA) report (GBRMPA 2009b) identified climate change as the greatest threat facing the GBR, with almost all species and habitats affected. Figure 27 shows that when CO_2 levels are above 450 ppm corals, seabirds and reef habitats are severely affected. Changes in sea temperature, pH and sea level are indicative only and provide the range of likely values.

Temperature

Increased sea water temperatures are likely to have a dramatic impact on marine ecosystems because temperature influences many biological processes including growth, metabolism, development and calcification (shell and skeleton formation). As well, many marine species can only tolerate a limited temperature range. Species may have some capacity to acclimatise to increased sea water temperatures or shift their range southwards. However, a southwards shift can only occur if a species has a means of getting there (through larval dispersal or mobile adults), if there is suitable habitat available and if they can compete with residents. Species that cannot move or acclimatise will decline in abundance.

As most corals live close to the upper limit of their temperature tolerance, prolonged high temperatures (1–2 °C above the average summer maximum temperature) can cause corals to bleach. If temperatures return to their previous level quickly, corals can recover but may still experience lower rates of growth and reproduction Fabricius *et al*. (2007).

Climate-related warming of sea-surface temperatures (SST) is projected to increase the frequency and severity of coral bleaching episodes, reducing the time available for recovery between episodes and resulting in higher rates of coral death. Annual SST on the GBR could rise by 1–3 °C from the present average temperature by 2100 (GBRMPA 2009b). An average SST increase of 2 °C is predicted to lead to annual bleaching of up to 97 per cent of reefs and coral death on a large scale (GBRMPA 2009a). Reefs that experience large-scale coral mortality from bleaching are at risk of being overgrown by fast-growing algae, making coral recovery difficult. Algal growth increases with nutrient runoff and predicted increases in rainfall intensity and subsequent increases in runoff could further compound the problems faced by inshore reefs (Fabricius *et al*. 2007).

Recent research found that high nutrient levels (particularly dissolved inorganic nitrogen) in the sea water surrounding reefs can potentially lower the temperature threshold at which corals bleach by 1.0–1.5 °C and by as much as 2.0–2.5 °C in the most nutrient-enriched locations (Wooldridge & Done 2009). Management strategies that reduce nutrient levels in terrestrial runoff could help to maximize the coral's resistance to heat stress and subsequent bleaching.

In the event of a total and permanent bleaching of the GBR, Oxford Economics (2009) estimated that there would be a 50 per cent reduction in reef visitors and a total monetary cost (in present value terms) to tourism and fishing (in present value terms) of about $37.7 billion, with an estimated cost of $16.3 billion to the Cairns area alone.

Impacts on coral populations will have extensive implications for thousands of other species (including fish, invertebrates and reptiles that use corals for food and/or shelter) and for biodiversity in general.

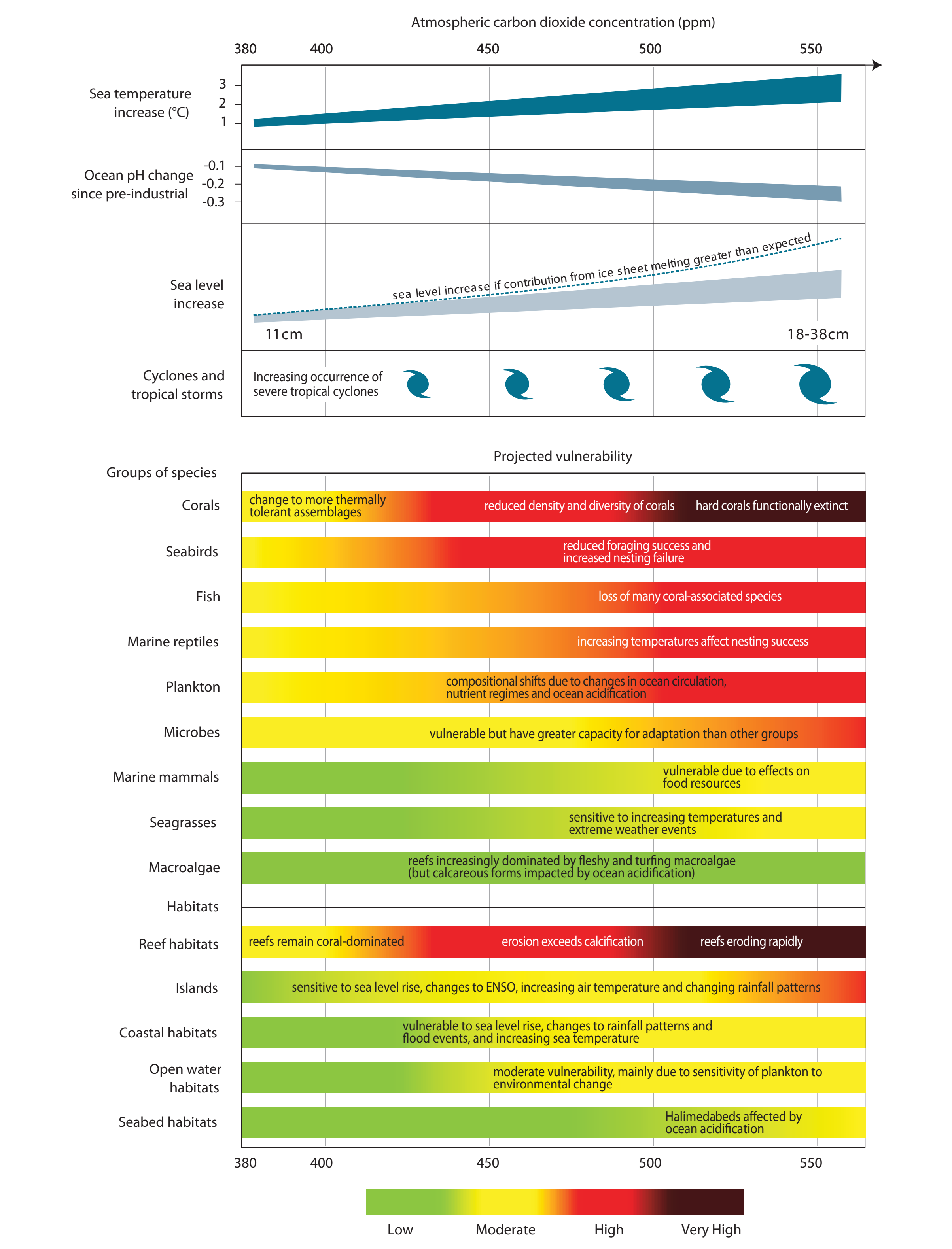


Figure 27: Projected vulnerabilities of GBR ecosystem components across a range of atmospheric CO_2 concentrations (Source: GBRMPA 2009b)

Elevated temperatures also have significant impacts on the breeding success of seabirds and turtles (GBRMPA 2009b). Seabirds have suffered complete nesting failures in very hot years due to the parents' inability to find sufficient fish to feed their chicks. Turtle gender is dependent on the temperature experienced by the eggs, with higher temperatures increasing the proportion of females.

Sea level rise

Low-lying islands such as Heron Island and Lady Musgrave Island are important nesting sites for seabirds and turtles. A sea level rise of only 0.38 metres will flood important turtle nesting beaches (GBRMPA 2009a). Saltwater intrusion into freshwater wetlands on the Queensland coast could reduce breeding habitat for many bird species. Coastal erosion is likely to be exacerbated by increased sea level combined with larger storm-tide events.

An additional sea level rise of up to 0.05 metres by 2070 is projected for the east coast of Australia due to the strengthening of the East Australian Current (CSIRO & BoM 2007). Sea level rise influences the inundation and establishment of coastal habitats and ecosystems (Brierley & Kingsford 2009) and could negatively affect intertidal organisms living on rocky shores. Such rocky shore inhabitants are often confined to distinct vertical zones and may simply run out of habitat as sea level rises. Rocky shores are common on Queensland's mainland coastline and islands.

Rainfall and floods

Projections for the far north of Queensland include more intense rainfall events particularly in summer, with possibly fewer but more intense tropical cyclones (OCC 2009).

Increased intensity of rainfall events will increase runoff, with elevated levels of sediments and nutrients reducing water quality and exacerbating other stressors for nearshore reefs and coastal habitats (Fabricius *et al*. 2007).

Cyclones and storm surge

Higher mean sea level combined with more intense weather systems could increase inundation of coastal areas, potentially impacting mangrove nursery areas and damaging aquaculture facilities, coastal developments and tourism infrastructure.

Strong winds, increased wave intensity and storm surge generated during cyclonic conditions can also disrupt bird and turtle nesting and damage corals. This damage reduces invertebrate and fish habitat and results in greater fragmentation of coral reefs and their communities.

Acidification

Ocean acidification is the term given to the ongoing process whereby increasing amounts of atmospheric CO_2 dissolve in sea water, lowering sea water pH (increasing acidity) and decreasing concentrations of carbonate ions. This makes it more difficult for calcifying organisms such as shellfish and corals, to form their shells and skeletons.

Corals may also be weakened and become more susceptible to storm damage if calcification rates are reduced due to ocean acidification (GBRMPA 2009b).

Global surface ocean pH has already decreased by 0.1 units since pre-industrial times and is projected to decrease a further 0.3–0.4 units by 2100 (Caldeira & Wickett 2003). In addition to this, McMullen & Jabbour (2009) found a 25 per cent reduction in the saturation states of calcite and aragonite, the key mineral forms of calcium carbonate used by organisms to form their shells and skeletons.

Under doubled CO_2 conditions, calcification rates of reef-building corals could decline by 9–60 per cent depending on the species (Guinotte & Fabry 2008). Analysis of cores taken from massive (i.e. non-branching) *Porites* coral on the GBR indicated that calcification had declined by

21 per cent over a 16-year period in two regions (Cooper *et al*. 2008), and 328 sites on 69 reefs showed a 14.2 per cent decline in *Porites* calcification since 1990 (De'ath *et al*. 2009).

An experimental study by Anthony *et al*. (2008) indicated that branching corals may be more sensitive to the effects of sea water warming and acidification than massive corals. This difference in species' susceptibility to climate change could change the community structure of future coral reefs, reducing structural complexity and habitat availability for fish and invertebrates.

Also at high risk are crustose coralline algae (CCA), with acidification significantly reduces their survival, growth, productivity and calcification and increasing the bleaching response (Anthony *et al*. 2008; Kuffner *et al*. 2008; Martin & Gattuso 2009). CCA are an important component of coral reef ecosystems, making a significant contribution to reef building and cementation.

Studies by Gazeau *et al*. (2007), Fabry *et al*. (2008), Kurihara *et al*. (2009) and Parker *et al*. (2009) found that ocean acidification impacts a wide range of other calcifying organisms. These include sea urchins and aquaculture species such as oysters, mussels and clams. Laboratory-scale studies have found that early life history stages are often susceptible to acidification, with negative impacts on fertilisation rates, development rates and the formation of larval skeletons in echinoderms and crustaceans (Fabry *et al*. 2008).

Fish may be less impacted by acidification than invertebrates because they are more efficient at regulating chemicals within their bodies to compensate for changes in water composition. However, Munday *et al*. (2009) found that acidification could affect the ability of larvae to locate suitable habitat. Indirect effects are also likely, with potential changes to ocean productivity affecting food supply.

Ocean currents

Climate change could alter the strength and pattern of ocean currents with wide-ranging consequences. The projected continued increase in the strength of the East Australian Current may extend warmer waters further south with possible impacts on marine ecosystems, species distribution and larval dispersal (Steffen *et al*. 2009).

Modelling of the dispersion of passive particles around Lizard Island (14° S) on the northern GBR in response to a two-degree southerly shift in the position of the South Equatorial Current resulted in modelled particles being transported to the north-west, rather than to the south (Munday *et al*. 2009). Such pronounced changes in dispersal patterns could have negative consequences, by moving larvae to unsuitable temperature regimes and habitats.

Ocean upwelling

Climate change could also reduce the intensity and duration of vertical circulation patterns (upwelling) that bring deep, often nutrient-rich, water to the surface. Such changes could result in reduced ocean productivity and biodiversity.

Adaptation

A species can adjust to environmental changes through physiological changes at the cellular level, behavioural changes at the level of individuals (termed acclimatisation) or genetic changes that occur over many generations (adaptation). Adaptation usually occurs over long geologic timeframes and, given the rapid rate of climate change, it is unknown whether organisms will be able to adapt quickly enough to their new environmental conditions.

Most marine larvae disperse away from the reef where they were born and join distant populations.

The best way to build the resilience of marine ecosystems to climate change impacts is by protecting source populations enhancing connectivity (physical connection) between populations and reducing other stressors such as pollution, nutrient runoff and overfishing. This ensures the continued supply of larvae and adults for recolonising populations depleted by storms, bleaching or runoff.

Steps have been taken to reduce non-climate stressors in the marine environment. The *Reef Water Quality Protection Plan* released in 2003 aims to manage diffuse sources of pollution from agricultural land.

To strengthen this protection, in 2009 the Queensland Government introduced regulations to improve land management and restrict the use of chemicals in the reef catchment. The aim was to achieve a 50 per cent reduction in the discharge of dangerous pesticides and fertilisers over four years.

In south-east Queensland a comprehensive ecosystem health monitoring project has been implemented to evaluate water quality condition and trends. This project includes ongoing community education.

Tourism industry leaders and GBRMPA, working together as the Tourism Climate Change Action Group, have developed the *Great Barrier Reef Marine Tourism Climate Change Action Strategy 2009–2012*. The strategy is intended to guide action to be taken by industry to improve reef health and the viability of the marine tourism industry.

A major challenge for scientists and policy makers is identifying thresholds at which major ecosystem changes might occur. It is predicted that ecological responses of ecosystems to climate change are likely to occur in a series of abrupt steps separated by intervals of relatively minor change (GBRMPA 2009b). More ecosystem-based research and management approaches, combined with adaptive management strategies, will help to identify and manage ecological thresholds.

Key research to fully understand the impacts of climate change on marine ecosystems and determine appropriate management strategies should address:

- how climate change will alter ocean currents and circulation patterns, habitat availability, and the physiology and development of larvae and reproductive adults. This research will inform management strategies to enhance population connectivity
- the implications of ocean acidification through long-term measurements of ocean chemistry and studies on a wider range of species, using experimental conditions that more adequately mimic the natural environment
- species' tolerances to projected climate change and their capacity for acclimatisation or genetic adaptation
- the identification of thresholds at which major ecosystem changes might occur. This will be addressed through both experimental studies and community dynamics modelling for each ecosystem type (e.g. coral reefs, seagrasses, rocky shores).

Primary industries

The Queensland primary industries sector is a key contributor to the Queensland economy, society, culture and environment, especially in regional areas. In 2006–07, primary industries contributed around six per cent of the Queensland economy with the gross value of production in the sector forecast to be more than $13 billion in 2008–09 (DPI&F 2008).

In Queensland, the beef and sugar industries comprise a large part of the primary industries sector, with fruit, vegetables and nuts also making up a significant proportion (Figure 28).

The grain industry is an important input to the beef industry, while the coastally located sugar industry generates $1 billion per annum for Queensland (DPI&F 2008).

Horticulture contributes $3 billion to the Queensland economy every year and is very climate sensitive in terms of crop type and cultivars (DPI&F 2008).

Of Queensland's total net greenhouse gas emissions in 2008 (160.3 Mt CO_2-e) 26.6 Mt (17 per cent) came from agriculture, with the majority being methane emissions from livestock (DCCEE 2010).

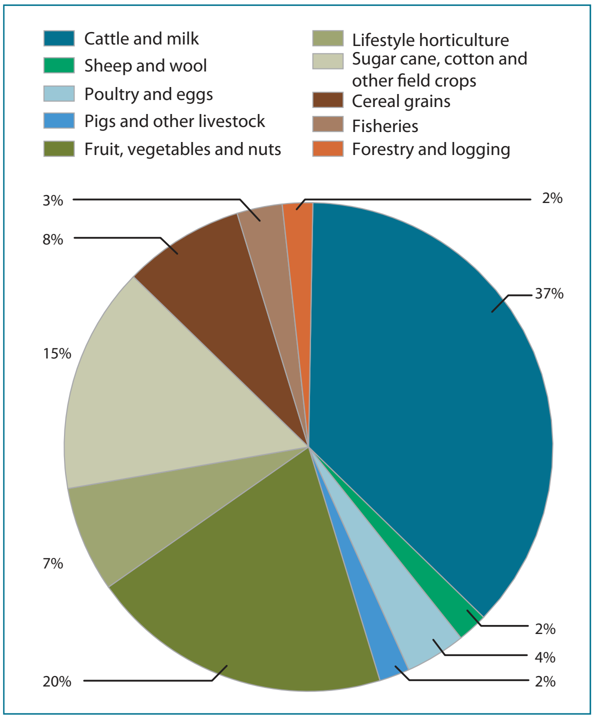


Figure 28: Queensland's major primary industries 2008–09 (Source: DPI&F, 2008)

Key messages

The effects of declining rainfall and runoff into streams are already being felt by primary producers and the effects of temperature changes are likely to be felt within the next decade. Key impacts on the primary industries sector are likely to include:

- warmer and drier weather in future decades over much of Queensland
- more frequent droughts and drier conditions
- increased frequency of severe weather events including flooding, which could also reduce primary and agricultural production through reduction in crop yields and through stock losses
- changes in average rainfall and temperatures, in seasonal distribution of rainfall and in rainfall variability, which directly affect crop production.

Land clearing is a significant factor in Australia's recent droughts and changing climate. The intensity and duration of droughts may have increased as a result of large-scale clearing of native vegetation, amplifying the effects of El Niño-related droughts. Maintaining adequate land cover could help reduce the impacts of climate change.

Climate risks

Recently there has also been increased recognition of the ecosystem services that biodiversity provides. Industries such as forestry, agriculture and other primary industries that rely directly on ecosystem services are most exposed to impacts of climate change on these services.

Climate change threatens to undermine Queensland and Australia's food security. Production from primary industries is projected to decline by 2030 over much of eastern Australia due to increased drought, reduced water resources and higher temperatures.

Queensland is projected to be warmer and drier in future decades. An assessment of the impact of climate change on extreme weather events found that events once considered exceptional may become more common in the future. For example, there may be an increase in the number of exceptionally hot years, with associated lower soil moisture and changes to evaporation and rainfall (Hennessy *et al*. 2008).

Climate change is also projected to have a significant adverse impact on Australia's agricultural production and exports (Stern 2006; Garnaut 2008).

Crop production is likely to be affected directly by changes in average rainfall and temperatures, in seasonal distribution of rainfall and in rainfall variability.

Australian production of beef, sheep meat and wool could decline by five to eleven per cent by 2030 under a business-as-usual case (Heyhoe *et al*. 2008). In northern Australia, the decline in beef production is expected to be 3.5 per cent by 2030 with significant impacts on the entire grazing industry (Heyhoe *et al*. 2008).

However, the agricultural sector's relatively good ability to adapt to changing climate conditions is also likely to mitigate some of the adverse impacts.

Not all impacts of a warming climate are negative for primary industries: some agricultural impacts are likely to be positive. For example, increases in CO_2 concentration will increase the rate of photosynthesis in some plants provided there is adequate moisture (Steffen & Canadell 2005).

However, this positive impact of carbon fertilisation is likely to be restricted by higher temperatures and lower rainfall, which are both expected to become more prevalent through the 21st century. Howden *et al*. (1999) and Crimp *et al*. (2002) found that a 10 per cent reduction in rainfall would be likely to remove the CO_2 fertilisation benefit.

Land clearing over the past 200 years is a significant factor in Australia's recent droughts and changing climate. Research by Deo *et al*. (2009) indicates that the intensity and duration of droughts has increased as a result of large-scale clearing of native vegetation, amplifying the effects of El Niño-related droughts and increasing the annual number of days with over 35 °C temperatures.

Adaptation

Understanding the implications of climate change would help the primary industries sector to adapt and develop new ways of functioning within a changing climate.

The Queensland Government is committed to working with rural communities to ensure that resources and skills are available to prepare for greater climate variability.

Queensland Government financial incentives in exceptional drought events provide support to primary producers.

The development of climate forecasting techniques and management tools that integrate climate information into producers' operations also helps prepare for changes in climate.

The Queensland Climate Change Centre of Excellence has developed a climate risk management matrix to assess climate change impact, risk and adaptation potential for the Queensland grazing industry (Table 4) (Cobon *et al*. 2009)

The cells in the matrix give information on likely impacts in relation to specific elements of climate change. For example, with higher minimum temperatures, a moderate increase in pasture growth is projected (and researchers are highly confident that climate change will bring higher minimum temperatures).

For some cells in the matrix, interactions are complex. These cells are completed using complex modelling tools. Other cells are filled subjectively, based on knowledge of climate change science along with local and industry knowledge.

Adaptation to the changing climate needs to address:

- capacity building to adapt to climate change
- awareness raising about the effects of climate change and the advantages of early action

- analysis of climate-related financial risks and opportunities
- development of industry sector plans and communication with commodity producers, businesses and decision makers on what climate change means for their businesses and industry
- communication with customers on industry actions to address climate change.

The Queensland Government, through its *ClimateQ* strategy, is investing $3.2 million to provide information and tools to help primary producers in Queensland manage climate change risks and take advantage of emerging opportunities. This initiative will support research on the impacts of climate change on primary industries (including fisheries and forestry); assess the flow-on impacts to farm business, local communities and the Queensland economy, and develop adaptation options to manage the risks.

The key to Table 4 is shown below. The blue shading indicates a level of positive impact and brown shading indicates a negative impact of climate change on the grazing industry.

LEVEL OF NEGATIVE IMPACT						LEVEL OF POSITIVE IMPACT				
	Negative consequences					**Positive consequences**				
Likelihood	Minor	Moderate	Major	Severe	Catastrophic	Minor	Moderate	Major	Extreme	Phenomenal
Rare	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Unlikely	Low	Low	Medium	Medium	Medium	Low	Low	Medium	Medium	Medium
Possible	Low	Medium	Medium	High	High	Low	Medium	Medium	High	High
Likely	Low	Medium	High	High	Extreme	Low	Medium	High	High	Extreme
Almost certain	Low	Medium	High	Extreme	Extreme	Low	Medium	High	Extreme	Extreme

Feature	Pasture Growth	Surface Cover	Plant Available Water Capacity	Wind Erosion	Rural Human Health and Wellbeing	Biodiversity
Elevated CO_2	Moderate increase in pasture growth due to Co_2 fertilisation	Minor increase in surface cover	Moderate increase in plant available water capacity due to increased surface cover and transpiration rates	Moderate reduction in wind erosion due to higher surface cover	No direct effect	Changes in species composition and structure for plant species
Increased evaporation	Decrease in pasture growth	Decrease in surface cover	Reduced plant available water capacity due to lower water availability/surface cover	Increased wind erosion due to lower surface cover	Decrease in human health and welfare related issues	Changes in species composition and structure for plant and freshwater dependent species
Higher minimum temperature	Moderate increase in pasture growth	Increased surface cover	Reduced plant available water capacity depending on extent of increase in surface cover	Reduced wind erosion due to higher surface cover	Small decrease in rural human health	Changes in insect and plant species composition
Less frost	Increase in pasture growth during winter	Increased surface cover	Increase in plant available water capacity due to higher surface cover	Reduced wind erosion due to higher surface cover	No direct effect or not measurable	Changes in insect and plant species composition
Higher maximum temperature °C	Decreases in pasture growth	Decrease in surface cover	Reduced plant available water capacity due to a reduction in water availability/surface cover	Increased wind erosion due to lower surface cover	Decrease in rural human health and capacity to cope at current rate of functioning	Changes in amphibian, insect and plant species composition

Feature	Pasture Growth	Surface Cover	Plant Available Water Capacity	Wind Erosion	Rural Human Health and Wellbeing	Biodiversity
More days over 35 °C	Decrease in pasture growth	Decrease in surface cover	Reduced plant available water capacity due to a reduction in water availability/surface cover	Increased wind erosion due to lower surface cover	Large decrease in rural human health and capacity to cope at current rate of functioning	Changes in plant structure and species composition
More droughts	Severe reduction in pasture growth	Severe reduction in surface cover	Severe reduction in plant available water capacity due to reduction in water availability/ surface cover	Increased wind erosion due to lower surface cover	Large decrease in human health, potential for stress related incidence	Major changes in plant and animal species composition
Increased storm intensity - same total rainfall	Decrease in pasture growth	Decrease in surface cover	Decrease in plant available water capacity	Increased wind erosion due to lower surface cover	No change	Changes in insect and plant species composition, siltation of waterholes
Decrease in winter rainfall	Minor decrease in pasture growth	Minor decrease in surface cover	Minor reduction in plant available water capacity due to lower water availability/surface cover	Minor increase in wind erosion due to lower surface cover	Minor decrease in rural human health	Major changes in plant and animal species composition
Decrease in summer rainfall	Severe reduction in pasture growth	Severe reduction in surface cover	Reduced plant available water capacity due to lower water availability/surface cover	Severe increase in wind erosion due to lower surface cover	Large decrease in human health, hardship and welfare, potential for stress related incidence	Changes in plant and animal species composition
More wildfires	Increase in pasture growth	Decrease in surface cover	Decrease in plant available water capacity due to lower surface cover	Increased wind erosion due to lower surface cover	Decrease in human health and welfare related issues	Changes in plant structure and species composition
Higher peak wind speeds	Decrease in pasture growth due to higher evaporation and erosion of topsoil especially in arid and semi-arid regions	Decreased surface cover due to higher evaporation, erosion of topsoil	Decrease in plant available water capacity due to lower surface cover (reduced infiltration into soil)	Increased wind erosion due to higher peak wind speeds	Decrease in human health and increase in welfare related issues	Damage to some tree and animal species
Overall estimate for the risk averse	Reduction in pasture growth	Decrease in surface cover	Decrease in plant available water capacity	Increased wind erosion	Decrease in human health and increase in welfare related issues	General negative long-term effects on ecosystem function

Table: 4: Climate change risk management matrix for the Queensland grazing industry (Source: Cobon *et al.* 2009).

Health and wellbeing

Climate change will have an impact on the social, health and lifestyle needs of all Queenslanders. This section provides an overview of some of the key impacts to human health under changes to climate in Queensland.

Existing literature on the impacts of climate change on human health is mostly descriptive rather than quantitative. It makes inferences about broad climate-related health risks (McMichael *et al.* 2009). Direct links between climate change and changes in many diseases or illnesses are difficult to establish but in general terms climate change can negatively affect the environment and a poor environment can negatively impact human health.

Key messages

The potential impacts of climate change on people's health and wellbeing are likely to include:

- increased intestinal illness as changing rainfall will affect water availability, quality and access
- increased illnesses caused by viruses carried by mosquitoes (e.g. Ross River fever) as changing temperatures and rainfall will affect mosquito breeding patterns
- increase in respiratory and allergic diseases as changing temperatures and weather patterns will affect airborne pollution
- increased heat-related illnesses as a result of increasing heatwaves and temperatures, including heat stress and illnesses affecting the vascular and respiratory systems
- trauma from extreme weather events and more mental illness in areas affected by long-term drought and other natural disasters
- increased pressure on health infrastructure and services across Queensland.

Climate risks

Climate change, particularly raised temperatures and variations in rainfall, are likely to result in health and wellbeing impacts across Queensland society.

Temperature increases can bring prolonged periods of hot days and warm nights, increasing the mortality rate, especially in the elderly.

Longer and more frequent droughts in regional Queensland can increase personal stress and mental illness.

Gradual sea level rise, coupled with stronger storm surges, will tend to bring more frequent and more severe coastal flooding, increasing environmental and social pressures and potentially requiring the relocation of communities, especially from low-lying islands (IPCC 2007c).

Projected increases in the frequency and severity of flooding and storms could result in the destruction of homes and essential services including health services. People living in marginal conditions are likely to be more at risk.

Figure 29 portrays the pathways linking climate change and health.

The World Health Organization estimates that in 2004 more than 140 000 deaths worldwide were attributable to climate change. Climate change was estimated to be responsible for 3 per cent of diarrhoea, 3 per cent of malaria and 3.8 per cent of dengue fever deaths worldwide in 2004 (WHO 2009). These impacts are likely to increase in the future.

Horton and McMichael (2008) predict that by 2020 it is likely that Australian doctors and hospitals will be treating patients with a range of climate change-related illnesses, including:

- heat stress
- other heat-related illness (affecting the heart, blood vessels and lungs)
- trauma from extreme weather events
- mental illness in areas affected by long-term drought and other natural disasters
- respiratory problems from airborne pollutants
- infectious diseases such as gastroenteritis
- dengue fever and Ross River virus due to changes in the distribution of disease-carrying mosquitoes.

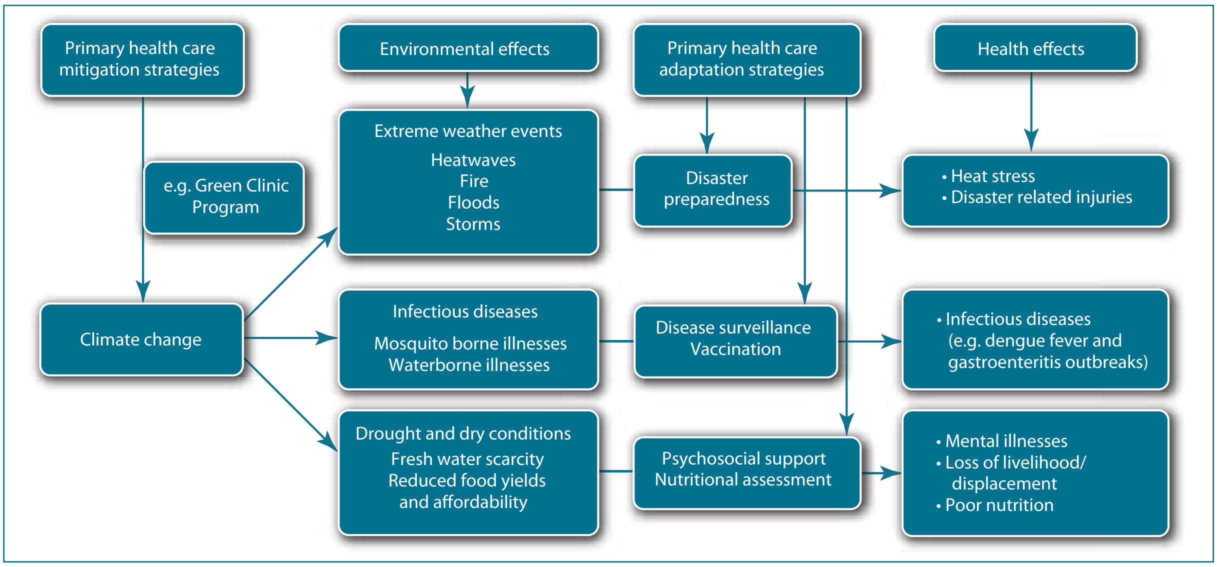


Figure 29: Pathways by which climate change can impact on health and potential primary health-care adaptive strategies (Source: Blashki *et al.* 2007)

Heatwaves

Heatwaves are viewed as a 'passive' hazard in contrast to the more widely studied catastrophic hazards such as tropical cyclones and earthquakes. According to Coates (1996), heatwaves kill more people than any other natural hazard experienced in Australia.

The most vulnerable groups are the sick, the young, the elderly and the poor. Heatwaves significantly increase human mortality and hospital admissions, especially for people with cardiovascular diseases (Queensland Health 2004). A Canadian study found the risk of mortality increased by 1–3 per cent per 1 °C change at high temperatures (Hajat & Kosatsky 2009).

Australia has an aging population. In 2007, people aged 65 years and over made up 13 per cent of the population (ABS 2008a). This proportion is projected to increase to 23–25 per cent in 2056 and to 25–28 per cent in 2101 (ABS 2008b).

The elderly (over 65 years) are particularly vulnerable to heatwaves, with limited mobility being an important mortality risk factor (Bambrick *et al.* 2008; Van Iersel & Bi 2009).

An investigation of all causes of death in Brisbane found a high correlation between higher temperatures and deaths in the elderly (Bi *et al.* 2008).

Taking into consideration changes in population and age demographics, McMichael *et al.* (2003) found that a temperature increase of 1.6 °C above 1990 levels could increase heat-related deaths in Brisbane from the current estimated 134 deaths per year to over 1000 deaths per year by 2050.

The number of annual temperature-related deaths in Queensland, in a scenario without climate change mitigation, is expected to rise to over 5800 deaths by 2100 (Garnaut 2008).

The January–February 2009 heatwave in Victoria provides an example of the potential effects of such events. The heatwave was of unprecedented intensity and duration with maximum temperatures 12–15 °C above normal for much of Victoria, while Melbourne endured three consecutive days of temperatures above 43 °C (BoM 2009d).

The heatwave caused major power disruptions in Melbourne leaving over half a million people without power. Ambulance Victoria (2009) reported a 70 per cent increase in emergency calls. Data for the week of the heatwave (26 January–1 February 2009) compared to the same period in previous years showed that there was a 62 per cent increase in total all-cause mortality, with 374 excess deaths (DHS 2009).

The total number of deaths was 980, compared to a mean of 606 for the previous five years. The greatest number of deaths occurred in those 75 years or older, representing a 64 per cent increase (DHS 2009).

The January 2000 heatwave in south-east Queensland resulted in 22 reported deaths and 350 injuries. The Queensland Audit Office (2005) estimated the cost at $2 million.

Preliminary data on the February 2004 heatwave in Brisbane indicated that it resulted in 12 recorded deaths and 221 heat-related hospitalisations (Queensland Health 2004). The highest temperature recorded in the 2004 heatwave was 42 °C. The highest recorded temperature was 34 °C during the same months of 2001–03 (Tong *et al.* 2009).

The impact of heatwaves will potentially be exacerbated by disruption to energy services, either through storm damage or as a result of increased demand. In the United States, the 2003 summer heatwave caused the electricity grid to fail, resulting in 50 million people being without power for several days (Miller *et al.* 2008).

Other extreme weather events

Other extreme weather events impacting on Queensland include cyclones, storms, floods, bushfires and drought. Future changes in extreme weather events are difficult to assess and model at regional scales.

Most of the deaths directly related to storms are a result of drowning (Sellman & Hamilton 2007). Direct health impacts from extreme weather events include traumatic injuries and post-traumatic stress syndrome.

Table 5 lists major disasters in Queensland from 1975 to December 2002, as identified by Emergency Management Australia. Each of these caused at least 12 fatalities or 50 injuries or resulted in at least $200 million in total estimated costs.

Date	Disaster Category	Location	Fatalities	Injured	Estimated Cost $ millions (1997 value)
Dec 1976	Cyclone Ted	Queensland	..	2	220
Jan 1985	Severe storm (including Tornado)	Brisbane	..	20	390
Jan 1986	Cyclone Winifred	Cairns-Ingham	3	12	325
Apr 1989	Cyclone Aivu (including storm surge)	Ayr, Home Hill, Wunjunga	2	13	200
Jan 1991	Flood (Cyclone Joy)	Central Coast	6	35	385
Jan 1994	Heatwave	northern including Townsville	5	150	8
Mar 1997	Cyclone Justine	Cairns-Innisfail	7	50	190
Jan 1998	Flash Floods	Townsville-Cairns	2	40	210
Jan 2000	Heatwave	south-east region	22	350	2

Table: 5: The cost to Queensland from natural and non-natural disasters (Source: adapted from Queensland Audit Office 2005)

Disasters do not generate 'new' diseases. According to Smith (1999), disasters may increase transmission of diseases that already exist in a region by:

- altering the environment through disruption and damage to power supplies, water and sewerage infrastructure, waste disposal facilities and services
- reducing access to clean food and water
- encouraging disease-carrying animals to thrive.

Unmitigated climate change could result in global sea level rise of one metre or more by 2100 and more intense storms. Under such conditions, heavy rain has been implicated as a source of infection (McMichael *et al*. 2009).

Climate change is expected to create a substantial increase in fire weather risk in much of south-eastern Australia (McMichael *et al*. 2009). The Victorian heatwave in January and February 2009 resulted in 374 excess deaths and generated extreme fire conditions. Resulting bushfires claimed 173 lives (Victoria Police 2009).

Mosquito-, water- and foodborne diseases

Climate change is projected to increase risks relating to vector- and waterborne and infectious diseases as well as impacting on food safety. Lower income groups are particularly at risk.

Mosquito-borne diseases

The IPCC predicts that by 2050, 0.6–1.4 million more people in the Oceanic region will be exposed to dengue fever (IPCC 2007c). The current distribution of dengue fever is at an historical low, even though cases have been reported in New South Wales and the dengue mosquito has been found throughout Queensland and in Victoria and Western Australia (Russell *et al*. 2009). Queensland's largest recorded dengue fever epidemic in at least 50 years began in November 2008 and was exacerbated by the early 2009 flooding. A total of 931 people in northern Queensland were confirmed as having the virus (Queensland Health 2009).

Queensland currently has the highest number of Ross River fever cases each year in Australia. Longer dry periods followed by intense rainfall and flooding are expected to bring added periods of mosquito activity followed by rapid outbreaks of disease. Poor maintenance of rainwater tanks can also cause mosquito proliferation and increase the spread of the disease (Woodruff & Bambrick 2008; McMichael *et al*. 2009).

Flooding across central Queensland in early 2008 may have been the cause of a substantial increase in notifications of Ross River fever. In Queensland, there were 1246 notifications compared with 535 notifications for the same period in 2007, when no major flooding occurred (McMichael *et al*. 2009).

A systematic literature review by Tong *et al.* (2004) between climate factors and Ross River virus transmission found that rainfall and temperature were major determinants of the spread of the disease.

Waterborne diseases

The European Centre for Disease Prevention and Control noted in a report on climate change and waterborne disease that climate change will alter the water cycle by increasing the frequency of extreme events such as excessive rainfall, storm surges, floods and droughts (ECDPC 2004). These events can affect water availability, quality or access, posing a health threat.

Waterborne pathogens often act through two major exposure pathways: drinking water and recreational water use (ECDPC 2009). Hot weather may increase the prevalence of these pathogens, resulting in widespread contamination of surface water supplies (McMichael *et al.* 2009).

Climate change is likely to increase health risk from two environmental pathogens associated with wet weather—leptospirosis and melioidosis (McMichael *et al.* 2009).

The potentially fatal disease melioidosis, which can cause external and internal abscesses or ulcers and blood poisoning, is endemic to northern Australia (Cheng *et al.* 2006) and can be spread by contact with contaminated soil or water.

There are typically 150–300 cases of leptospirosis per year, mostly from Queensland, with increases in cases associated with severe weather events (Inglis *et al.* 2004; Currie *et al.* 2009).

Sudden heavy rainfall and associated flooding can overload some sewer and stormwater systems, potentially leading to faecal contamination of stormwater released into the environment. Heavy rainfall events will also tend to flush out pathogens from upstream water catchments, especially in farm runoff. As a result, *Cryptosporidium, Giardia* and other pathogens may enter surface water supplies (McMichael *et al.* 2009).

Rodents act as reservoirs and carriers for various diseases, and increase in numbers in temperate regions following mild wet winters. Rodent-borne diseases associated with flooding include leptospirosis, tularaemia and viral haemorrhagic diseases (WHO 2010). Infections with these diseases occur through eating or drinking of contaminated food or water.

Many diarrhoeal diseases vary seasonally, suggesting sensitivity to climate. In the tropics diarrhoeal diseases typically peak during the rainy season. Both floods and droughts increase the risk of diarrhoeal diseases (WHO 2010).

Reduced rainfall increases the risk of toxic algal blooms and can increase the salinity of drinking water (IPCC 2007c; McMichael *et al.* 2009) while rising water temperature may promote earlier and longer lasting algal blooms (Moore *et al.* 2008). Hunter (2003) found that increases in the nutrient content and water temperature of dams, caused by heavy precipitation, can also lead to blooms of toxic algae.

Foodborne disease

Heatwaves may cause failure of electricity supplies which could result in food spoilage, increasing the likelihood of infection (Cretikos *et al.* 2007; McMichael *et al.* 2009). *Salmonella* is a bacterium that causes salmonellosis—one of the most common intestinal infections. *Campylobacter* is another common cause of bacterial foodborne illness. There are strong seasonal patterns for *Salmonella* and *Campylobacter* infection in Australia: warmer weather increases infections and cooler weather reduces infections (Hall *et al.* 2002).

Climate change, combined with changes in production, distribution and management of food, has the potential to affect foodborne disease (Hall *et al.* 2002). D'Souza *et al.* (2004) conducted a study in five Australian cities, including Brisbane, which showed a long-term increase in salmonellosis notifications between 1991 and 2001. Seasonal patterns in salmonellosis notifications were fully explained by changes in temperature. A later study found that rainfall and temperature in Brisbane and Townsville correlated positively with the number of cases of salmonellosis (Zhang *et al.* 2009).

Air quality

Air quality is also affected by climate change (IPCC 2007c). Air pollution, including ozone (O_3) and other contaminants (such as smoke, dust and moulds) can cause respiratory and cardiovascular problems (such as asthma attacks and bronchitis) and premature death among the elderly and young (Galbally *et al.* 2007; Jalaludin *et al.* 2009). Horton and McMichael (2008) found that increased temperatures may interact with air pollution to compound such illnesses. Premature deaths due to air pollution-related illnesses are estimated to be in the thousands annually across Australia (Potterton 2005).

Ozone

Most O_3 is found in the upper atmosphere, where it acts to screen out much of the harmful radiation from the sun. Upper-level O_3 is an important part of the Earth's life support system.

Lower-level O_3 is created when sunlight hits hydrocarbons and nitrogen oxides are released into the lower atmosphere by industrial and vehicle emissions and natural processes.

Higher temperatures hasten the chemical reactions that lead to the formation of certain pollutants such as ground-level O_3, the primary constituent of urban smog.

Ground-level O_3 is likely to increase with increasing temperature and this could increase the incidence of asthma (Wilson & King 2003). Researchers (Shea *et al.* 2007; Blashki *et al.* 2007) have concluded that climate change may cause increased respiratory illnesses from temperature-enhanced pollution.

Contaminants

Air contaminants such as smoke from bushfires, dust from dust storms, airborne pollens and moulds may increase as a result of climate change. Potterton (2005) found that smoke, agricultural sprays and windblown dust from mining and agriculture are health issues in rural and regional Australia.

Climate change will result in much of Australia becoming warmer and drier (CSIRO & BoM 2007). Drought and long-term drying conditions will increase the risks of exposure to dust and smoke (Horton & McMichael 2008). Chen *et al.* (2006) and McMichael *et al.* (2009) found correlations between increased smoke and windblown dust from bushfires and a rise in hospital admissions for respiratory complaints.

Dust events may be associated with changes in asthma severity in Brisbane, particularly if the level of fine particulates increases (Rutherford *et al.* 1999).

UV exposure

Now that stratospheric ozone depletion is under control by the Montreal Protocol, interest has turned to the effects of climate change on the ozone layer.

As the Earth warms, the overturning circulation of the upper atmosphere is projected to speed up. Model simulations suggest that this will increase the movement of O_3 from the stratosphere to the troposphere and alter surface levels of ultraviolet radiation (Stevenson 2009).

A study by Hegglin and Shepherd (2009) showed that under the IPCC A1B emissions scenario, global stratosphere-to-troposphere O_3 flux would increase by 23 per cent between 1965 and 2095 as a result of climate change.

Changes to the distribution of O_3 in the atmosphere may increase exposure to photochemical atmospheric pollution. Stratospheric O_3 depletion, together with more sun exposure in warmer weather could accelerate the existing rise in the incidence of skin cancer and increase the risk of cataracts (Bentham 1992).

Climate change will also influence surface UV radiation through changes in clouds and in the ability of the Earth's surface to reflect light (WMO 2007).

Mental health

Impacts of climate change such as increases in extreme weather events and disruption to communities have implications for mental health. Fritze *et al.* (2008) found that the aftermath of extreme events can include stress-related problems such as depression, anxiety disorders, drug and alcohol abuse and increased suicide attempts.

Drought and prolonged dry periods are projected to become more common in the future for much of Australia (Hennessy *et al.* 2008). Various studies have been carried out on the impacts of drought on the mental health of Australians. McMichael *et al.* (2003) concluded that drought-related stress increased suicide rates, while several authors report a higher proportion of young men being affected (Page & Fragar 2002; Berry *et al.* 2008; McMichael *et al.* 2009).

The connection between an increase in mental health problems and the financial hardship that drought brings for many rural Australian families is well established (Nicholls *et al.* 2006; Berry *et al.* 2008; McMichael *et al.* 2009). A New South Wales study by Nicholls *et al.* (2006) found that a decrease in rainfall of about 300 millimetres was associated with an 8 per cent increase in the long-term mean suicide rate. These problems would be exacerbated if climate change brought prolonged and more frequent droughts, as is expected to be the case.

Berry *et al.* (2008) found that high humidity has been associated with poorer concentration and increased fatigue. In addition increasing temperatures (especially lengthy spells of hot weather) has been associated with higher rates of criminal and aggressive behaviour, suicides and hospital admissions.

Remote communities and Indigenous health

Sea level rise, storm surges and saltwater intrusion on low-lying islands will impact on the long-term viability of remote and Indigenous communities in the far north of Queensland and the Torres Strait (CSIRO 2007; Green 2008).

It is anticipated that at least 8000 people in the Torres Strait Islands could be displaced if sea levels rise by one metre (HREOC 2008). Forced relocation resulting in loss of traditional connection with land could cause serious distress and mental illness (Green 2008).

The climate change impacts of higher temperatures, increased flooding and bushfires could also result in increased mosquito-borne diseases, heat stress, respiratory problems and diarrhoeal diseases (HREOC 2008; McMichael *et al.* 2009; Green *et al.* 2009).

Storms and floods can facilitate the spread of infectious intestinal diseases that cause diarrhoea in young children. Indigenous people living in remote communities are at increased risk with the number of Aboriginal children being admitted to hospital with diarrhoea likely to increase by 10 per cent by 2050 (DCC 2009b).

Health-care services

Health-care services, including their supporting infrastructure, would be subject to increased demands if the frequency and intensity of extreme events increased, assuming that such services are not damaged or isolated by the event (Carthey *et al.* 2008).

Bell (2009) considered that education and training of rural and remote practitioners is needed to help deal with climate change health impacts.

Similarly the increased demands placed on health-care services as a result of increased extreme weather events require strategies to plan, design, deliver and operate health-care infrastructure to maintain an appropriate standard of health service.

An Australian Research Council linkage project is currently assessing the potential vulnerability of hospital facilities and their ability to adapt to climate-related extreme weather events.

Adaptation

Adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects (IPCC 2007c). Blashki *et al.* (2007) identified a range of primary health-care adaptation strategies including:

- public education and awareness
- early alert systems to warn of impending weather extremes or infectious disease outbreaks
- disaster preparedness, including increasing the health system's 'surge' capacity to respond to emergencies
- enhanced infectious disease control programs
- food safety programs, vaccine programs, vector control, case detection and treatment
- improved surveillance of risk indicators (e.g. mosquito numbers, allergen concentration) and health outcomes (e.g. infectious disease outbreaks, rural suicides, seasonal asthma peaks)
- appropriate health workforce training (e.g. updated understanding of climate influences on health, training in public health).

Some of these strategies are associated with specific climate change impacts on human health; for example, disaster preparedness is associated with extreme weather events and enhanced infectious disease control programs are associated with the impacts of climate change on infectious disease risk.

An example of disaster preparedness in the case of heatwaves is the *Queensland Heatwave Response Plan (2004)* which aims to coordinate agencies, raise public awareness and minimise the impact of heat on service providers (Queensland Health 2004).

To further increase community awareness, the Bureau of Meteorology is developing a heatwave warning system (McMichael *et al.* 2009). Other strategies, such as public education and awareness and health workforce training, work across many different climate change impacts.

Emergency management

Queensland's natural risk hazard cost profile is dominated by flood, storm surge and tropical cyclones, severe storm and bushfire (Figure 30). Other hazards experienced include landslip, earthquake, tsunami and heatwaves (COAG 2007). While flooding accounts for the greatest share of the costs of natural disasters to Queensland, the other natural hazards also represent a risk to communities, especially coastal communities.

Climate variability due to climate change is expected to affect the behaviour of natural hazards in different ways. For example, some areas of the Queensland coast can expect intense rainfall and more intense and southerly moving cyclonic events. Many of the climate projections summarised in Chapter 3 will impact on the emergency management sector in the long term.

Climate change represents another risk that must be incorporated within a broad-based disaster risk reduction framework.

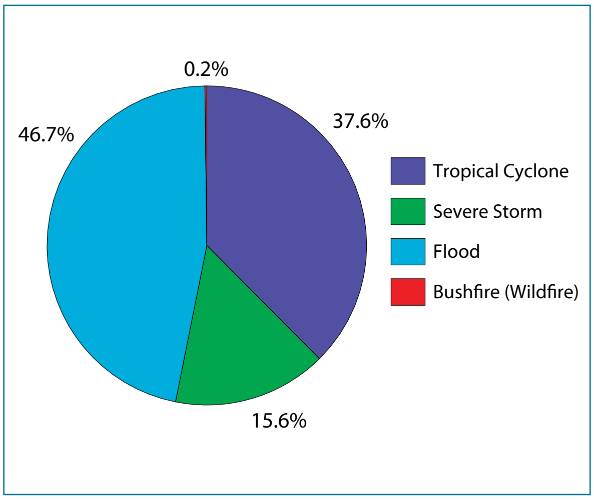


Figure 30: Costs by type of disaster in Queensland 1967-1999 (Source: BTE 2001).

Key messages

Queensland's natural hazard risk profile is dominated (in priority order) by flood, storm surge and tropical cyclones, severe storm and bushfire. The potential impacts of climatic changes on the emergency management sector include:

- an increase in the number of severe tropical cyclones which could increase the risk to communities located in regions with a history of cyclones
- a southward shift in the region in which cyclones develop, exposing additional communities to risk, including south-east Queensland
- temperature rises throughout Queensland with the potential to increase the intensity of future heatwaves, increasing the demand for emergency services
- projected increased intensity of rainfall events in some locations, potentially resulting in increased flooding which is one of the most costly natural hazards in Queensland.

The National Climate Change Adaptation Research Facility (NCCARF) climate change adaptation research plan highlights the infancy of planning for climate change risks in Australia's emergency management sectors.

Climate risks

Natural disasters and extreme events result in significant cost to life as well as damage to property and the natural environment. In the period 1967–1999, 265 natural disasters, with each event costing over $10 million, cost the Australian community a total of around $37.8 billion (in 1999 prices) or $85 per person per year (BTE 2001).

The Council of Australian Governments found that natural disasters cause an average of $1.14 billion damage each year to homes, businesses and infrastructure (COAG 2002). The vast majority of major Australian insurance events are weather-related. New South Wales and Queensland account for 66 per cent of total disaster costs and 53 per cent of the total number of disasters (BTE 2001).

Table 5 indicates the relative financial costs of natural disasters in Queensland. It shows that these costs are historically dominated by climatic events.

Under climate change conditions there is a greater chance that multiple extreme events will occur at the same time (or one will occur while the effects of another are still being felt), limiting resources available to be reallocated from different regions for aid in response and recovery efforts (Pearce *et al.* 2009).

As extreme weather events become more common under a climate change scenario, greater stress will be placed on governments and communities. This will be felt especially during times of high storm, rainfall and bushfire activity.

Floods

In terms of economic costs, flooding is Australia's and Queensland's most damaging natural hazard. On average, flooding cost Australia $420 million per annum over the period 1967–1999 (BTE 2001). Across Australia there are around 170 000 residential properties in the areas considered susceptible to a flood recurring every 100 years on average (Attorney-General's Department 2009).

Figure 31 shows the flood potential across Australia associated with coastal and inland rivers. In inland Australia, floodwater can spread thousands of kilometres and persist for weeks, whereas flooding in the coastal regions is generally faster flowing, localised and over a shorter period. All population centres on the Queensland east coast are exposed to short-duration, rapid-onset floods (COAG 2007).

Floods represent Queensland's most significant natural hazard risk, accounting for the greatest share of claims made under the Natural Disaster Relief and Recovery Arrangements (NDRRA) and for mitigation projects funded under the Natural Disaster Mitigation Program. For example, Queensland's January and February 2008 floods are estimated to have caused $1.85 billion in overall economic losses (Munich Re 2009).

During times of probable maximum flood, the total value of the assets at risk is estimated at over $100 billion (Attorney-General's Department 2009). Projections for increases in intense rainfall events and hence flooding, especially in the more densely populated regions of northern and south-eastern Queensland, are therefore likely to have great economic consequences.

Tropical cyclones

Cyclones also represent a significant natural hazard risk for Queensland. Damage from tropical cyclones results from severe wind, heavy rain and/or storm surge. In 2006, Cyclone Larry caused US$1300 million in economic losses across north Queensland (Munich Re 2007).

Although the exact change in behaviour of tropical cyclones under climate change is uncertain, projections indicate an increase in the number of severe tropical cyclones as well as a southward shift in the cyclone genesis region (Walsh *et al.* 2004; Leslie *et al.* 2007). For much of Queensland's east coast, storm tide heights are projected to increase beyond the contribution from rising sea levels.

An increase in the number of severe tropical cyclones could increase the risk to communities located in regions with a history of cyclones. However, a southward shift in the cyclone genesis region exposes additional communities to risk, including densely populated south-east Queensland.

According to the international reinsurance agency Munich Re, south-east Queensland 'has Australia's highest exposed values in terms of the tropical cyclone peril' and in the event of a major cyclone 'would suffer the highest accumulated losses'. It estimates that a Category 3 cyclone hitting south-east Queensland could cause up to US$200 billion in damage (Munich Re 2007).

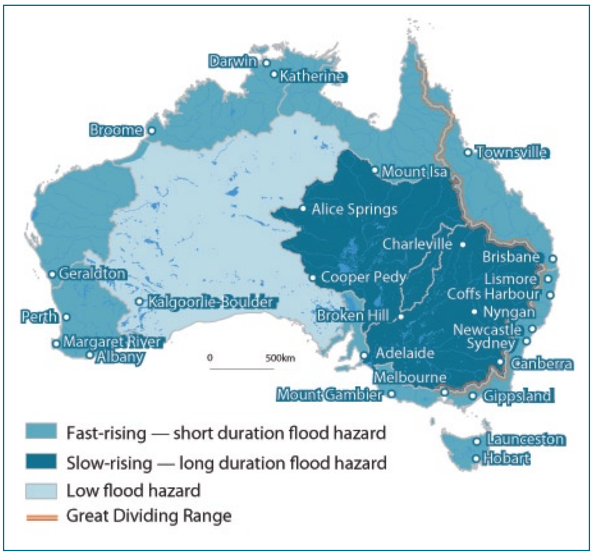


Figure 31: Flood potential in Australia for coastal and inland river systems (Source: Geoscience Australia, in COAG 2007)

Severe storms

Severe storms are Australia's most frequent major natural hazard and the resultant hail, strong winds and lightning pose a significant risk in Queensland. As such, the costs associated with severe storms make up a significant component of the cost of natural disasters in Queensland (Figure 30).

An example of the devastating effect of severe storms is the Sydney hailstorm in April 1999. This storm cost $1.7 billion, more than the estimated cost for Tropical Cyclone Larry (COAG 2007). In Queensland, severe storms in Brisbane and the south-east on Sunday 16 November 2008 particularly affected the suburbs of The Gap, Keperra, Ferny Hills and Arana Downs. Mt Tamborine, the Gold Coast hinterland and Beaudesert also experienced hailstorms. The storms were the first in a series that hit south-east Queensland from 16–22 November 2008 and impacted over 8000 properties (DCS 2008).

Bushfires

Bushfires made up just 0.2 per cent of the total damage cost from natural hazards in Queensland (1967–1999) compared to almost 35 per cent in Victoria (BTE 2001). This is mainly due to the higher moisture content in the atmosphere over Queensland during summer which reduces the fire risk.

The fire season in Queensland normally commences in the Gulf and Cape York Peninsula during August and progresses southwards through spring and summer. However, these timeframes can vary significantly each year, as they are largely dependent on the fuel loads as well as long-term climate and short-term weather conditions in each area.

Northern Australia's pastoral lands and savannahs are affected by grassfires. Although these fires can account for the majority of area burnt by bushfires they have comparatively little economic impact on life and property. However, they may have a significant impact on pastoral economies and may also result in long-term environmental impacts. As such, the risk posed by the projected increase in high fire danger days could be significant.

Heatwave

The number of hot days (days with maximum temperature over 35 °C) is projected to increase across Queensland under all emissions scenarios. High temperature conditions already have a significant effect in Queensland. For example, the January 2000 heatwave in south-east Queensland resulted in 22 recorded deaths and 350 injuries costing an estimated $2 million (Queensland Health 2004).

The projected temperature rises throughout Queensland have the potential to increase the intensity of future heatwaves and thus their impacts, increasing the demand for emergency services. It is estimated that heatwaves killed 4500 people in Australia between 1803 and 1999 compared with 2500 for floods and 2200 for tropical cyclones (BTE 2001).

Landslide

The Geoscience Australia Landslide Database indicates that there have been 201 landslides recorded in Queensland since 1848 (Geoscience Australia 2010). Historically landslides have not contributed significantly to the economic costs of natural hazards in Queensland. However, they do pose a threat to people and property. For example, the Currumbin Hill landslides in 2005 on the Gold Coast caused structural damage to nine properties (Golder Associates Pty Ltd 2006).

The combination of longer dry periods interrupted by more intense rainfall events, as projected for Queensland, is expected to increase the likelihood of landslides (COAG 2002).

Adaptation and emergency management practice

The emergency management approach to climate change risk involves applying existing tools and practices. The current goal of emergency management is to establish resilience in the community, making communities better prepared for possible emergencies (COAG 2007; Yates & Bergin 2009).

Community resilience also involves partnering among a number of stakeholders; including Australian, Queensland and local governments and local communities, not-for-profit organisations and volunteers, businesses, families and individuals.

Climate projections can aid in planning to increase community resilience; therefore, projections of extreme weather events are of interest in the emergency management sector.

The COAG 2002 report, *Natural Disasters in Australia*, established a national disaster mitigation grants program and modernised relief and recovery arrangements. The 2009 *National Disaster Resilience Strategy* reiterates well known principles used by the sector to improve national coordination of disaster resilience across government.

Emergency managers take a 'comprehensive approach' to managing disasters, treating prevention, preparedness, response and recovery as a continuum. Along with an 'all hazards approach', this increases efficiency by using the same systems in response to natural and human-induced hazards.

In Queensland, emergency and disaster response is managed principally through the *Disaster Management Act 2003* and the *Fire and Rescue Service Act 1990*. Prevention, preparedness and recovery are managed through a range of national, state and local government policies, procedures and governance arrangements. These include:

- *planning measures*—regional and urban planning, land-use planning, development planning, building codes and associated engineering standards
- *policy interventions*—individual education and health initiatives as well as regional economic development
- *the market*—raising community awareness of risk through price signals e.g. cost of insurance as well as provision of relief and recovery
- *government grants*—funding of resilience-building and community awareness-raising activities
- *emergency response*—residual natural hazard risk is managed by governments through emergency and disaster response planning, early warning, response arrangements, hazard-specific response plans (e.g. *Queensland Heatwave Response Plan*), maintaining volunteer capacity, communications networks, evacuation planning and community recovery. The *ClimateQ* strategy acknowledges the following initiatives as climate change aspects to Queensland disaster management plans:
  - » incorporating climate change considerations into local disaster management plans
  - » implementing Queensland's heatwave response plan to minimise mortality and morbidity from heatwaves
  - » developing storm-tide maps for the Queensland coastline (OCC 2009)

- *empowered communities and individuals*. It is not possible to mitigate all of the impacts of natural disasters. A significant source of resilience is a community's own efforts to prepare for, respond to, and recover from natural disasters and associated climate change impacts. Community resilience to natural disasters can be boosted through activities such as:
  - » community awareness of local natural hazard risks
  - » business continuity planning
  - » risk management
  - » early warning
  - » well-known evacuation routes and assembly points
  - » emergency stores and caches
  - » coordinated recovery efforts by local providers
  - » partnerships between local government and small businesses.

The emergency management sector is also very dependent on volunteers. NCCARF's *Emergency Management and Climate Change National Adaptation Research Plan* estimates that there are approximately 500 000 emergency services volunteers nationwide, 350 000 of whom are involved in response and recovery activities (i.e. those activities required after the event has occurred).

To improve emergency management planning and response, the research plan (Pearce *et al*. 2009) identifies the following priority research areas:

- understanding the nature and location of risk posed by climate change—there is considerable uncertainty associated with climate change projections (especially those for extreme events) which limits understanding of the risk. For this reason effectively communicating the uncertainty associated with climate change risk is essential
- enhancing community and organisational resilience to climate change risks—the effects of climate change on community resilience and how community resilience is best promoted are the main research objectives identified
- developing and implementing adaptive strategies—this would involve research into how climate change will affect the emergency management sector's ability to support preparedness, response and recovery and the private sector's role in supporting disaster response.

Chapter 5: Climate change science and research priorities

For Queensland to respond to challenges posed by global climate change and a naturally highly variable climate, scientific research that (i) continues to enhance and refine our knowledge of the climate system, (ii) delivers reliable climate change projections, and (iii) strengthens the application of science to key sectors affected by climate risks is crucial.

National climate change science research

The Australian Government is supporting a broad range of climate change science research activities through its $31 million Australian Climate Change Science Program (ACCSP). The ACCSP is the focus of national efforts to improve our understanding of the causes, nature, timing and consequences of climate change in Australia. The program is administered by the Department of Climate Change and Energy Efficiency and conducted in partnership with the Commonwealth Scientific and Research Organization (CSIRO), the Bureau of Meteorology (BoM) and leading universities. The research is helping us to better understand global and regional climate change and its potential impact on Australia's natural and managed systems.

The program covers six themes:

- understanding the key drivers of climate change in Australia
- improved climate modelling system
- climate change, climate variability and extreme events
- regional climate change projections
- international research collaboration
- communications.

In December 2009, the Australian Government released *Australian Climate Change Science: A national framework* (DCC 2009c). The framework identifies the national climate change science priorities and proposes approaches to direct and coordinate climate change research. The framework links climate system science with adaptation responses, mitigation science and technology, and policy development. The framework contains four elements:

- challenges—key areas of climate science research addressing projected changes in greenhouse gas emissions, rainfall, evaporation, sea level rise, ocean acidification and extreme events
- capabilities—areas that must be maintained or developed to meet the climate change challenges
- people and infrastructure—investment in skilled workers or improved infrastructure to undertake modelling and research
- implementation through coordination of activities and investment.

The Australian Government is also investing $387 million in marine and climate science research through the Marine and Climate Super Science Initiative. It is funding high-performance computing and new observing systems and replacing key facilities.

Key Australian research-based organisations making significant scientific contributions on climate science include the CSIRO, BoM, the Antarctic Climate and Ecosystems Cooperative Research Centre and the National Climate Change Adaptation Research Facility (NCCARF). Many Australian universities are also advancing understanding of climate change risks and impacts.

A number of collaborative research projects are already addressing climate change in specific Australian regions. For example the South Eastern Australian Climate Initiative (SEACI) is a research program of around 40 projects addressing the impact of climate change on water availability, temperature, bushfires and other climate-related features in south-eastern Australia. Launched in

2006, SEACI is a partnership involving government and industry and includes the CSIRO and the BoM as research partners.

The Indian Ocean Climate Initiative (IOCI) which commenced in 1998 is a research partnership between the Western Australian State Government, CSIRO and the BoM. IOCI is investigating the causes of the changing climate in Western Australia and is developing projections of the state's future climate.

Queensland climate change science research

A key element of evidence-based policy development is that decisions are underpinned by the best available science. The Queensland Government is taking a leading role in contributing to climate science research through the Queensland Climate Change Centre of Excellence (QCCCE).

The QCCCE is an integral part of the Office of Climate Change within the Queensland Department of Environment and Resource Management and is undertaking research on climate change, climate variability and extreme weather events in Queensland to inform planning and policy decisions.

The QCCCE has established collaborations with leading international climate science research centres; including The Walker Institute for Climate System Research at the University of Reading, the UK Met Office Hadley Centre for Climate Change and the Ministry of Science and Technology, China. These collaborations encourage the sharing of data and models, information exchange and cooperative research programs.

The QCCCE also maintains and provides a range of climate analysis, coastal and land management monitoring and impact tools and information which assist with assessing the impacts of climate change. SILO is the QCCCE's climate database of temperature, rainfall and radiation. AussieGRASS is an Environmental Calculator, used to assess current and future impacts of climate variability on natural resource systems throughout Australia. Seasonal climate outlooks produced by the Centre allow primary producers to plan their planting and grazing regimes.

In addition, the QCCCE's coastal expertise provides information on wave heights and tidal conditions to support coastal planning and regional and local emergency management planning.

Current research programs address climate forecasting and modelling, climate change scenarios, climate variability, extreme weather events and adaptation.

Climate forecasting and modelling

To accurately project climate into the future we need to understand what has happened in the past, including the key drivers affecting Queensland's climate. The QCCCE is one of a number of climate centres around the world involved in the Atmospheric Circulation Reconstructions over the Earth's surface (ACRE) project.

The aim of ACRE is to provide a record of global climate back to the mid-1800s. These climate reconstructions are valuable because they support the outputs from climate models (historical and future analyses). They provide important insights into climate cycles that affect Queensland, such as ENSO.

Like ACRE, the Climate of the 20th Century project is also improving our knowledge of past climate. The QCCCE along with climate research centres around the world is contributing to investigating the ability of global climate models to reproduce major climatic events such as droughts and floods. This work provides important insights into the climate drivers that influence Queensland's climate, and will also allow for more accurate seasonal climate forecasts.

Predicting changes in rainfall is highly complex. To develop an improved understanding of the key processes that influence rainfall over a range of timescales, the QCCCE is working with the University of Reading's Walker Institute to investigate decadal-scale climate processes. The outputs of such collaborations are critical for deriving more robust climate projections, especially for rainfall and extreme events, such as flooding, droughts and cyclones.

The development of the *IPCC Fifth Assessment Report* to be released in 2014 involves the contribution of modelling results from around the globe. The QCCCE and CSIRO are working together to provide a set of climate models simulating the past, present and future climate for use in the assessment.

Climate change scenarios for Queensland

Queensland's size, diverse climatic conditions, broad range of settlement patterns and potential for extreme events generates complexities for adaptation responses.

Regional climate change data is therefore important to support sector-based planning for the impacts of climate change.

In collaboration with the CSIRO, global climate change projections are being tailored to increase the robustness of Queensland climate change projections at the regional scale. Thirteen comprehensive regional climate change assessments have been developed for use in climate risk vulnerability projections, policy development and planning (see Chapter 3).

Improved forecasting of severe storms, sea level rise, cyclones and flooding remains an important area for further research. The QCCCE's coastal impacts team monitors waves and tides and prepares storm-tide and wave networks for each cyclone season, including updating storm-tide inundation assessment maps for Emergency Management Queensland.

To improve our understanding and management of the impacts of sea level rise, storm surge and erosion along Queensland's coastline, the Queensland Government is investing $8 million to deliver a high resolution digital elevation model. It will underpin more accurate modelling of sea level rise and flooding in Queensland and will inform planning and emergency management decisions.

The QCCCE is also researching an approach to managing inland flood risks that takes account of the latest climate change science to help plan for and manage existing flood risk, as well as residual risks resulting from the impacts of climate change.

The modelling of future climate change scenarios is a dynamic and a continually evolving exercise. Over the coming years, there will be further gains made by the QCCCE in conjunction with the CSIRO and the BoM in downscaling global climate models to provide improved climate forecasting at the regional scale.

Adaptation and mitigation initiatives

The Queensland Government committed $3 million towards establishment of the NCCARF to support the development of climate change adaptation research plans across a range of sectors; including water, biodiversity, agriculture, infrastructure, health and emergency management.

The Office of Climate Change has developed a Climate Change Impact Statements assessment tool, which will assist planners and developers of major projects to take the impacts of climate change into consideration. This tool assesses the potential greenhouse gas emissions as well as the potential risks to major building and infrastructure projects from climate change.

At the sectoral level, the QCCCE is working with Queensland Health, the Department of Community Safety and Queensland University of Technology to evaluate the impacts of heatwaves on community health in south-east Queensland.

The QCCCE is collaborating with the University of Queensland and the CSIRO on a three-year project to analyse climate model projections in order to determine the effect of land cover on climate and to investigate how reafforestation may be used to reduce the impact of extreme events.

The QCCCE has developed a climate risk matrix which promotes a risk management approach to climate change adaptation. Developed specifically for the grazing industry in western Queensland, the matrix can be tailored for use by any industry or sector.

The regional projections developed by the QCCCE are being used by a number of research institutions, for example the Marine and Tropical Sciences Research Facility, to support studies of climate change impacts on ecosystems such as the Wet Tropics rainforest and the Great Barrier Reef.

With industry and government support, considerable research is also being undertaken in Queensland academic institutions with industry and government support on mitigation of greenhouse gas emissions through sequestration and carbon capture and storage.

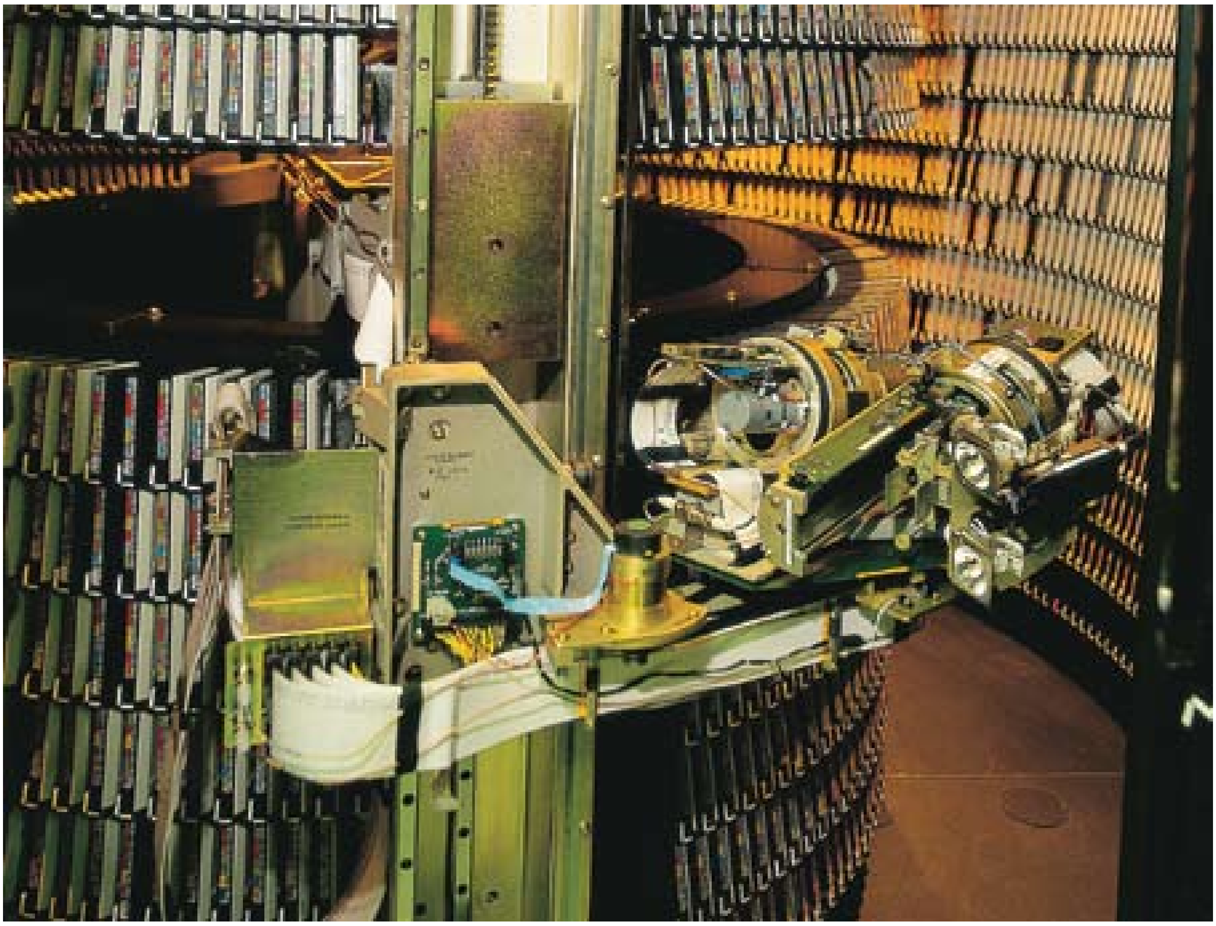
Research challenges

Forecasting the impacts of climate change on the generation of cyclones, on rainfall patterns and on changes in storm frequency and intensity requires extensive, ongoing research. Regional and localised climate information is also a priority for land-use planning and disaster preparedness.

Specific areas of research that are required to provide improved predictions of climate and its impacts on Queensland include:

- tropical cyclone generation and intensity
- frequency and magnitude of extreme events
- influence of ENSO, movement of the Hadley cell, and other ocean–atmosphere interactions
- impact of aerosols on atmospheric circulation and rainfall
- sea level rise and the role of the oceans
- magnitude and statistical significance of trends
- understanding natural climate variations and the impacts of climate change on natural climate variability
- improved regional climate projections
- regional and sector-based risk/vulnerability assessments to identify adaptation options.

For policy makers, the need for ongoing research means that policies will need to be regularly reviewed and revised to reflect the latest scientific knowledge and data.



Glossary

Adaptation – Adjustment in natural or human systems in response to actual or expected climatic changes or their effect, which moderates harm or exploits beneficial opportunities.

Aerosols – Small particles or droplets in the atmosphere which are both natural and anthropogenic. Their net effect is a direct cooling influence on climate by reflecting sunlight back into space. The increase of aerosols in the atmosphere is thought to be masking the upward trend in global temperatures. They also have an indirect effect by acting as condensation nuclei to increase cloud formation.

Anthropogenic – Resulting from or produced by human activities, in particular, factors that affect the atmosphere due to burning of fossil fuels, deforestation and other land-use change.

Carbon cycle – Description of the movement of carbon in various forms (for example, as carbon dioxide or methane) through the atmosphere, ocean, plants, animals and soils.

Carbon dioxide equivalency (CO_2–e) – A measure that allows comparison of different greenhouse gases to carbon dioxide in terms of their global warming potential. Methane has a global warming potential 25 times that of CO_2.

Climate –The atmospheric conditions over a long time interval, generally referring to the average state of the weather for a particular area.

Climate change – A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability over comparable time periods.

Coral bleaching – A process that occurs when the coral host expels its symbiotic zooxanthellae (microscopic algae that live in the coral's tissues and provide energy to the coral) in response to stress. Most commonly resulting from prolonged high water temperatures, but also from high light levels, sedimentation, pollutants and changes in salinity. The pigments of the zooxanthellae give corals much of their colour and when the zooxanthellae are expelled, the coral's white skeleton is visible through the transparent tissues of the coral, hence the term 'bleaching'.

CSIRO – The Commonwealth Scientific and Industrial Research Organisation, Australia's national science agency.

El Niño Southern Oscillation (ENSO) – Year-to-year oscillations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (the warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. Over much of Australia La Niña tends to bring above average rain, and El Niño tends to bring below average rainfall. A common measure of ENSO is the Southern Oscillation Index (SOI) which is normalised mean sea level pressure difference between Tahiti and Darwin. The SOI is positive during La Niña events and negative during El Niño events.

Emission – Amount of substance (e.g. CO_2) released into the atmosphere from a specific source and in a specific time frame. Emissions are generally expressed by the mass per time period (e.g. millions of tonnes (Mt) per year).

Emissions scenario – A plausible future pathway of human-made emissions (e.g. greenhouse gases and other pollutants) that can affect climate, based on a consistent set of assumptions about factors such as demographic and socioeconomic development, technology change and their key relationships.

Enhanced greenhouse effect – The addition of anthropogenic greenhouse gases that bolster the natural greenhouse effect increasing the surface temperature of the Earth.

Extreme weather event – An infrequent event, here specifically related to weather, at the high and low end of the range of values of a particular variable.

Global warming – An increase in global average surface temperatures due to natural or anthropogenic climate change.

Global warming potential (GWP) – The index used to translate the level of emissions of greenhouse gases into a common measure in order to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations.

Greenhouse effect – An effect created by greenhouse gases in the Earth's atmosphere. These gases allow short-wavelength (visible) solar radiation to pass through to the surface and absorb the long-wavelength radiation that is reflected back, leading to a warming of the surface and lower atmosphere.

Greenhouse gases – Natural and anthropogenic gases in the atmosphere that absorb and emit infra-red or heat radiation, causing the greenhouse effect. The main greenhouse gases are water vapour, carbon dioxide, nitrous oxide and methane.

Hadley cell – The process by which an air mass undergoes convergence at the tropics and divergence at 30 °C N or 30 °C S latitude in one large convection cell.

Hot days – Days with maximum temperature over 35 °C.

Indian Ocean Dipole (IOD) – The difference between sea-surface temperature in the western and eastern tropical Indian Oceans. A positive IOD occurs when the western basin is warmer than average and the eastern basin is cool.

Inter-decadal Pacific Oscillation (IPO) – An irregular inter-decadal cycle of rising and falling sea-surface temperatures in the Pacific Ocean which modulates the strength of the ENSO.

Madden-Julian Oscillation (MJO) – A tropical atmospheric phenomenon, with a timescale ranging from 30 to 60 days which develops over the Indian Ocean and travels eastward through the tropics.

Mitigation – A lessening in force or intensity; specifically used to describe a reduction in the source of greenhouse gases or enhancement of greenhouse gas sinks.

Ocean acidification – Increase in acidity of sea water forms carbonic acid due to the increased uptake of CO_2 emissions by the Earth's oceans. Increased acidity lowers the pH of the ocean and causes acidification.

Radiative (climate) forcing – Radiative forcing is a measure of the change in the energy balance of the atmosphere. It is also used as an index of the influence a factor has as a potential climate change mechanism. A positive radiative forcing increases the energy of the Earth–atmosphere system, leading to a warming of the system. In contrast, a negative radiative forcing decreases the energy, leading to a cooling of the system.

Sequestration – Removal of carbon from the atmosphere by, and storage in, terrestrial or marine reservoirs.

Southern Annular Mode (SAM) – Refers to the north–south movement of the band of westerly winds south of Australia. SAM is positive when there is a poleward shift of the westerly wind belt and is associated with enhanced spring and summer rainfall in New South Wales and Queensland.

Storm surge – A temporary increase, at a particular location, in the height of the sea, due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The excess above the level expected from the tidal variation alone at that time and place.

Storm tide – The absolute combined mean water level reached when storm surge is combined with the normal astronomical tide variation and the wave contribution at the coast. It is the storm tide level which must be accurately predicted to determine the extent of coastal inundation.

Stratosphere – The region the atmosphere above the troposphere. The stratosphere is characterised by the presence of ozone and by temperatures which rise slightly with altitude, due to the absorption of ultraviolet radiation.

Sub-Tropical Ridge (STR) – A ridge of high pressure which moves north and south of Australia depending on the time of year. During the southern hemispheric summer (November to April), the ridge is located south of the Australian continent. During autumn it moves north and remains over the Australian continent for most of the colder half of the year (May to October).

Tipping point – A specific threshold point or unstable state where the response of a climate effect or perturbation can be sudden, severe and have long-term consequences for the climate system.

Thermal expansion – The increase in volume (and decrease in density) that results from expansion of warming water. A warming of the ocean leads to an expansion of the ocean volume and hence to sea level rise.

Troposphere – The lowest region of the atmosphere within which nearly all cloud formations occur and weather conditions manifest themselves. In the troposphere, temperatures decrease with increasing altitude.

Walker circulation – The east–west movement of trade winds across the tropical Pacific Ocean, bringing moist surface air to the west with dry air returning along the surface to the east.

Weather – The state of the atmosphere at a particular place, at a particular time.

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APPENDIX 5 – CLIMATE COMMISSION –

THE CRITICAL DECADE

CLIMATE
COMMISSION

THE CRITICAL DECADE

Climate science, risks and responses

Contents

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Preface

With critical decisions to be made in 2011 on responses to climate change, I hope that this report provides useful information from the scientific community to a wide range of audiences – our political leaders, the general public, the private sector, NGOs, and the media. More specifically, the aim of this report is to provide up-to-date information on the science of climate change and the implications of this knowledge for societal responses, both for mitigation strategies and for the analysis of and responses to risks that climate change poses for Australia.

Over the past two years, a large number of excellent reviews and syntheses of climate change science have been produced by academies of science, by groups of experts, and as outcomes of major international meetings. Much of this information is still current, and I have drawn heavily on it for this report; a list of these documents is given below. Scientific knowledge on climate change is continuously evolving, however, and I have also included information from key papers published in recent months.

I have tried to be as brief as possible in treating the various topics covered in this report, with the aim of providing the key points only. For interested readers, further information on the topics covered can be found in the reports listed below, and, of course, from the original sources of information in the peer-reviewed literature. These are presented in the reference list at the end of this report and in similar lists at the end of the reports below.

At several places in this report, I have made my own syntheses and judgements based on large bodies of work where there is no clear consensus in the peer-reviewed literature. As an example, on my reading of the literature to date and on discussions with experts, I expect the magnitude of global average sea-level rise in 2100 compared to 1990 to be in the range of 0.5 to 1.0 metre. For this and other such judgements, I take full and sole responsibility.

This report has been extensively reviewed by 15-20 colleagues from CSIRO, the Bureau of Meteorology and the university sector. They are all widely recognised experts in their fields of climate science, and I am grateful for the care and thoroughness with which they read and commented on earlier drafts of the report.

I also thank my colleagues on the Science Advisory Panel of the Climate Commission, who critically reviewed drafts of the report.

During the preparation of this report, I have worked closely with Professor Ross Garnaut and his team as they have undertaken their update of climate science. I appreciated the availability of earlier drafts of their update, and for the opportunity for frequent discussions on particularly topical and contentious areas of climate science.

I am grateful to many colleagues in the Department of Climate Change and Energy Efficiency for many useful discussions and for ongoing support of various kinds.

Will Steffen
Climate Commissioner
Canberra
May 2011

THIS UPDATE REVIEWS WHAT THE SCIENCE IS TELLING US ABOUT THE NEED TO ACT ON CLIMATE CHANGE, AND THE RISKS OF A CHANGING CLIMATE TO AUSTRALIA.

Sources that were drawn upon in the compilation of this report

Australian Academy of Science (AAS). (2010). *The Science of Climate Change: Questions and Answers*. August 2010. www.science.org.au/policy/climatechange2010.html

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Richardson, K., Steffen, W., Schellnhuber, H.-J., Alcamo, J., Barker, T., Kammen, D.M., Leemans, R., Liverman, D., Munasinghe, M., Osman-Elasha, B., Stern, N. and Waever, O. (2009). *Synthesis Report. Climate Change: Global Risks, Challenges & Decisions*. Summary of the Copenhagen Climate Change Congress, 10-12 March 2009. University of Copenhagen, 39 pp.

Richardson, K., Steffen, W., Liverman, D., Barker, T., Jotzo, F., Kammen, D., Leemans, R., Lenton, T., Munasinghe, M., Osman-Elasha, B., Schellnhuber, J., Stern, N., Vogel, C., and Waever, O. (2011). *Climate Change: Global Risks, Challenges and Decisions*. Cambridge: Cambridge University Press, 501 pp.

Royal Society (UK). (2010). *Climate change: a summary of the science*. London: The Royal Society, September 2010, 17 pp.

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WBGU (German Advisory Council on Global Change). (2009). *Solving the Climate Dilemma: The Budget Approach*. Special Report. Berlin: WBGU Secretariat, 54 pp.

Over the past two or three years, the science of climate change has become a more widely contested issue in the public and political spheres. Climate science is now being debated outside of the normal discussion and debate that occurs within the peer-reviewed scientific literature in the normal course of research. It is being attacked in the media by many with no credentials in the field. The questioning of the Intergovernmental Panel on Climate Change (IPCC), the "climategate" incident based on hacked emails in the UK, and attempts to intimidate climate scientists have added to the confusion in the public about the veracity of climate science.

By contrast to the noisy, confusing "debate" in the media, within the climate research community our understanding of the climate system continues to advance strongly. Some uncertainties remain and will continue to do so, given the complexity of the climate system, and the impossibility of knowing the future pathways of human political, social and technological changes. Meanwhile there is much climate change science that is now well and confidently understood, and for which there is strong and clear evidence.

THE EVIDENCE THAT THE EARTH'S SURFACE IS WARMING RAPIDLY IS NOW EXCEPTIONALLY STRONG, AND BEYOND DOUBT. EVIDENCE FOR CHANGES IN OTHER ASPECTS OF THE CLIMATE SYSTEM IS ALSO STRENGTHENING. THE PRIMARY CAUSE OF THE OBSERVED WARMING AND ASSOCIATED CHANGES SINCE THE MID-20TH CENTURY – HUMAN EMISSIONS OF GREENHOUSE GASES – IS ALSO KNOWN WITH A HIGH LEVEL OF CONFIDENCE.

However, the behaviour of several important components or processes of the climate system, including some associated with serious risks such as sea-level rise and changes in water resources, are much less well understood and are the subject of intense scientific research and debate.

The purpose of this update is to review the current scientific knowledge base on climate change, particularly with regard to (i) the underpinning it provides for the formulation of policy and (ii) the information it provides on the risks of a changing climate to Australia.

The first chapter of the update focuses on the fundamental understanding of the climate system, which is an important element in framing and informing the formulation of policy. The analysis starts with observations of the climate system and how it is changing, followed by the reasons for these observed changes. It then focuses on the behaviour of the carbon cycle, which is the primary process in the climate system that policy aims to influence. Finally, the often confusing issue of certainty in climate science is explored, with an emphasis on what is known with a high degree of certainty but also where considerable uncertainty remains about important features of the climate system.

Chapter 2 describes some of the most significant risks that are associated with a changing climate. The section is focussed strongly on the implications of our understanding of the climate system for risk assessments, but does not attempt to undertake the sector-by-sector risk assessments themselves. While it is clear that climate change has potential impacts on a wide range of sectors – human health, agriculture, settlements and infrastructure, tourism, biodiversity and natural ecosystems, and others – many other non-climatic factors affect the risks that these sectors face and the outcomes that eventually occur.

For example, there is little doubt that extreme weather events such as bushfires and floods have significant impacts on human health and well-being. The 2011 Queensland floods have led to long-term, mental health and related problems, such as depression, bereavement, post-traumatic stress disorders and other mood and anxiety disorders; and the 2009 Victorian bushfires also led to considerable psychological distress, some of it prolonged, to those who experienced the fires and survived (A.J. McMichael, personal communication). Such extreme weather events have occurred before the advent of human-induced climate change, and the degree to which climate change affects risks associated with extreme events is a very active area of research.

In addition to the intensity of the weather event itself, the severity of the Queensland floods were affected by several other factors, many of which are not related to climate. These include the land cover and condition of catchments and the efficacy of protective structures such as dams. The ultimate health outcomes were additionally influenced by the vulnerability of individuals and communities and the effectiveness of warnings and of emergency management actions.

The Great Barrier Reef, an oft-cited example of an iconic natural ecosystem vulnerable to the potential impacts of climate change, illustrates the importance of considering multiple, interacting stresses and not climate change in isolation. While climate-related risks for coral reefs, such as temperature extremes and increasing ocean acidity, have been widely documented and some are well understood (e.g., Hoegh-Gulberg et al. 2007), other non-climatic factors are also critical for maintaining coral reefs as well-functioning ecosystems. These include overfishing and declines in water quality (Bryant et al. 1998), as well as pollutants, low salinity, turbidity, sedimentation and pathogens, which put further pressure on reefs (Anthony et al. 2007). Thus, risk assessments for particular sectors, such as human health and natural ecosystems, are best undertaken by experts for the particular sector, drawing on the insights that climate science can offer as well as on non-climate knowledge and information.

This chapter aims to provide an up-to-date synthesis of our scientific understanding of five major aspects of the climate system that are important for risk assessments across many sectors. These are: (i) sea-level rise; (ii) ocean acidification; (iii) the water cycle; (iv) extreme events; and (v) abrupt, non-linear and irreversible changes in the climate system.

Finally, Chapter 3 provides a link between the science of climate change and the policy options for reducing emissions of greenhouse gases, particularly carbon dioxide (CO_2). The approach taken here circumvents the complexity and confusion of the targets/timetables/baselines approach by turning to a much simpler budget – or aggregate emissions – analysis. The approach directly relates the further amount of emissions, in billions of tonnes of CO_2, that global society can emit to achieve a particular temperature limit, such as 2 °C above the pre-industrial level.

Each chapter opens with a brief introductory paragraph presenting the main thrust of the section, followed by a series of short bulleted statements. These are brief, summary statements without references. Each of these statements is supported by more detailed text, with references and figures, in the main body of each section.

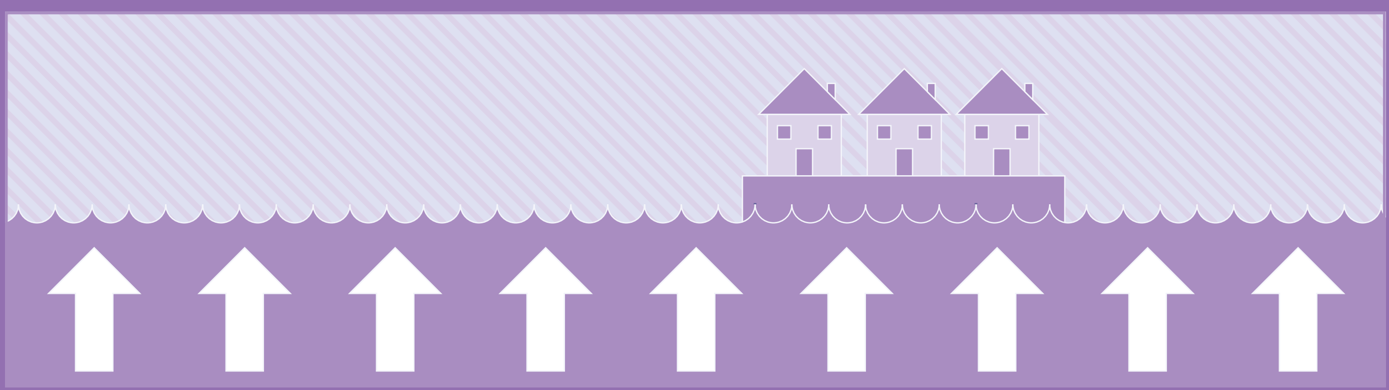
CHAPTER 1: DEVELOPMENTS IN THE SCIENCE OF CLIMATE CHANGE

DID YOU KNOW...

FOR THE MOST RECENT 10-YEAR PERIOD (2001-2010), GLOBAL AVERAGE TEMPERATURE WAS 0.46 °C ABOVE THE 1961-1990 AVERAGE, THE WARMEST DECADE ON RECORD.

85%

MORE THAN 85% OF THE ADDITIONAL HEAT DUE TO THE ENERGY IMBALANCE AT THE EARTH'S SURFACE IS ABSORBED BY THE OCEAN (IPCC 2007a).



GLOBAL SEA LEVEL HAS RISEN BY ABOUT 20 CM SINCE THE 1880s, WHEN THE FIRST GLOBAL ESTIMATES COULD BE MADE.

1.1 Observations of changes in the climate system

Recent observations of changes in the climate system strengthen the conclusions of the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (2007a) and the Garnaut Review (2008) that contemporary climate change is indeed real, and is occurring at a rapid rate compared with geological time scales. From a human perspective, the rate of climate change is already discernible to the present generation, and will be even more prominent in the lives of our children and grandchildren. It is leading to significant risks today, and more serious risks in the coming decades, as described in Chapter 2.

In this section the focus is on evidence for the long-term warming trend, while other changes in the climate system – extreme events, the water cycle and abrupt changes, for example – are treated in the discussion of climate risks in Chapter 2. The main conclusions of this section are:

- The average air temperature at the Earth's surface continues on an upward trajectory at a rate of 0.17 °C per decade over the past three decades.
- The temperature of the upper 700 m of the ocean continues to increase, with most of the excess heat generated by the growing energy imbalance at the Earth's surface stored in this compartment of the system.
- The alkalinity of the ocean is decreasing steadily as a result of acidification by anthropogenic CO_2 emissions.
- Recent observations confirm net loss of ice from the Greenland and West Antarctic ice sheets; the extent of Arctic sea ice cover continues on a long-term downward trend. Most land-based glaciers and ice caps are in retreat.
- Sea-level has risen at a higher rate over the past two decades, consistent with ocean warming and an increasing contribution from the large polar ice sheets.
- The biosphere is responding in a consistent way to a warming Earth, with observed changes in gene pools, species ranges, timing of biological patterns and ecosystem dynamics.

Surface air temperature

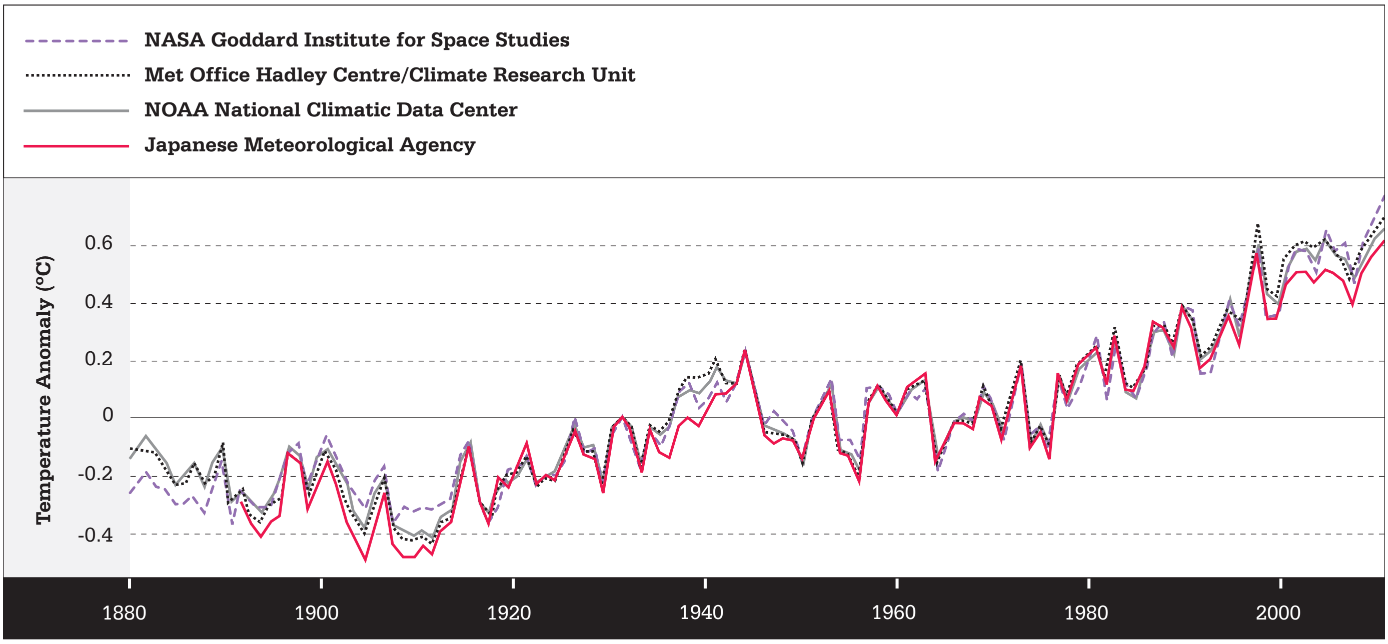
The average temperature at the Earth's surface has continued to increase. The global combined land and sea surface temperature (SST) for 2010 was 0.53 °C above the 1961-1990 average (WMO 2011) and thus 2010 ranks amongst the three warmest years on record.

FOR THE MOST RECENT 10-YEAR PERIOD (2001-2010), GLOBAL AVERAGE TEMPERATURE WAS 0.46 °C ABOVE THE 1961-1990 AVERAGE, THE WARMEST DECADE ON RECORD.

However, time series of at least three decades – and preferably much longer – are required to differentiate with confidence a long-term climatic trend from shorter term variability. Figure 1 shows the global average temperature record from the late 19th century to the present. Over the last three decades, the rate of warming has been 0.17 °C per decade, a very high rate from a geological perspective.

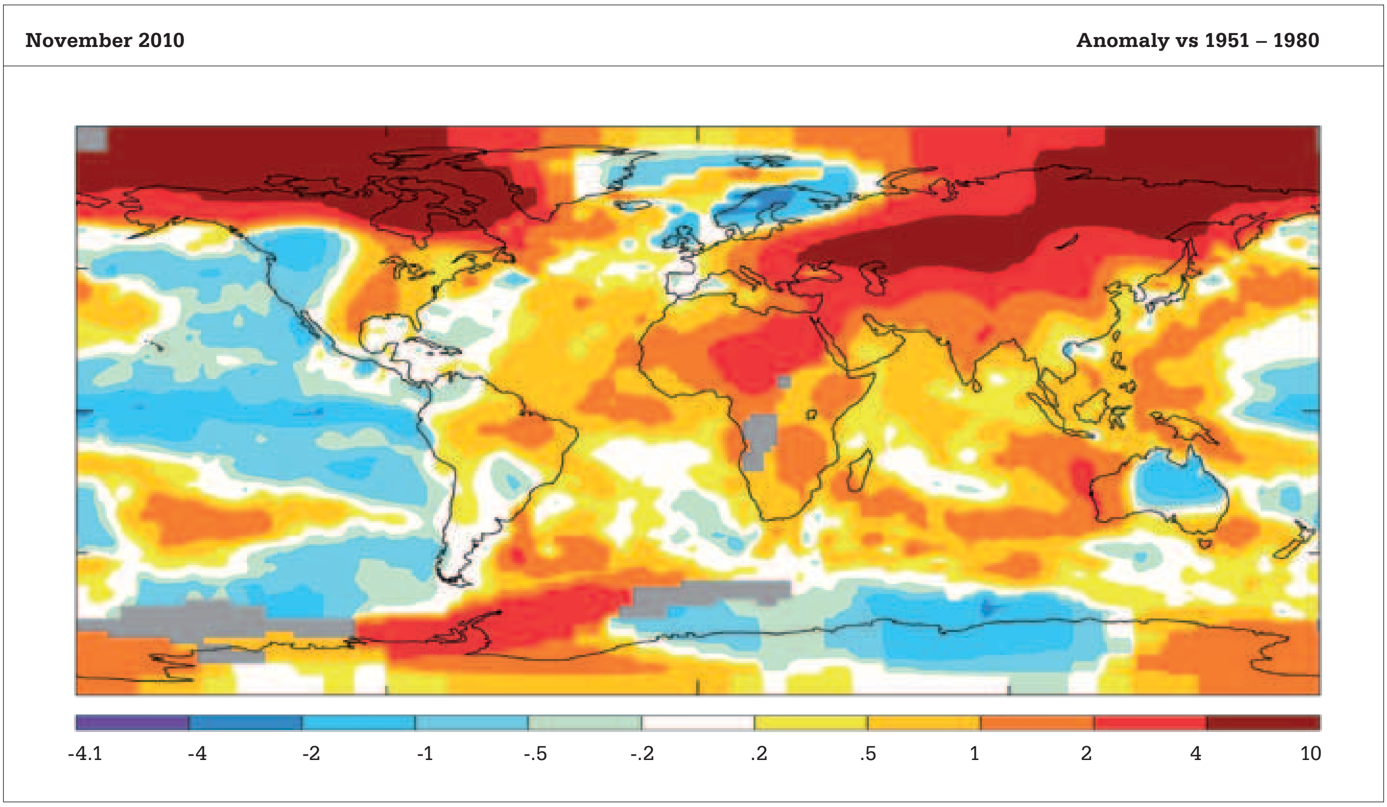
There has been considerable confusion in the media and in the public between shorter term patterns of variability in climate and weather and longer term (multi-decadal) trends in climate. The problem is the inappropriate tendency to expect weather patterns and changes over short time periods and in particular regions to always follow changes in global trends over long periods of time. An example is the extremely cold and snowy weather experienced by parts of Europe and North America in the November-December 2010 period. Does this signal an end to global warming? Absolutely not. As noted above, 2010 was one of the three warmest years on record. Furthermore, the month of November 2010 was exceptionally warm, with extremely high temperatures around the northern high latitudes more than compensating for the cold, snowy weather in western Europe and parts of North America (Figure 2).

Figure 1. Surface air temperature trend from the 1880s to the present. The baseline for the analysis is the 1951-1980 average.



Source: NASA GISS Surface Temperature Analysis.

Figure 2. Global map of surface temperature anomalies for November 2010 showing the unusually cold conditions in parts of Europe and North America but the extreme warmth in other parts of the northern hemisphere.



Source: NASA GISS Surface Temperature Analysis.

Ocean temperature

Although there is a very strong focus on air and sea surface temperature in both the climate research community and the general public, ocean temperature is a better measure of changes in the climate system.

MORE THAN 85% OF THE ADDITIONAL HEAT DUE TO THE ENERGY IMBALANCE AT THE EARTH'S SURFACE IS ABSORBED BY THE OCEAN (IPCC 2007a).

Since the 1960s measurements of the heat content of the upper 700 m of the ocean have been available, and since 2004, measurements to lower depths (up to 2 km) have become widely available with the deployment of Argo floats (Gould and the Argo Science Team 2004).

Figure 3 shows the record of ocean thermal expansion from 1950 through 2008, showing the clear long-term trend of warming (Domingues et al. 2008, and updates). The Domingues et al. updated curve in this figure, which uses the carefully checked and corrected Argo data of Barker et al. (2011), indicates that multi-decadal warming has continued to the end of the record in December 2008 (Church et al. 2011). This record is quantitatively consistent with the observed rate of sea-level rise over the past half-century. Although most of the additional heat stored in the ocean is found in the upper 700 m, recent observations show that warming of the deeper ocean waters in both the Southern and Atlantic Oceans is now occurring (Purkey and Johnson 2010).

Ocean acidification

Increasing the atmospheric concentration of CO_2 leads to more dissolution of CO_2 in surface ocean waters, increasing their acidity (decreasing their alkalinity) via the formation of carbonic acid. Through a series of chemical reactions, increasing the concentration of carbonic acid reduces the concentration of carbonate ions in seawater (Kleypas et al. 2006). This process has implications for marine organisms that form calcium carbonate shells (see Section 2.2). Observations of the acidity of the ocean's surface waters show the expected decrease of about 0.1 pH unit since the pre-industrial era (Guinotte et al. 2003).

Sea ice and polar ice sheets

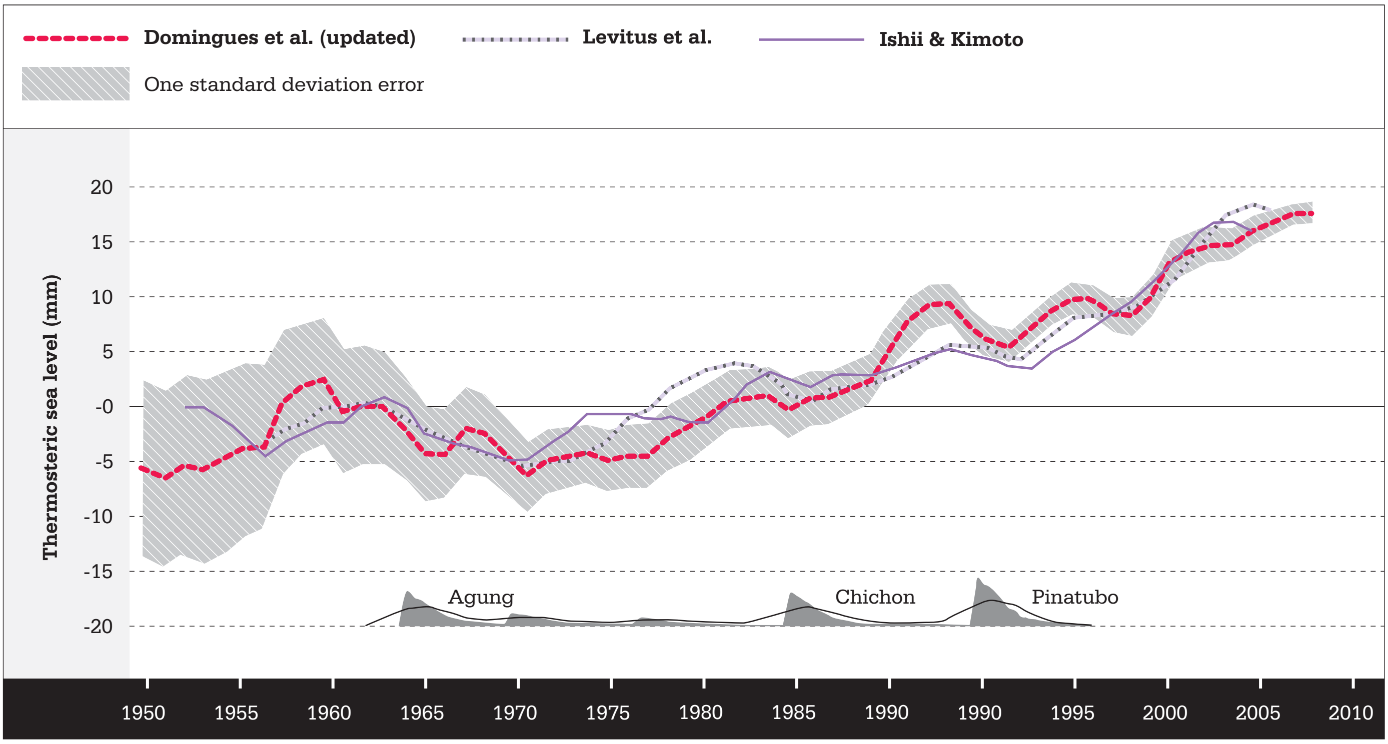
Evidence from the cryosphere (snow, ice and frozen ground) is consistent with the warming of the surface of the Earth. The most striking evidence comes from the northern high latitudes, where the sea ice covering the Arctic Ocean has decreased significantly over the last several decades (Figure 4). Changes to the sea ice surrounding Antarctica are more complex, with no appreciable change in overall extent over the past several decades.

The large polar ice sheets on Greenland and West Antarctica, which are important factors influencing sea-level rise, are currently losing mass to the ocean through both melting and dynamical ice loss; that is, by break-up and calving of blocks of ice. However, there is considerable uncertainty about the rate at which the latter process is occurring. In addition, these trends are often based on shorter term observational records (often the last 10-15 years), and it is not entirely clear whether these are long-term trends that will be maintained into the future or are at least partly the result of natural decadal-scale variability (e.g., Rignot et al. 2008).

Over the past decade one of the most common observational tools for estimating changes in ice mass is the GRACE satellite gravity technique, which estimates the loss of mass from changes in the gravity field. GRACE measurements have been prominent in confirming a trend of ice loss from polar ice sheets, especially Greenland (Figure 5). However, the GRACE observational technique itself is complex with significant uncertainties; a recent re-analysis of the Greenland gravity change data suggests that the rate of ice loss has been overestimated by a factor of two (Bromwich and Nicolas 2010; Figure 6).

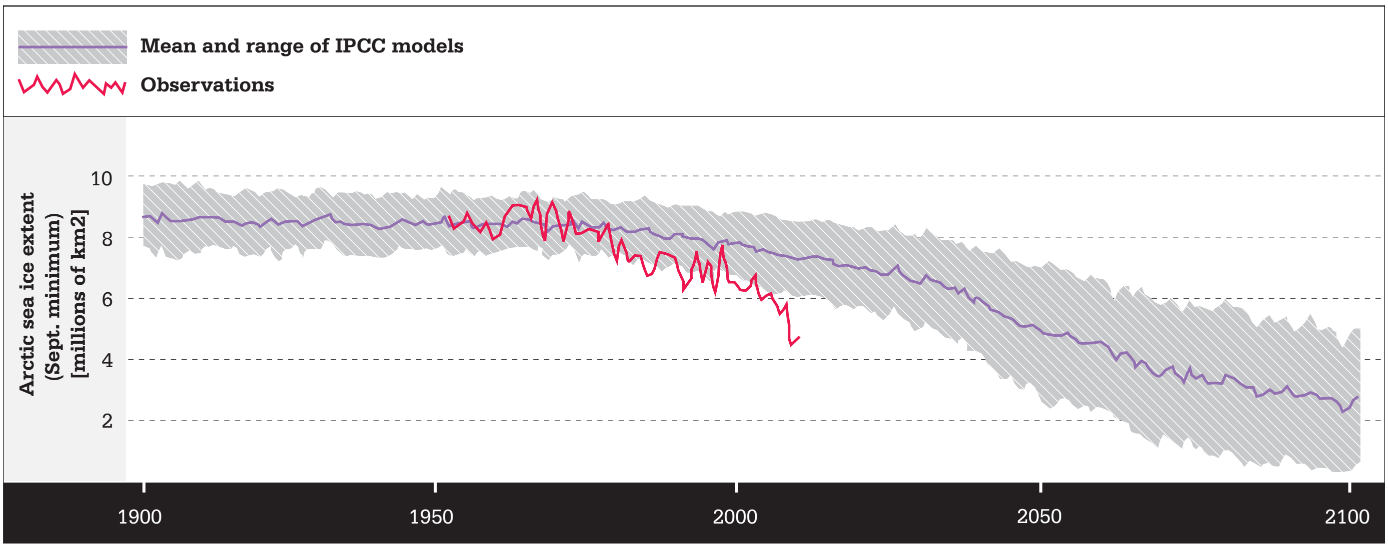
Nevertheless, a synthesis of all observations shows that there is a net loss of mass from the Greenland (and West Antarctic) ice sheets; the uncertainty refers to the rate at which this ice loss is occurring, with some evidence that this rate of loss may be accelerating (Rignot et al. 2011).

Figure 3. Updated estimates of ocean thermal expansion relative to 1961. The updated Domingues et al. (2008) time series is shown as a red broken line, and one standard deviation uncertainty estimates are indicated by the grey shading. The estimates for Ishii and Kimoto (2009) and Levitus et al. (2009) are shown as purple and broken purple lines respectively. The estimated stratospheric aerosol loading (arbitrary scale) from the major volcanic eruptions is shown at the bottom.



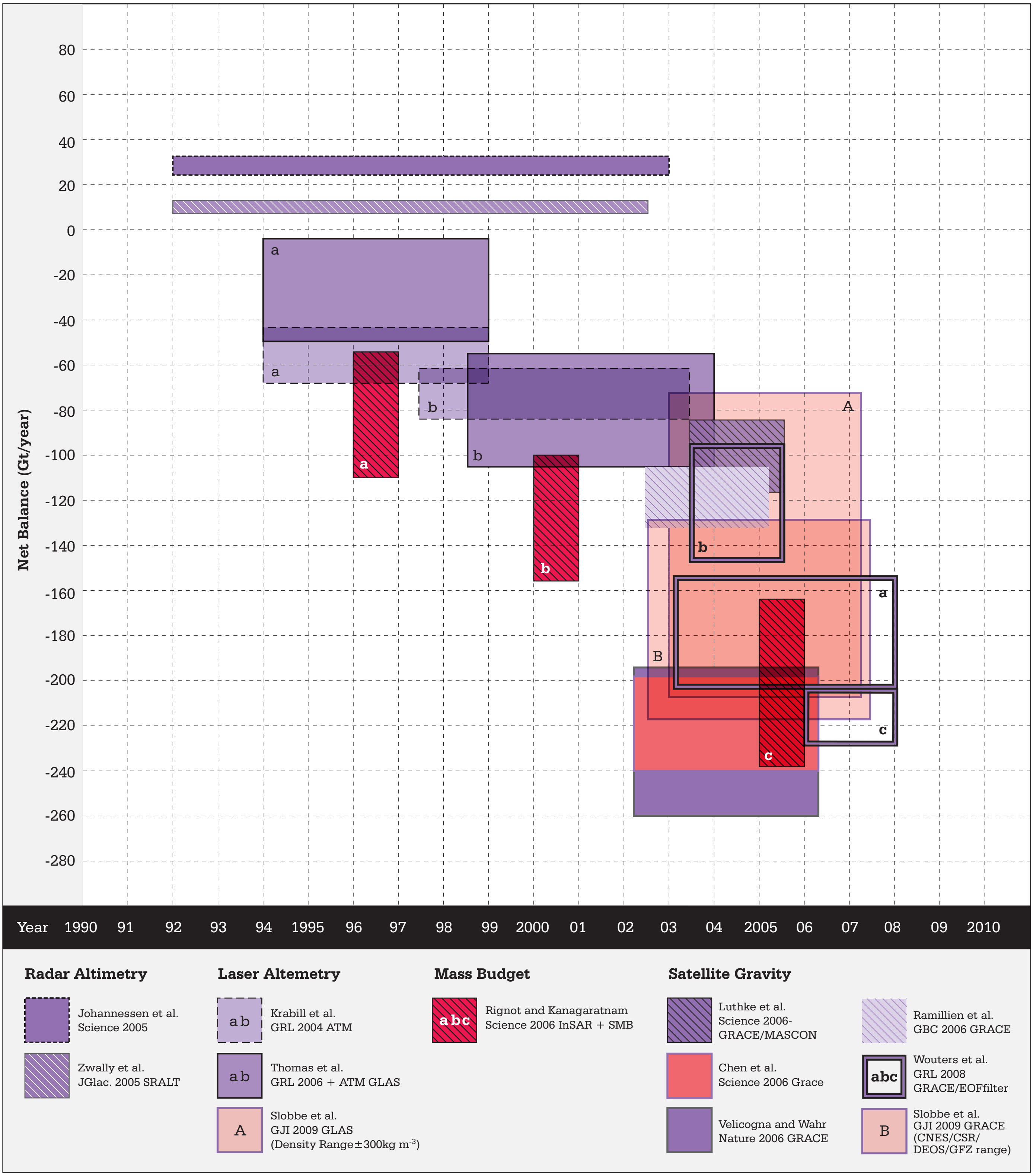
Source: Church et al. (2011).

Figure 4. Observed (red line) and modelled September (end of summer) Arctic sea ice extent in millions of square kilometres. The solid purple line is the ensemble mean of the 13 IPCC AR4 models and the edges of the grey shaded area represent the range of model projections.



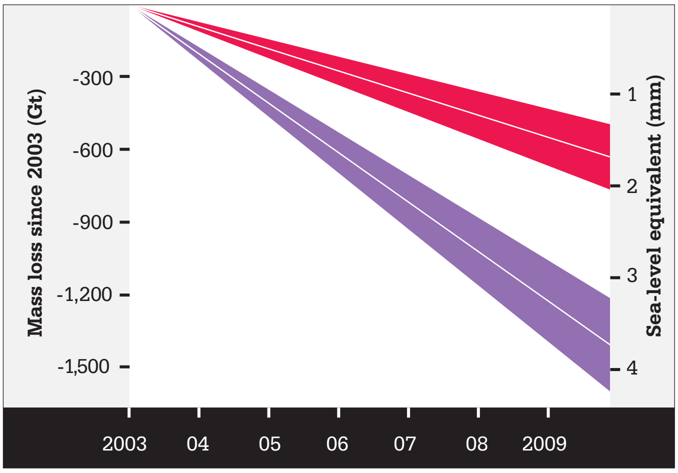
Source: Stroeve et al. (2007), updated to include data for 2008.

Figure 5. Results from the recent large area total mass balance measurements of the Greenland ice sheet, placed into common units and displayed versus the time intervals of the observations. The heights of the boxes cover the published error bars or ranges in mass change rate over those intervals.



Source: AMAP (2009), which includes references to the individual data sets shown in the figure.

Figure 6. Cumulative mass loss of the Greenland ice sheet. The estimate by Wu et al. (2010) of mass loss since 2003 (red) is considerably lower than an earlier predicted value (Velicogna 2009) (purple), owing in part to larger than previously estimated subsidence rates of underlying bedrock. The curves and their differences can thus be interpreted in terms of contribution to global mean sea level (right-hand vertical axis). The shaded areas reflect uncertainties.



Source: Bromwich and Nicolas (2010).

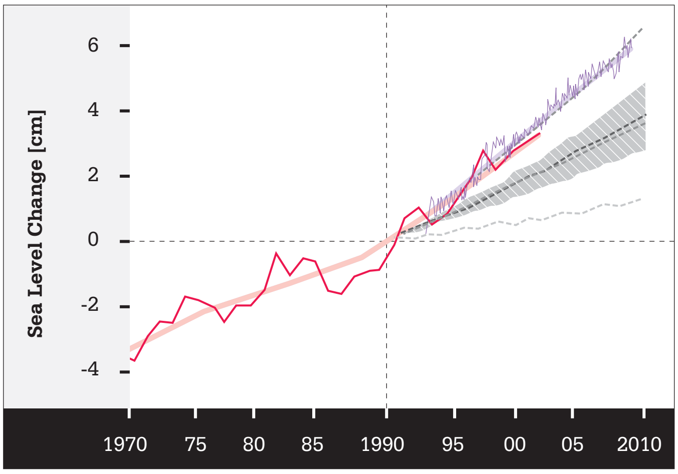
Land-based glaciers and ice caps

Most glaciers and mountain ice-caps around the world have been in retreat the past century and are estimated to be contributing about 0.8 mm per year to sea level rise at the beginning of this century (IPCC 2007a). Glaciers and ice caps are not yet in equilibrium with the present climate, and that adjustment would lead to a mass loss equivalent to another 18 cm sea-level rise (Bahr et al. 2009). However, the climate is still warming and will almost surely continue to warm through this century, with current warming trends leading to an estimated mass loss equivalent to about 55 cm of sea-level rise by the end of the century (Pfeffer et al. 2008).

Sea-level rise

Global sea level has risen by about 20 cm since the 1880s, when the first global estimates could be made. The rate of increase has risen to about 3.2 mm yr[1] for the 1993-2009 period, based on satellite altimeter data (Cazenave et al. 2009; Domingues et al. 2008; Church and White 2011), compared to a rate of 1.7 mm yr[1] for the 1900-2009 period (Church and White 2011). Figure 7 shows a comparison of the observed sea-level rise to projections from climate models, which first became available in 1990 and were summarised in the two most recent IPCC reports (2001; 2007a). Observed sea level since 1993 is tracking near the upper end of the model projections, pointing towards significant risks of sea-level related impacts in the 21st century (see Section 2.1).

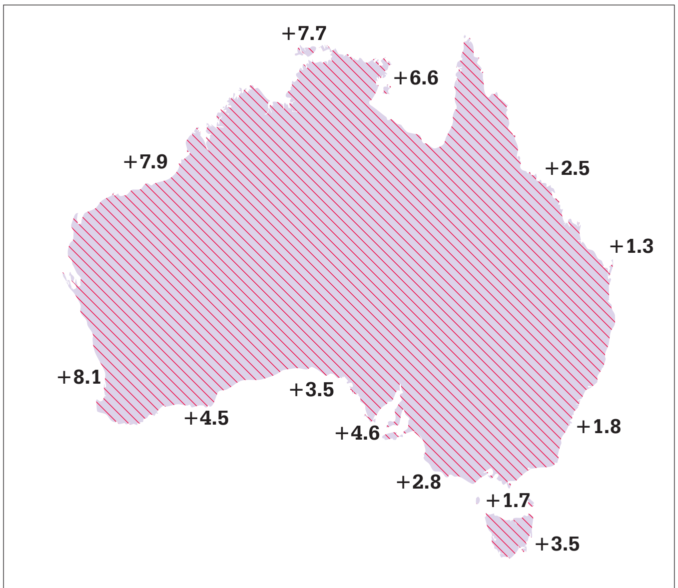
Figure 7. Sea-level change from 1970 to 2008. The thin red line from 1970 to 2002 is based on tide gauge data, and the jagged purple line from 1993 to 2008 is based on satellite data. The thick purple and red lines are running means. The envelope of IPCC projections (broken lines from 1990) are shown for comparison.



Source: after Rahmstorf et al. (2007), based on data from Cazenave and Narem (2004); Church and White (2006), Cazenave (2006) and A. Cazenave for 2006–08 data.

Several processes contribute to sea-level rise, and a quantitative budget of their relative contributions for the 1961-2003 period has been generated (Domingues et al. 2008). The budget shows that about 40% of the rise over this period can be attributed to the thermal expansion of the ocean as it warms, about 35% to the melting of continental glaciers and ice caps (e.g., the Andean and Himalayan mountain glaciers) and about 25% from the large polar ice sheets on Greenland and Antarctica. Estimates of these individual terms aggregate to a total of 1.5 +/- 0.4 mm yr^{1}, which is not significantly different from the observed rate for the same period of 1.6 +/-0.2 mm yr^{1}.

Figure 8. Local sea-level rise (mm/year) around Australia from the early 1990s to 2008.



Source: NTC 2008

Global average values of sea-level rise mask large regional differences. For example, around Australia (Figure 8) recent sea level rise (from the early 1990s to 2008) has been below the global average along the east coast, near the global average along the much of the southern coast, but at least double the global average along much of the northern coastline. Such regional differences are important in assessing the risks posed by sea-level rise at particular locations.

Terrestrial and marine biosphere

The biosphere responds to significant changes in the abiotic environment, so the long-term increase in temperature should be evident in biospheric responses.

INDEED, A CLIMATE CHANGE (WARMING) SIGNAL IS NOW CLEAR IN AN INCREASING NUMBER OF AUSTRALIAN AND GLOBAL OBSERVATIONS OF THE RESPONSES OF BIOLOGICAL SPECIES AND ECOSYSTEMS (E.G., PARMESAN 2006; ROOT ET AL. 2005; IPCC 2007b).

Australian observations that show a clear response to a climate signal, distinguishable from the responses to other stressors on ecosystems, include genetic shifts in the populations of fruit flies (Umina et al. 2005), migration of both native and feral mammals to higher elevations in alpine regions (Green and Pickering 2002; Pickering et al. 2004), the southward expansion of the breeding range of black flying foxes (Welbergen et al. 2007), earlier arrival and later departure times of migratory birds (Chambers 2005, 2008; Chambers et al. 2005) and the earlier mating and longer pairing of the large skink *Tiliqua rugosa* (Bull and Burzacott 2002).

In the marine realm responses to a warming climate have also been observed. These include southern range extension of the barrens-forming sea urchin from the mainland to Tasmania (Ling et al. 2008, 2009), significant changes in the growth rates of long-lived Pacific fish species (Thresher et al. 2007), and a southward shift in the distribution of over half of the intertidal species along the east coast of Tasmania (Pitt 2008).

Perhaps the best known marine example of response to climate change is the increase in bleaching events on the Great Barrier Reef; there have been eight mass bleaching events on the GBR since 1979 with no known such events prior to that date (Done et al. 2003).

1.2 Why is the climate system changing now?

The evidence for a long-term warming trend in Earth's climate is overwhelming. The critical question is: what is causing this warming trend, and the associated changes in the climate system?

This section explores the possible reasons for the observed warming trend by first placing contemporary climate change in a longer term perspective and then examining the various potential causes for the warming. The main conclusions are:

- There is no credible evidence that changes in incoming solar radiation can be the cause of the current warming trend.
- Neither multi-decadal or century-scale patterns of natural variability, such as the Medieval Warm Period, nor shorter term patterns of variability, such as ENSO (El Niño-Southern Oscillation) or the North Atlantic Oscillation, can explain the globally coherent warming trend observed since the middle of the 20th century.
- There is a very large body of internally consistent observations, experiments, analyses, and physical theory that points to the increasing atmospheric concentration of greenhouse gases, with carbon dioxide (CO_2) the most important, as the ultimate cause for the observed warming.
- Improved understanding of the sensitivity of the climate system to the increasing atmospheric CO_2 concentration has provided further evidence of its role in the current warming trend, and provided more confidence in projections of the level of future warming.

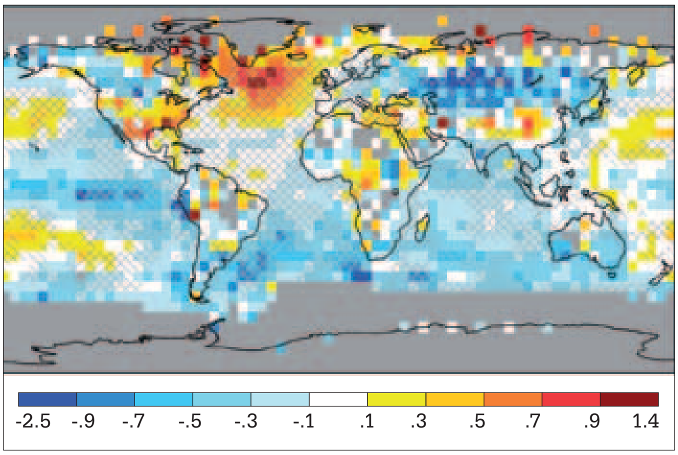
The longer-term context

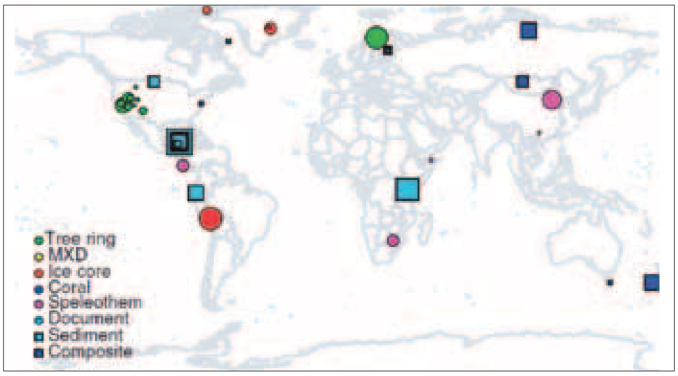
Earth has been much warmer and much colder in the distant past, but for humans the period of relevance is the last half-million years, during which fully modern humans evolved. In particular, the last 12,000 years – the Holocene – is important; during this period agriculture, villages and cities, and more complex societies and civilisations, including our current civilisation, have developed. Compared to the pattern of long ice ages and much shorter interglacial periods over the past 420,000 years (Petit et al. 1999), the Holocene has been an unusually long and stable warm period, facilitating the development of human society beyond the hunter-gatherer stage. The behaviour of the climate system during the Holocene provides a useful, human-relevant baseline against which to test possible explanations for contemporary warming.

Changes in solar radiation

Variation in the amount of solar radiation reaching the Earth has been implicated in temperature fluctuations earlier in the Holocene, for example, as a possible factor in the Medieval Climate Anomaly, often called the Medieval Warm Period (Mann et al. 2009). Variations in solar radiation have been known with better accuracy since the late 1800s, and especially in the last three to four decades, and could have contributed at most 10% to the observed warming trend in the 20th century (Lean and Rind 2008). In particular, there has been no significant change in solar radiation over the past 30 years (IPCC 2007a), when global average temperature has risen at about 0.17 °C per decade. Furthermore, *patterns* of warming over recent decades are inconsistent with solar forcing. In particular, solar forcing would produce a warming of the stratosphere, in addition to that of the troposphere. In fact stratospheric *cooling* has been observed, inconsistent with solar forcing but consistent with CO_2-dominated forcing (IPCC 2007a).

Figure 9. Reconstructed surface temperature pattern for the Medieval Climate Anomaly (MCA, 950 to 1250 C.E., sometimes called the Medieval Warm Period). Shown are the mean surface temperature anomaly (left) and associated relative weightings of various proxy records used (indicated by size of symbols) for the low-frequency component of the reconstruction (right). Anomalies are defined relative to the 1961-1990 reference period mean. Statistical skill is indicated by hatching (regions that pass validation tests at the p=0.05 level with respect to RE (CE) are denoted by / (\) hatching). Grey mask indicates regions for which inadequate long-term modern observational surface temperature data are available for the purposes of calibration and validation.





Source: Mann et al. (2009), which contains further information on methodology.

Modes of natural variability

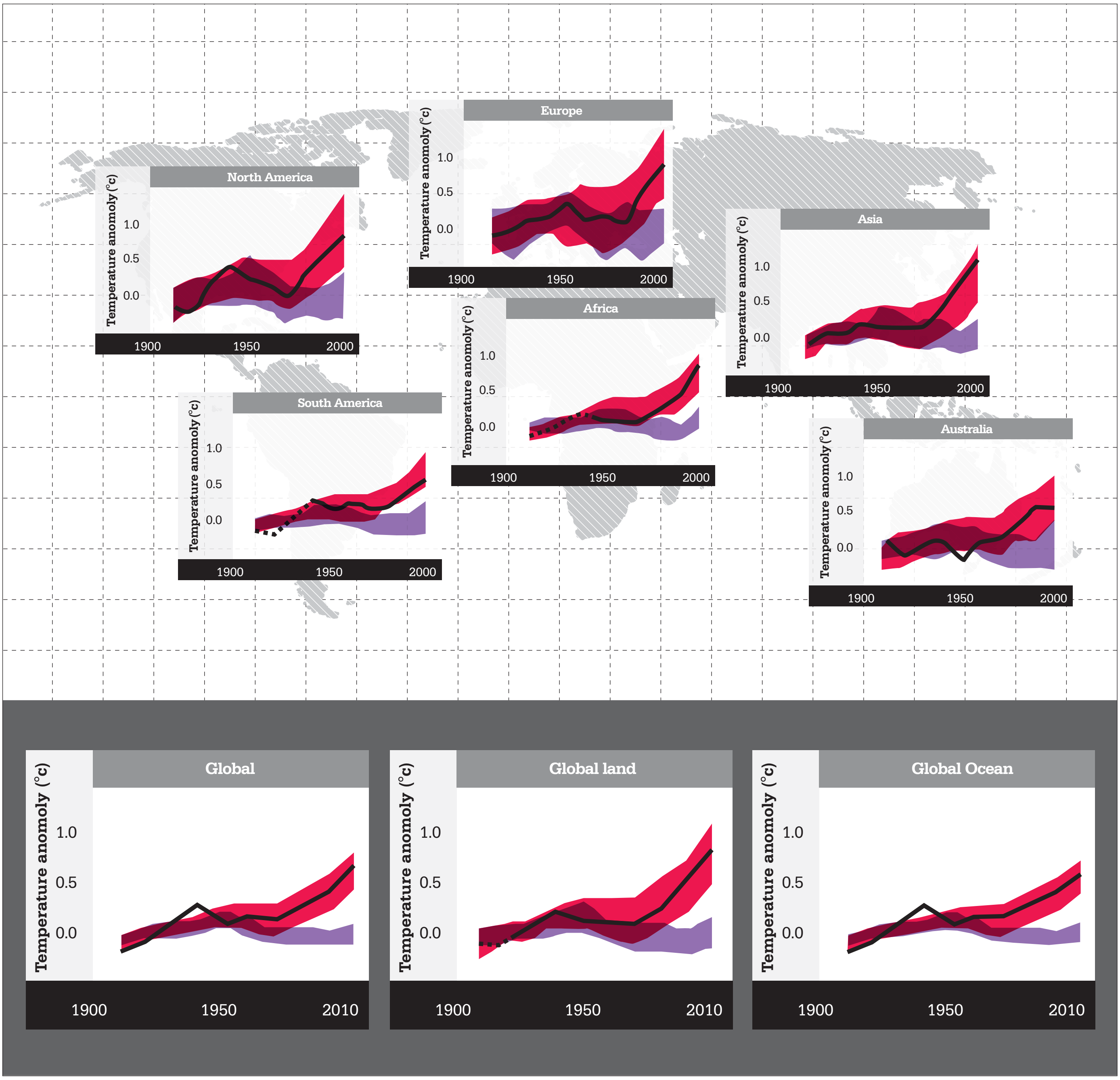
The Medieval Climate Anomaly (MCA), a somewhat warmer period from about 1000 to about 1250 or 1300 AD, has sometimes been invoked to infer that the contemporary warming is nothing unusual in the Holocene and that it is thus likely due to natural variability. However, the bulk of evidence for the MCA comes from the northern hemisphere, which makes it difficult to determine whether the MCA was truly global in scale. Furthermore, a spatially explicit synthesis of all available temperature reconstructions around the globe suggests that the MCA was highly heterogeneous, even in the northern hemisphere, with globally averaged warming much below that observed over the last century (Mann et al. 2009; Figure 9). Thus, the MCA is different in magnitude and extent from contemporary warming (Figure 10).

Shorter-term modes of natural variability, such as ENSO and the NAO (North Atlantic Oscillation), are very important influences on the weather that people experience from year to year, but they cannot explain recent multi-decadal, globally synchronous trends in temperature. Rather, such modes of natural variability are driven by changes in coupled oceanic and atmospheric circulation; in general, they redistribute heat between ocean and atmosphere as well as redistribute it geographically around the planet.

Greenhouse gas forcing

The physics by which greenhouse gases influence the climate at the Earth's surface is now very well established and accepted; it was first proposed in 1824 by Joseph Fourier, experimentally verified in 1859 by John Tyndall (Crawford 1997) and quantified near the end of the 19th century by Svante Arrhenius (Arrhenius 1896). Much research in the 20th century (e.g., Weart 2003; Fleming 2007; Revelle and Suess 1957) has strengthened the scientific basis for the theory as well as sharpened our understanding of it. For example, the very large differences in surface temperature among Earth, Venus and Mars can only be explained by the very different amounts of CO_2 in their atmospheres (Lacis et al. 2010). Also, the difference in globally averaged temperature between an ice age and a warm period, about 5-6 °C, can only be explained by changes in greenhouse gas concentrations and in the reflectivity (albedo) of the Earth's surface that amplify the original modest changes in temperature due to variations in incoming solar radiation caused by cyclical changes in the Earth's orbit around the sun (Rahmstorf and Schellnhuber 2006).

Figure 10. Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Purple shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.



Source: IPCC (2007a)

As knowledge of the greenhouse effect improves, changes in the climate system more subtle than globally averaged temperature yield patterns of change consistent with the influence of CO_2 and other greenhouse gases, and inconsistent with changes in solar radiation. Such "fingerprints of greenhouse gas forcing" include, for example, the observation that winters are warming more rapidly than summers and that overnight minimum temperatures have risen more rapidly than daytime maximum temperatures (IPCC 2007a). An apparent inconsistency between observations with greenhouse theory was the alleged failure to find a so-called "tropical hot spot", a warming in the tropical atmosphere about 10-15 km above the Earth's surface. In reality, there was no inconsistency between observed and modelled changes in tropical upper tropospheric temperatures, allowing for uncertainties in observations and large internal variability in temperature in the region. Furthermore, recent thermal wind calculations have indeed shown greater warming in the region (Allen and Sherwood 2008), confirming that there is no inconsistency and providing another fingerprint of enhanced greenhouse forcing.

Climate sensitivity

The rise in globally averaged temperature at equilibrium due to a given change in radiative forcing is known as the "climate sensitivity". In the context of human-driven climate change, climate sensitivity usually refers to the equilibrium temperature rise resulting from a doubling of CO_2 concentration (from 280 to 560 ppm; ppm = parts per million). With no other responses of the climate system (e.g. changes in water vapour, albedo or clouds), a doubling of CO_2 alone would result in around 1 °C warming – a number easily derived from well established radiation calculations. Importantly, water vapour amounts are closely tied to temperature, increasing with warming, and trapping extra heat. Theory, modelling studies and observations all strongly support there being a strong positive (reinforcing) water vapour feedback, which roughly doubles the initial warming from CO_2. Other feedbacks, due to responses from surface albedo (positive), temperature 'lapse rate' (negative) and clouds also contribute, with cloud feedbacks being the most uncertain.

SOME OF THE MOST IMPORTANT RESEARCH IN RECENT YEARS HAS REDUCED THE UNCERTAINTY SURROUNDING ESTIMATES OF CLIMATE SENSITIVITY.

Multiple simulations by climate models driven by a 560 ppm CO_2 atmosphere have generated a probability density function with most of the values for sensitivity falling between 2 and 4.5 °C and a peak near 3 °C (IPCC 2007a). An analysis of the transition of the Earth from the last ice age to the Holocene, which infers climate sensitivity from the observed change in temperature and the corresponding changes in the factors that influence radiative forcing, also estimates a value of about 3 °C (Hansen et al. 2008). Much of the uncertainty on the magnitude of climate sensitivity is associated with the direction and strength of cloud feedbacks. Recent observational evidence from short-term variations in clouds suggests that short-term cloud feedbacks are positive, reinforcing the warming, consistent with the current model-based estimates of cloud feedbacks (Clement et al. 2009; Dessler 2010).

A recent model study comparing the relative importance of various greenhouse gases for the climate estimates a sensitivity of approximately 4 °C for a doubling of CO_2 (Lacis et al. 2010). In addition, the study points to the importance of CO_2 as the principal "control knob" governing Earth's surface temperature. Although CO_2 accounts for only about 20% of Earth's greenhouse effect (other long-lived greenhouse gases account for 5% and water vapour and clouds account for 75% via their fast feedback effects), it is the one that effectively controls climate because of its very long lifetime in the atmosphere. Water vapour amounts are determined by atmospheric temperatures, which in turn are governed by concentrations of the long-lived greenhouse gases such as CO_2. In fact, without these long-lived greenhouse gases, the Earth's temperature would drop rapidly and drive the planet into an ice-bound state.

1.3 How is the carbon cycle changing?

The analysis in the previous two sections shows that (i) the Earth's surface is warming at a relatively rapid rate, and (ii) the primary reason for this warming, at least since the middle of the 20th century, is the increase in CO_2 in the atmosphere. These conclusions focus attention strongly on the carbon cycle – both how the natural carbon cycle operates and how human activities are modifying the cycle.

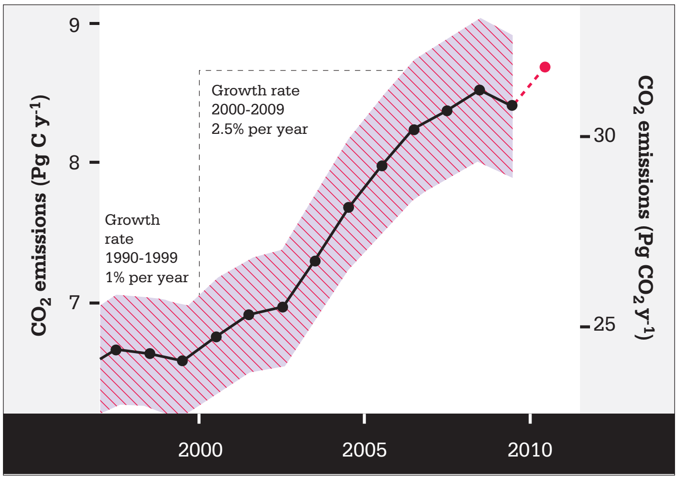
This section summarises the most recent research on changes in the behaviour of the carbon cycle and potential changes to the cycle in the future:

- Despite the dip in human emissions of greenhouse gases in 2009 due to the Global Financial Crisis, emissions continue on a strong upward trend, on average tracking near the top of the family of IPCC emission scenarios.
- Ocean and land carbon sinks, which together take up more than half of the human emissions of CO_2, appear to be holding their proportional strengths compared to emissions, although some recent evidence questions this conclusion and suggests a loss of efficiency in these natural sinks over the past 60 years.
- If global average temperature rises significantly above 2 °C (relative to pre-industrial), there is an increasing risk of large emissions from the terrestrial biosphere, the most likely source being methane stored in permafrost in the northern high latitudes.

Human emissions of CO_2

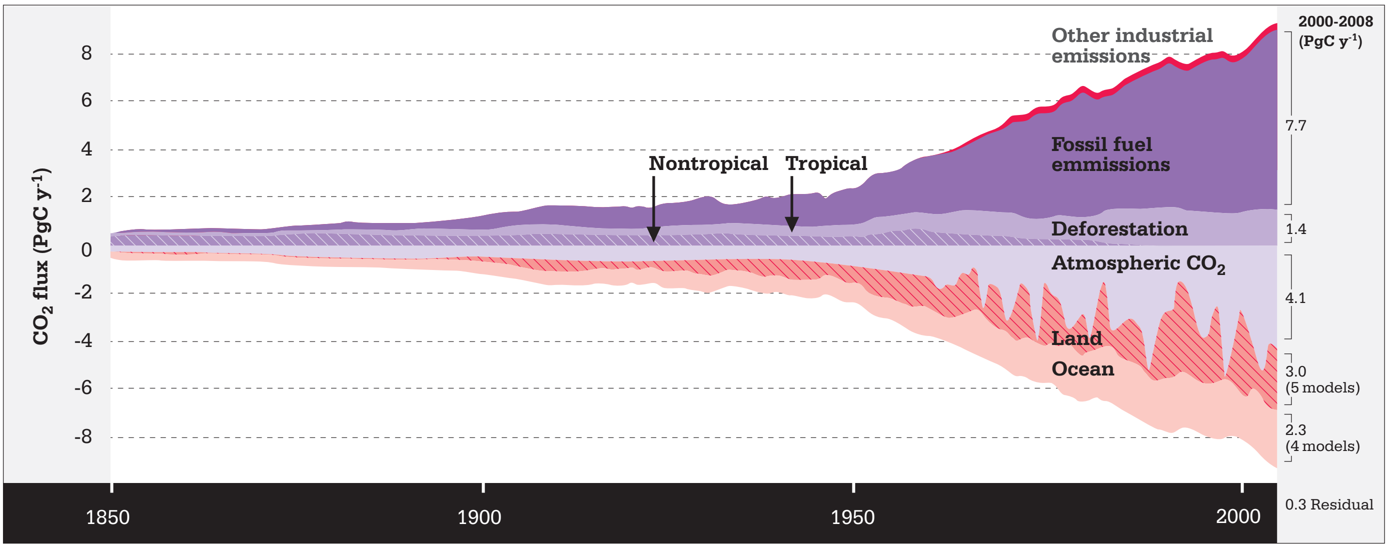
The Global Financial Crisis led to a drop in 2009 of 1.3% in the global emissions of CO_2 from fossil fuel combustion, in sharp contrast to the average annual rise in fossil fuel CO_2 emissions of 3.2% for the 2000-2008 period (Friedlingstein et al. 2010). The growth rate of emissions is expected to resume its upward trend of 3% or greater in 2010 and subsequent years, barring a further sharp economic downturn or rapid and vigorous reductions in emissions in response to climate change (Figure 11; Raupach and Canadell 2010). Given the strong rise in emissions over the past decade, current emissions are about 37% larger than those in 1990, sometimes used as the baseline against which to measure emission reductions. The current rate of emissions lies near the top of the envelope of IPCC projections (Raupach and Canadell 2010). Over the last few years, coal has overtaken oil as the largest source of CO_2 from fossil fuel combustion (Le Quéré et al. 2009: CDIAC 2010). Despite the drop in the absolute amount of emissions in 2009, the atmospheric concentration of CO_2 still rose by 1.6 ppm during the year, compared to an average growth rate of 1.9 ppm per year for the 2000-2008 period (Tans and Conway 2010).

Figure 11. Global CO_2 emissions since 1997 from fossil fuel and cement production. Emissions were based on the United Nations Energy Statistics to 2007, and on BP energy data from 2007 onwards. Cement CO_2 emissions are from the US Geological Survey. Projection for 2010 is included in red.



Source: Friedlingstein et al. (2010), and references therein.

Figure 12. Terms in the global CO_2 budget for the period 1850-2008 inclusive. Anthropogenic CO_2 emissions, shown as positive fluxes into the atmosphere, comprise contributions from fossil fuel combustion and other industrial processes, and land use change, mainly deforestation. The fate of emitted CO_2, including the accumulation of atmospheric CO_2, the land CO_2 sink and the ocean CO_2 sink, is shown by the balancing negative fluxes. Values of average fluxes for 2000-2008 (shown at right) include a small residual because all terms were estimated independently from measurements or models, without a priori application of a mass-balance constraint.



Source: Raupach and Canadell (2010), based on Le Quere et al. (2009).

Ocean and land carbon sinks

Natural sinks of carbon on land and in oceans (e.g., uptake of CO_2 by growing vegetation; dissolution of CO_2 in seawater) have historically removed over half of the human emissions from the atmosphere – for example, 57% for the 1958-2009 period (Le Quéré et al. 2009). The carbon is taken up in approximately equal proportions by land and ocean (Raupach and Canadell 2010; Figure 12), although there is considerable variability in the strength of these natural sinks from year to year, largely in response to climate variability. Over the past half-century the capability of these natural sinks has generally kept pace with the increasing human emissions of CO_2. However, there is evidence that the efficiency of these sinks is declining (Canadell et al 2007; Raupach et al. 2008; Le Quéré et al. 2009), particularly in the Southern ocean (Le Quéré et al. 2007). There are uncertainties with some of these results, and some scientific controversy over the declining trend particularly in recent years (Francey et al. 2010; Knorr 2009; Poulter et al. 2011).

The ongoing strength of these natural sinks is crucially important for the level of effort that will be required to limit climate change to no more than a 2 °C rise above pre-industrial, often referred to as the 2 °C guardrail (Council of the European Union 2005; IPCC 2007a; Copenhagen Accord 2009). This target, often quoted as defining the boundary of “dangerous” climate change, is based on value judgements, informed by scientific understanding, and has been developed through a political process. There is considerable scientific evidence (e.g., Smith et al. 2009; Richardson et al. 2011) that values of temperature rise above 2 °C are “dangerous” by most definitions, but this evidence also shows that there are significant risks of serious impacts in various sectors and locations at temperature increases of less than 2 °C. Nevertheless, the 2 °C guardrail has been a widely accepted and quoted political goal.

Vulnerable new sources of carbon

In addition to the potential weakening of the current natural carbon sinks as temperature increases, there is the potential for activating new natural sources of carbon emissions from pools that are currently inactive. Examples include methane hydrates stored under the sea floor, organic material stored in tropical peat bogs and organic material stored in permafrost in the northern high latitudes and the Tibetan plateau. Of these potential sources, the permafrost carbon is generally considered to be the most important.

THERE ARE OVER 1,700 BILLION TONNES OF CARBON STORED IN PERMAFROST (TARNOCAI ET AL. 2009), WHICH IS ABOUT TWICE THE AMOUNT STORED IN THE ATMOSPHERE AT PRESENT.

There is uncertainty about the vulnerability of this potential new source of carbon (e.g., Lawrence and Slater 2005; Lawrence et al. 2008), but there is already evidence of some loss of methane from the northern high latitudes (e.g., Dorrepaal et al. 2009). One analysis of future vulnerability assesses that about 100 billion of the 1,700 billion tonnes are vulnerable to thawing this century (Schuur et al. 2009).

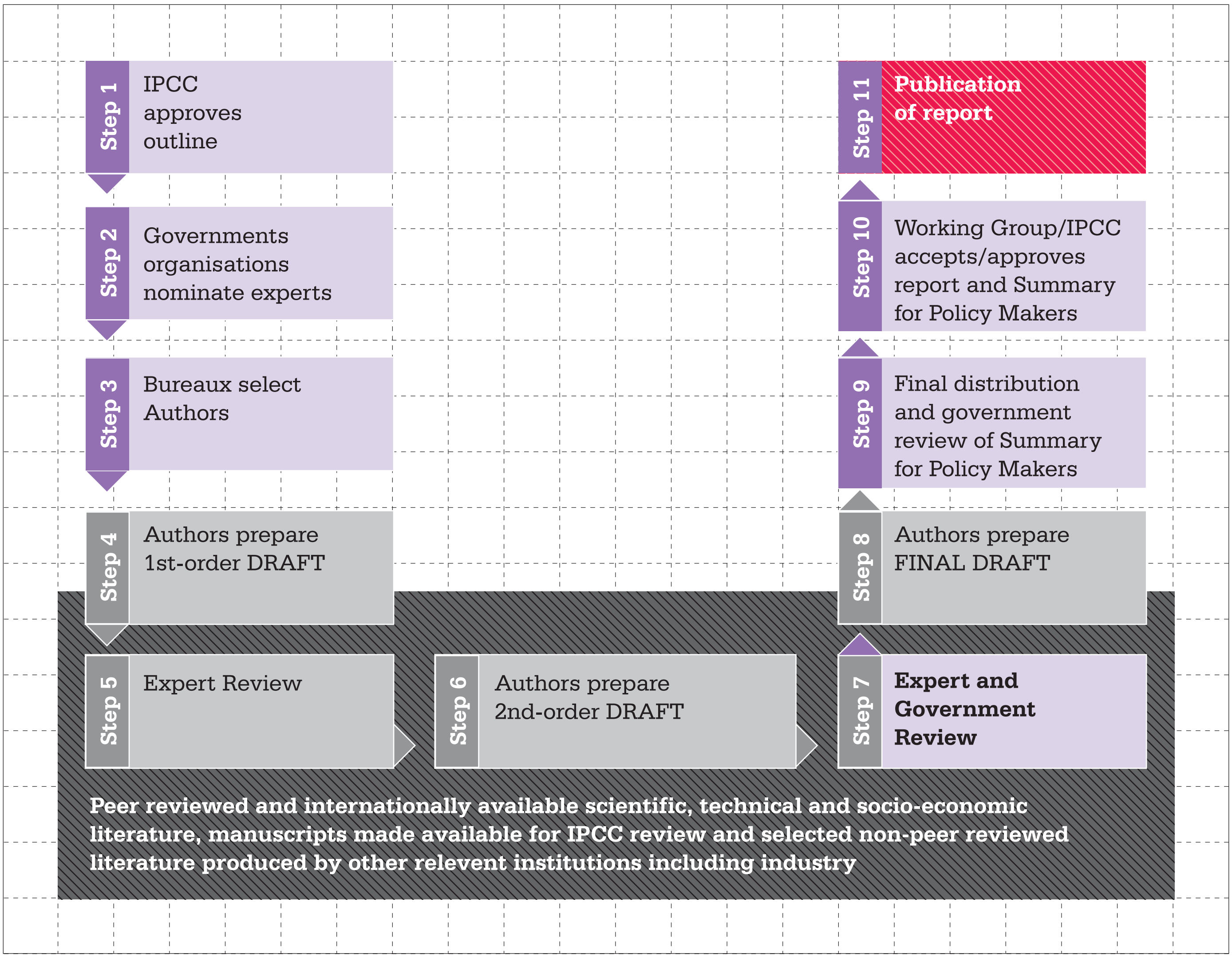
1.4 How certain is our knowledge of climate change?

Following criticisms of the IPCC, the so-called "climategate" incident in the UK (the hacking of emails of climate scientists at the University of East Anglia), and numerous attacks in the media and elsewhere on climate science, there has been much focus on the veracity of climate science and on the level of certainty or uncertainty surrounding knowledge of climate science. The key question is: Are we confident enough about (i) our understanding of the climate system, (ii) the human influence on climate, and (iii) the consequences of contemporary climate change for societies and ecosystems to provide a reliable knowledge base on which to base policy and economic responses?

This section will briefly explore the level of certainty and uncertainty surrounding the knowledge base on which scientific understanding of contemporary climate change rests. The main messages are:

- The IPCC's Fourth Assessment Report has been intensively and exhaustively scrutinised and is virtually error-free.
- The Earth is warming on a multi-decadal to century timescale, and at a very fast rate by geological standards. There is no doubt about this statement.
- Human emissions of greenhouse gases – and CO_2 is the most important of these gases – is the primary factor triggering observed climate change since at least the mid 20th century. The IPCC AR4 (2007a) report attached 90% certainty to that statement; research over the past few years has strengthened our confidence in this statement even more.
- Many uncertainties surround projections of the particular risks that climate change poses for human societies and natural and managed ecosystems, especially at smaller spatial scales. However, our current level of understanding provides some useful insights: (i) some social, economic and environmental impacts are already observable from the current level of climate change; (ii) the number and magnitude of climate risks will rise as the climate warms further.

Figure 13. The process by which the IPCC carries out an assessment, including the careful and exhaustive, two-tiered review process.



Source: IPCC (2011).

The IPCC

As the primary source of information on climate change for the policy community, the IPCC produces periodic assessments of the literature by scientific experts approximately every six years, as well as interim special reports. There are three working groups – one each for the fundamental climate science; impacts, adaptation and vulnerability; and mitigation of climate change. The Fourth Assessment Report (AR4), published in 2007, involved about 1,250 expert authors and 2,500 reviewers, who produced about 90,000 comments on drafts, each one of which was addressed explicitly by the authors. This exhaustive, thorough process is shown schematically in Figure 13.

The IPCC AR4 has been intensively and exhaustively scrutinised, including formal reviews such as that by the InterAcademy Council (2010), and only two peripheral errors, both of them in the WG 2 report on impacts and adaptation, have yet been found (in a publication containing approximately 2.5 million words!). No errors have been found in any of the main conclusions, nor have any errors been found in the 996-page WG 1 report, which describes our understanding of how and why the climate system is changing. The IPCC AR4 WG 1 report provides the scientific input to the development of climate policy. Several official “assessments of the assessment” have concluded that the conclusions of the AR4 are sound (InterAcademy Council 2010; Royal Society 2010; National Research Council 2010).

In summary, despite intensive, and ultimately unsuccessful, attempts to find important errors in the assesments, the IPCC has been confirmed as a source of reliable scientific information on climate change.

Certainty of warming

The evidence that the Earth is warming on a multi-decadal timescale, and at a very fast rate by geological standards, is now overwhelming. Some of this evidence has been presented above. The IPCC used the word "unequivocal" to describe our confidence in the observations of a warming Earth. Observations since 2007 have strengthened our confidence in this statement.

Human causation

Based on its thorough assessment of the evidence, the IPCC in 2007 stated that:

> **"MOST OF THE OBSERVED INCREASE IN GLOBAL AVERAGE TEMPERATURES SINCE THE MID-20TH CENTURY IS VERY LIKELY DUE TO THE OBSERVED INCREASE IN ANTHROPOGENIC GREENHOUSE GAS CONCENTRATIONS".**

The term *very likely* in the IPCC definitions of uncertainty is associated with a greater than 90% certainty that the statement is correct (IPCC 2007a). Research over the past few years has further strengthened our confidence in the IPCC's assessment of attribution. Such research, described earlier, includes better estimates of climate sensitivity, more observations of the patterns of climatic changes – "fingerprints" characteristic of greenhouse gas forcing, and improved understanding of the long-term role of CO_2 in the climate system.

Large uncertainties

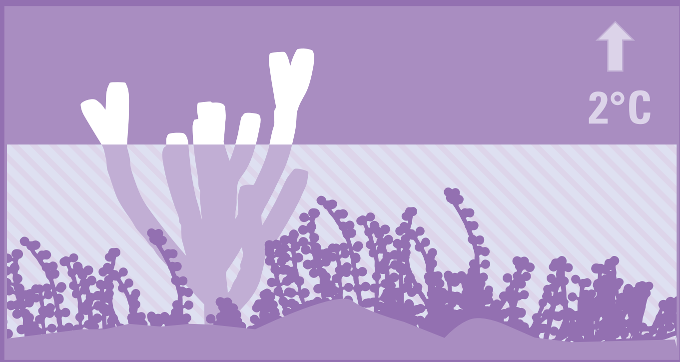
Although the fundamental features of climate change, as described above, are very well known, significant uncertainties surround our understanding of the behaviour of important parts of the climate system. For example, the ways in which the large polar ice sheets on Greenland and Antarctica are responding and will respond in future to warming are not well known, and are generating intense discussion and further research in the scientific community. Similarly, although considerable evidence points toward an acceleration of the hydrological cycle as the climate warms – increased evaporation, more water vapour in the atmosphere, and increased precipitation – this trend is still being debated in the research community, as is the influence of climate change on spatial patterns of precipitation across the Earth's surface and on the temporal patterns of precipitation – droughts and intense rainfall events. These uncertainties, however, in no way diminish our confidence in the observation that the Earth is warming and in our assessment that human emissions of greenhouse gases are the primary reason for this warming.

Many uncertainties also surround our understanding of the risks that climate change poses for human societies and natural and managed ecosystems. These uncertainties stem from several factors: (i) uncertainties in the projections of potential impacts from future climate change; (ii) uncertainties associated with the dynamics of systems being impacted by climate, such as agricultural systems, natural ecosystems, or urban systems; and (iii) uncertainties in the ways in which humans will respond to the threats of climate change by reducing their vulnerability or increasing their adaptive capacity. Despite these seemingly daunting uncertainties, a number of social, economic and environmental impacts can be observed that are consistent with what is anticipated from the current level of climate change. The number and magnitude of climate-related risks will rise considerably as the climate warms towards 2 °C above the pre-industrial level; and above the 2 °C guardrail, the risks may rise dramatically (Smith et al. 2009; Richardson et al. 2011). The most serious risks are associated with potential abrupt or irreversible changes in large features of the climate system, such as the switch to a dry state of the Indian Summer Monsoon (Lenton et al. 2008). Decision-making in the face of such uncertainties will remain a big challenge for the policy and management communities.

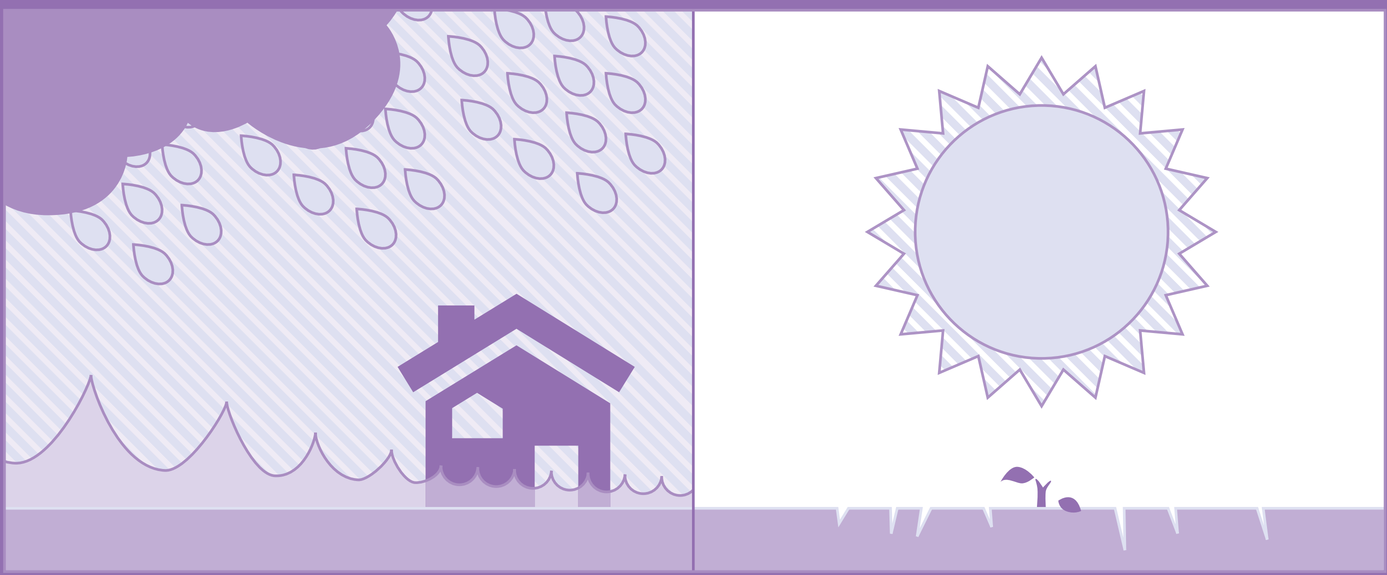
CHAPTER 2: RISKS ASSOCIATED WITH A CHANGING CLIMATE

DID YOU KNOW...

CORAL-DOMINATED ECOSYSTEMS ARE SENSITIVE TO SMALL RISES IN THE TEMPERATURE OF THE WATER IN WHICH THEY RESIDE. WHEN THE SEA TEMPERATURE RISES 1-2°C ABOVE NORMAL FOR A SIX-EIGHT WEEK PERIOD THE CORALS ARE “BLEACHED”.



WHAT WE CAN SAY WITH CERTAINTY IS THAT RAINFALL PATTERNS WILL CHANGE AS A RESULT OF CLIMATE CHANGE AND OFTEN IN UNPREDICTABLE WAYS, CREATING LARGE RISKS FOR WATER AVAILABILITY.



TEMPERATURE INCREASES OF 1 OR 2 °C MAY SEEM MODEST, BUT THEY CAN LEAD TO DISPROPORTIONATELY LARGE CHANGES IN THE FREQUENCY AND INTENSITY OF EXTREME WEATHER EVENTS.

2.1 Sea-level rise

With much of our population and a high fraction of our infrastructure located close to the coast, Australia is vulnerable to the risks posed by sea-level rise. Although sea level will continue to rise for many centuries (Solomon et al. 2009), the more immediate concern is the level of risk associated with sea-level rise out to 2100, when some of our existing infrastructure and much new infrastructure will be at risk. The rate at which sea level will rise through this century is a critical factor in determining the degree of exposure to risk.

This section builds on Section 1.1 on observations of sea-level rise to explore the range of rates at which sea-level could rise this century and the implications of such rises for the inundation of parts of our coastline.

The key messages are:

- A plausible estimate of the amount of sea-level rise by 2100 compared to 2000 is 0.5 to 1.0 m. There is significant uncertainty around this estimate, the largest of which is related to the dynamics of large polar ice sheets.
- Much more has been learned about the dynamics of the large polar ice sheets through the past decade but critical uncertainties remain, including the rate at which mass is currently being lost, the constraints on dynamic loss of ice and the relative importance of natural variability and longer-term trends.
- The impacts of rising sea-level are experienced through "high sea-level events" when a combination of sea-level rise, a high tide and a storm surge or excessive run-off trigger an inundation event. Very modest rises in sea-level, for example, 50 cm, can lead to very high multiplying factors – sometimes 100 times or more – in the frequency of occurrence of high sea-level events.

Projections of future sea-level rise

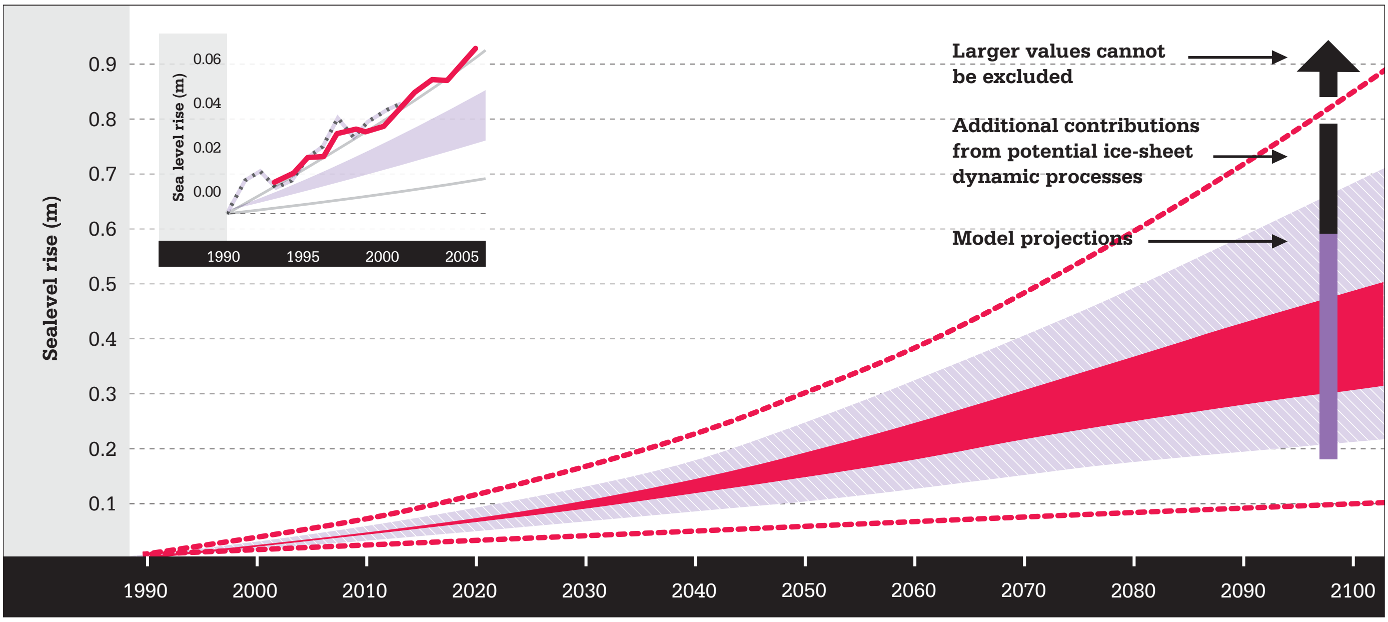
PROJECTIONS OF SEA-LEVEL RISE FOR THE REST OF THE CENTURY VARY WIDELY, FROM THE OFT-QUOTED RANGE OF 0.19-0.59 M BASED ON THE IPCC AR4 (2007a) TO NEARLY 2 METRES (VERMEER AND RAHMSTORF 2009).

The IPCC projections are often misquoted as they do not take into account the loss of ice due to dynamical processes in the large polar ice sheets.

When estimates for this process are included, the range changes to 0.18 – 0.76 m, and the IPCC is careful to note that higher values cannot be excluded (IPCC 2007a; Figure 14). By comparison, the Third Assessment Report of the IPCC (2001) projected a sea-level rise of 0.11 – 0.88 m for this century.

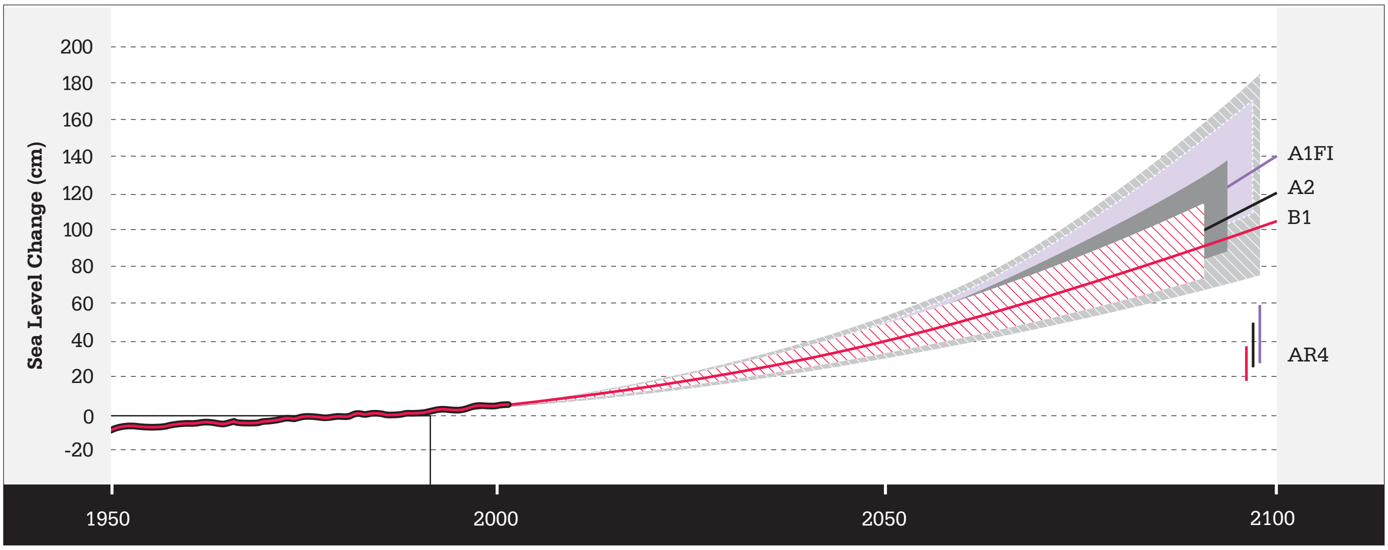
The projections yielding higher ranges of sea-level are often based on statistical or semi-empirical models that relate the observed sea-level rise over the past 120 years to the observed temperature rise over that period (e.g., Rahmstorf 2007; Horton et al. 2008; Grinsted et al. 2009). The approach is to use projections of temperature rise to 2100 to estimate the corresponding rise in sea-level based on the observed relationship. The range of temperature increases then yields a range of projected sea-level changes. Projections using semi-empirical models are generally higher than those of the IPCC because they incorporate the observed acceleration of sea-level rise during the 1990-2009 period and project that further acceleration will occur as the climate warms. Figure 15 shows an example of projected changes in sea level based on a semi-empirical model (Vermeer and Rahmstorf 2009).

Figure 14. Projections of sea-level rise from 2100 from the IPCC Third Assessment Report (TAR) and the Fourth Assessment Report (AR4). The TAR projections are indicated by the shaded regions and the broken red lines are the upper and lower limits. The AR4 projections are the bars plotted in the 2090-2100 period. The inset shows sea level observed with satellite altimeters from 1993 to 2006 (red) and observed with coastal sea-level measurements from 1990 to 2001 (purple dashes).



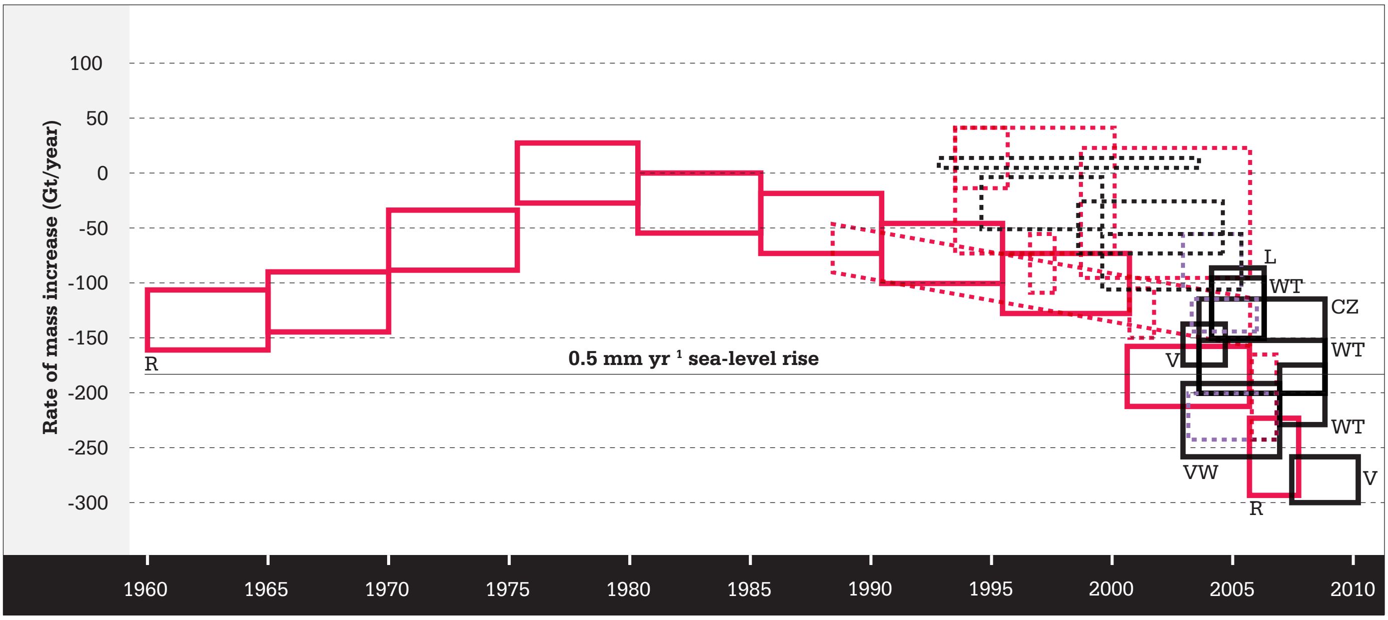
Source: ACE CRC 2008.

Figure 15. Projection of sea-level rise from 1990 to 2100, based on IPCC temperature projections for three different emission scenarios (labelled on right, see Vermeer and Rahmstorf (2009) for explanation of uncertainty ranges). The sea-level range projected in the IPCC AR4 (2007a) (excluding contributions from ice-sheet dynamic processes) for these scenarios is shown for comparison in the bars on the bottom right. Also shown is the observations-based annual global sea-level data (solid red line to 2003) including artificial reservoir correction.



Source: Vermeer and Rahmstorf (2009), and references therein.

Figure 16. Estimates of the net mass budget of the Greenland ice sheet since 1960. A negative mass budget indicates ice loss and sea-level rise. Dotted boxes represent estimates used by the IPCC (2007a). The solid boxes are post-IPCC AR4 assessment (R=Rignot et al. 2008b; VW=Velicogna and Wahr 2006; L=Luthcke et al. 2006; WT=Wouters et al. 2008; CZ=Cazenave et al. 2009; V=Velicogna 2009).



Source: The Copenhagen Diagnosis (2009).

An estimate of the likely magnitude of sea-level rise this century is useful information for risk assessments. A continuation of the currently observed rate of 3.2 mm yr[1] would give a rise of about 0.32 m by 2100, about the mid-range of the IPCC scenarios. However, sea level is currently tracking near the upper range of the scenarios, and it seems unlikely that the rate of sea-level rise will remain fixed for nearly a century at its current level as the temperature continues to rise. On the other hand, projections of 1.5 or 2.0 metres seem high in light of recent questions surrounding estimates of the current rate of mass loss from polar ice sheets (see Figure 6).

An estimate for the most likely magnitude of sea-level rise in 2100 relative to 2000 taking polar ice sheet dynamics into account is about 0.8 m (Pfeffer et al. 2008), and an expert assessment of Greenland ice sheet dynamics suggests that it will contribute about 20 cm to global sea-level rise by 2100 (Dahl-Jensen and Steffen 2011). These are both consistent with an estimate of a 0.5–1.0 m rise in sea level by 2100.

Dynamics of large polar ice sheets

The largest uncertainty in the projections of sea-level rise discussed above is the behaviour of the large masses of ice on Greenland and Antarctica. Projections at the upper levels of the ranges of sea-level rise assume a much greater contribution from these polar ice sheets, and, in particular, from dynamical processes that discharge large blocks of ice into the sea. Observations over the past 20 years, either by satellite or aircraft altimeters that measure changes in the height of the ice sheets or by satellite gravity measurements that infer changes in mass, show accelerating decreases in the mass of the Greenland ice sheet over the past 15 years (Figure 16) and in the mass of the Antarctic ice sheet over the past decade. Such observations appear to support higher estimates of sea-level rise by 2100.

However, the measurements are for very short periods of time and so are difficult to extrapolate to longer time scales. For example, Figure 16 includes only one record of mass change in the Greenland ice sheet that is longer than 20 years, the record of Rignot et al. (2008b) from 1958. That observational record shows considerable variability on a decadal time scale, making it more difficult to extrapolate the observations of the last 10-15 years into the future with a high degree of certainty. Furthermore, a recent analysis of the gravity measurement methodology (Bromwich and Nicolas 2010) argues that estimates of the cumulative mass loss of the Greenland ice sheet are too large by a factor of two or so (Figure 6). The study of Pfeffer et al. (2008) of the kinematic constraints on rapid ice discharge from the large polar ice sheets suggests an absolute maximum sea-level rise of 2 metres by 2100, but only under extreme climatic forcing.

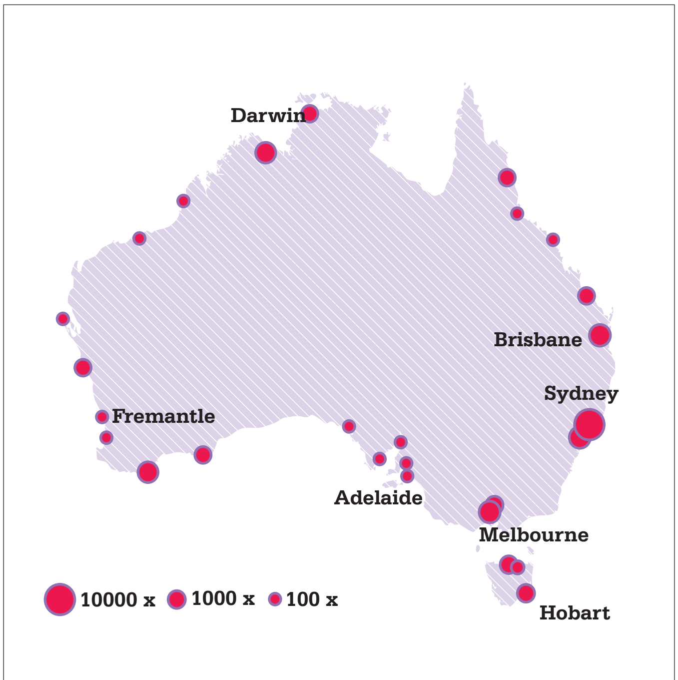
GIVEN THE IMPORTANCE OF THE LARGE POLAR ICE SHEETS FOR THE RATE OF SEA-LEVEL RISE TO 2100 AND BEYOND, THESE ONGOING UNCERTAINTIES ABOUT THE BEHAVIOUR OF THE ICE SHEETS UNDER FURTHER GLOBAL TEMPERATURE INCREASES COMPRISE ONE OF THE MOST PRESSING SCIENTIFIC RESEARCH CHALLENGES THAT REQUIRE URGENT RESOLUTION.

High sea-level events (inundation)

Many of the risks due to sea-level rise are associated with inundation events, which damage human settlements and infrastructure in low-lying coastal areas, and can lead to erosion of sandy beaches and soft coastlines. While a sea-level rise of 0.5 m – less than the average waist height of an adult human – may not seem like a matter for much concern, such modest levels of sea-level rise can lead to unexpectedly large increases in the frequency of extreme high sea-level events. These are defined as inundation events associated with high tides and storm surges, amplified by the slow rise in sea level. Such events are very sensitive to small increases in sea level, and the probability of these events rises in a highly nonlinear way with rising sea level.

Figure 17 shows the results of an analysis exploring the implications of sea-level rise for extreme sea-level events around the Australian coastline (Church et al. 2008). A sea-level rise of 0.5 m, at the lower end of the estimates for 2100, was assumed in the analysis shown in the figure, and leads to surprisingly large impacts. For coastal areas around Australia's largest cities – Sydney and Melbourne – a rise of 0.5 m leads to very large increases in the incidence of extreme events, by factors of 1000 or 10,000 for some locations. A multiplying factor of 100 means that an extreme event with a current probability of occurrence of 1-in-100 – the so-called one-in-a-hundred-year event – would occur every year. A multiplication factor of 1000 implies that the one-in-a-hundred-year inundation event would occur almost every month.

Figure 17. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events caused by a sea-level rise of 0.5 metres. High sea-level events are very sensitive to small increases in sea level.



Source: ACE CRC 2008.

The observed sea-level rise of about 20 cm from 1880 to 2000 should already have led to an increase in the incidence of extreme sea-level events. Such increases have indeed been observed at places with very long records, such as Fremantle and Fort Denison, where a 3-fold increase in inundation events has occurred (Church et al. 2006). This is consistent with the methodology used to produce Figure 17.

A more detailed assessment of the potential impacts of sea-level rise has been carried out by the then Department of Climate Change (DCC 2009), providing estimates of areas of inundation for a sea-level rise of 1.1 m, just above the upper end of our projection range for 2100. The Department has recently released more detailed maps to highlight low-lying coastal areas vulnerable to inundation from sea-level rise.

2.2 Ocean acidification

Changes in the alkalinity/acidity of the ocean represent a change in a fundamental environmental condition for marine ecosystems. In particular, those marine organisms that form calcium carbonate shells are at risk from decreasing alkalinity of the ocean, which reduces the concentration of carbonate ions in seawater. Corals are probably the most well-know of these organisms, but other calcifying organisms are important for the marine carbon cycle and play fundamental roles in the dynamics of marine ecosystems.

This section provides information on the projected magnitude and rate of change of ocean alkalinity/acidity through this century, and on observations of the impacts of increasing acidity on marine ecosystems. The key messages are:

- The contemporary rate of increase in ocean acidity (decrease in alkalinity) is very large from a long-time perspective.
- The effects of increasing acidity are most apparent in the high latitude oceans, where the rates of dissolution of atmospheric CO_2 are the greatest.
- Increasing acidity in tropical ocean surface waters is already affecting coral growth; calcification rates have dropped by about 15% over the past two decades.
- Rising SSTs have increased the number of bleaching events observed on the Great Barrier Reef (GBR) over the last few decades. There is a significant risk that with a temperature rise above 2 °C relative to pre-industrial levels and at CO_2 concentrations above 500 ppm, much of the GBR will be converted to an algae-dominated ecosystem.

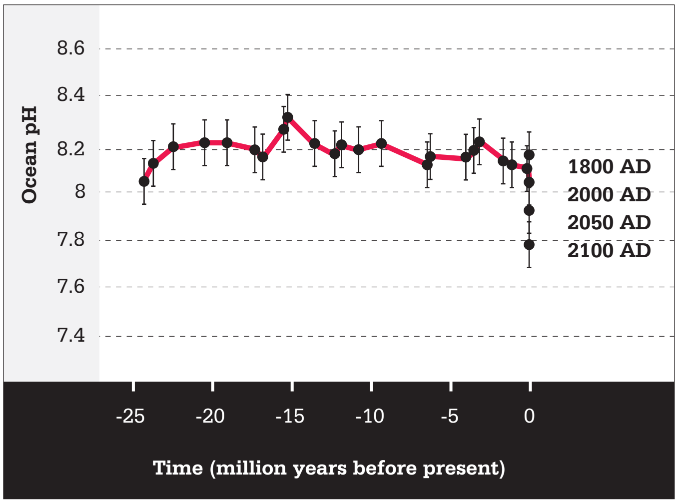
Ocean acidity in a long-time context

The rate at which ocean acidity is increasing is important, especially from an evolutionary perspective. Figure 18a shows the change in ocean acidity over the past 25 million years and projected to 2100 (Turley et al. 2006; 2007).

Ocean acidity has varied considerably over that period, but the level of acidity today is as high as it was 25 million years ago, the previous most acidic state in the record.

MORE STRIKING IS THE RATE OF CHANGE IN ACIDITY THAT HAS ALREADY OCCURRED FROM 1800 TO 2000 AND THAT WHICH IS PROJECTED TO 2100. THIS IS AN EXCEPTIONALLY RAPID RATE OF CHANGE, LIKELY UNPRECEDENTED IN THE 25 MILLION YEARS OF THE RECORD, AND WOULD NO DOUBT PLACE SEVERE EVOLUTIONARY PRESSURE ON MARINE ORGANISMS. (FIGURE 18b)

Figure 18a. Ocean acidity (pH) over the past 25 million years and projected to 2100. The lower the pH, the more acidic the ocean becomes. Prehistoric surface-layer pH values were reconstructed using boron-isotope ratios of ancient planktonic foraminifera shells. Future pH values were derived from models based on IPCC mean scenarios.

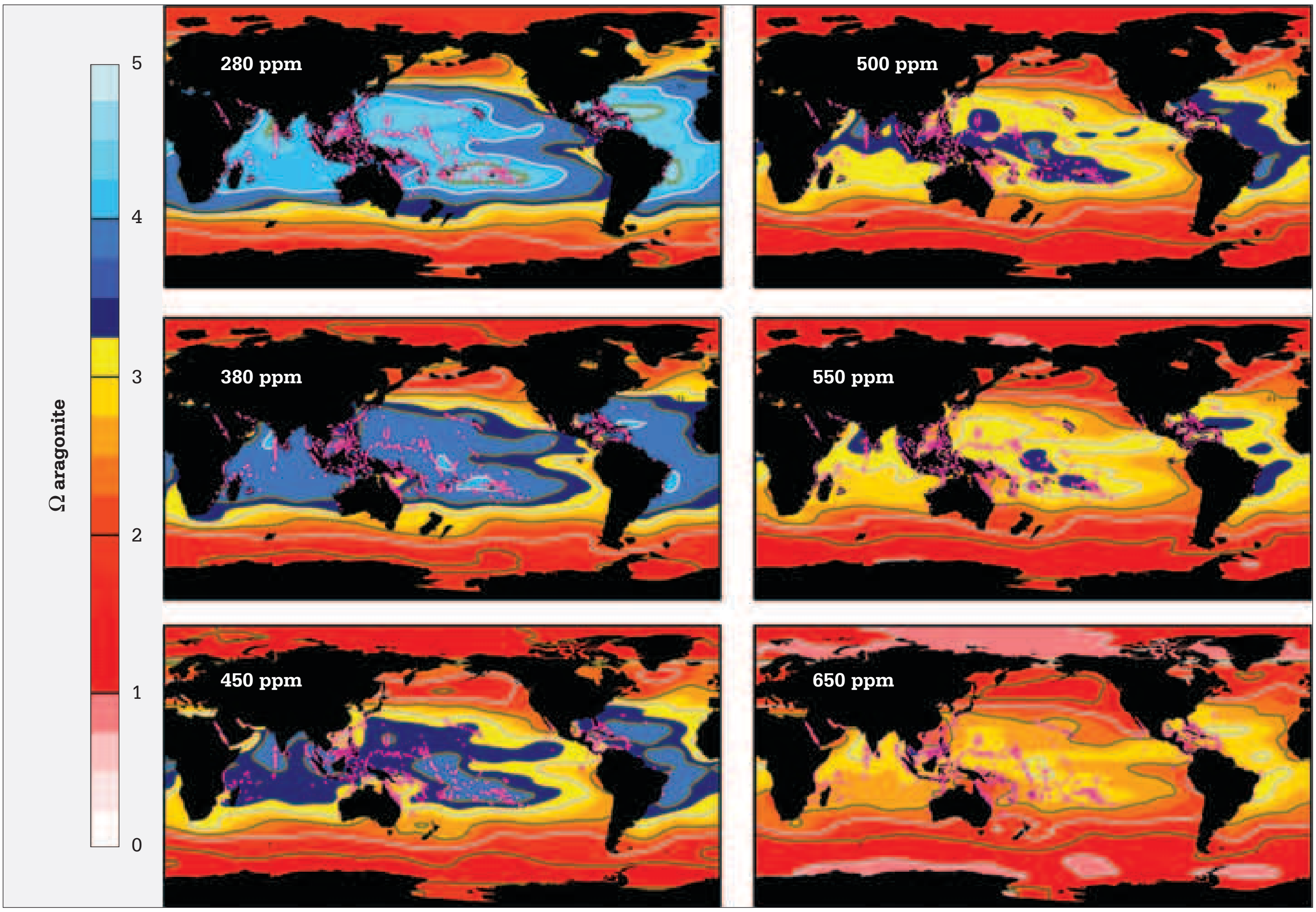


Source: Turley et al. (2006).

Marine ecosystems

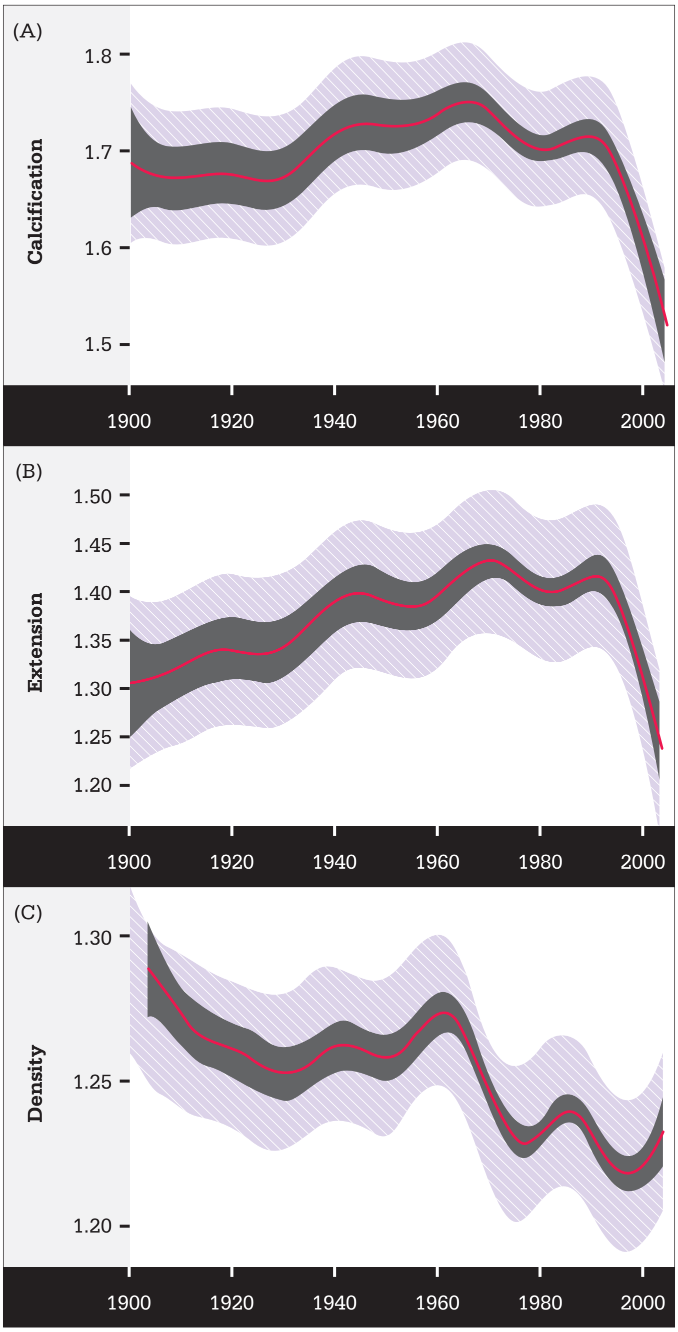
The impacts of increasing ocean acidity are already evident in some marine species (Moy et al. 2009). Many of the earliest impacts are expected in polar or sub-polar waters, as CO_2 is more soluble in cold water than warm and so acidification is expected to proceed more rapidly there. Observational studies in the Southern Ocean of acidity and carbonate ion concentration show strong seasonal minimums in winter; conditions deleterious for the growth of calcifying plankton species could occur as early as 2030 in winter (McNeil and Matear 2008). Experiments in sea water with the acidity level expected in 2100 have shown a 30% reduction in calcification rates for a common pteropod (pelagic marine snail), an important component of marine food chains (Comeau et al. 2009). Even larger reductions in calcification rates of around 50% have been found in experiments with a deepwater coral (Maier et al. 2009). Impacts of acidification further up marine food chains, including fish, are largely unknown as yet (Turley and Findlay 2009). Previous ocean acidification events are likely to have been significant factors in mass extinction events in marine ecosystems (Veron 2008).

Figure 18b. Changes in relative aragonite saturation predicted to occur as atmospheric CO_2 concentrations (ppm – upper left of panels) increase over shallow-water coral reef locations (pink dots).



Source: Hoegh-Guldberg et al. (2007), which gives more information on the figure. See also Figure 20a for the connection between aragonite saturation and coral reef state.

Figure 19. Variation of (a) calcification (grams per square centimetre per year), (b) linear extension (centimetres per year) and (c) density (grams per cubic centimetre) in *Porites* over time. Dark grey bands indicate 95% confidence intervals for comparison between years, and purple bands indicate 95% confidence intervals for the predicted value for any given year.



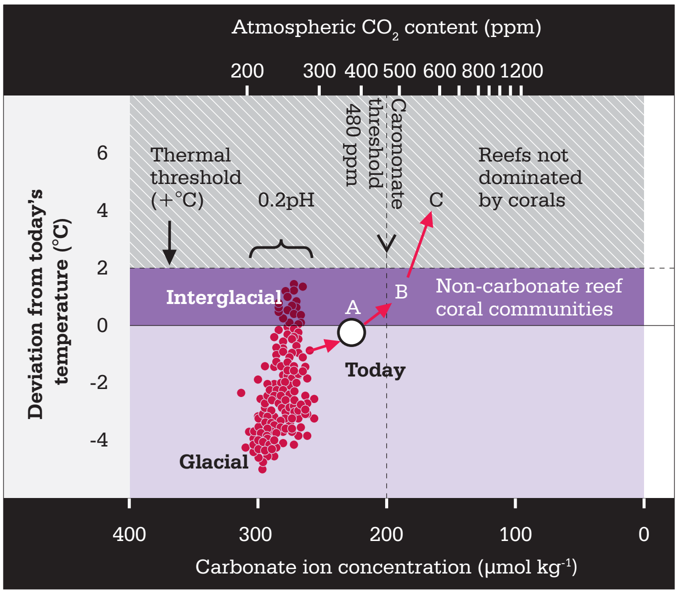
Source: De'ath et al. (2009).

Coral reefs

The risks of climate change for coral reefs are particularly important for Australia, given the iconic status and economic importance of the Great Barrier Reef (Oxford Economics 2009).

There is evidence that shows a possible impact of the increase in acidity that has already occurred, based on a study of changes in the calcification rate of the coral *Porites* (De'ath et al. 2009). The observational study was carried out using 328 sites on 69 reefs and showed a precipitous drop in calcification rate, linear extension and coral density, all indicators of coral growth, in the last 15-20 years of a 400-year record (Figure 19). These data are suggestive of a highly nonlinear response of corals to ocean acidity (in combination with other stressors), perhaps taking the form of threshold-abrupt change behaviour (cf. Section 3.5).

Figure 20a. Temperature, atmospheric CO_2 concentration and carbonate ion concentrations reconstructed for the past 420,000 years. Carbonate concentrations were calculated from Vostok ice core data. Acidity of the ocean has varied by +/- 0.1 pH units over the past 420,000 years. The thresholds for major changes to coral communities are indicated for thermal stress (+2 °C) and carbonate ion concentration (200 micro-mol kg^{-1}); the latter corresponds to an approximate aragonite saturation of 3.3 and an atmospheric CO_2 concentration of 480 ppm. Red arrows pointing towards the upper right indicate the pathway currently followed towards atmospheric CO_2 concentration of more than 500 ppm.



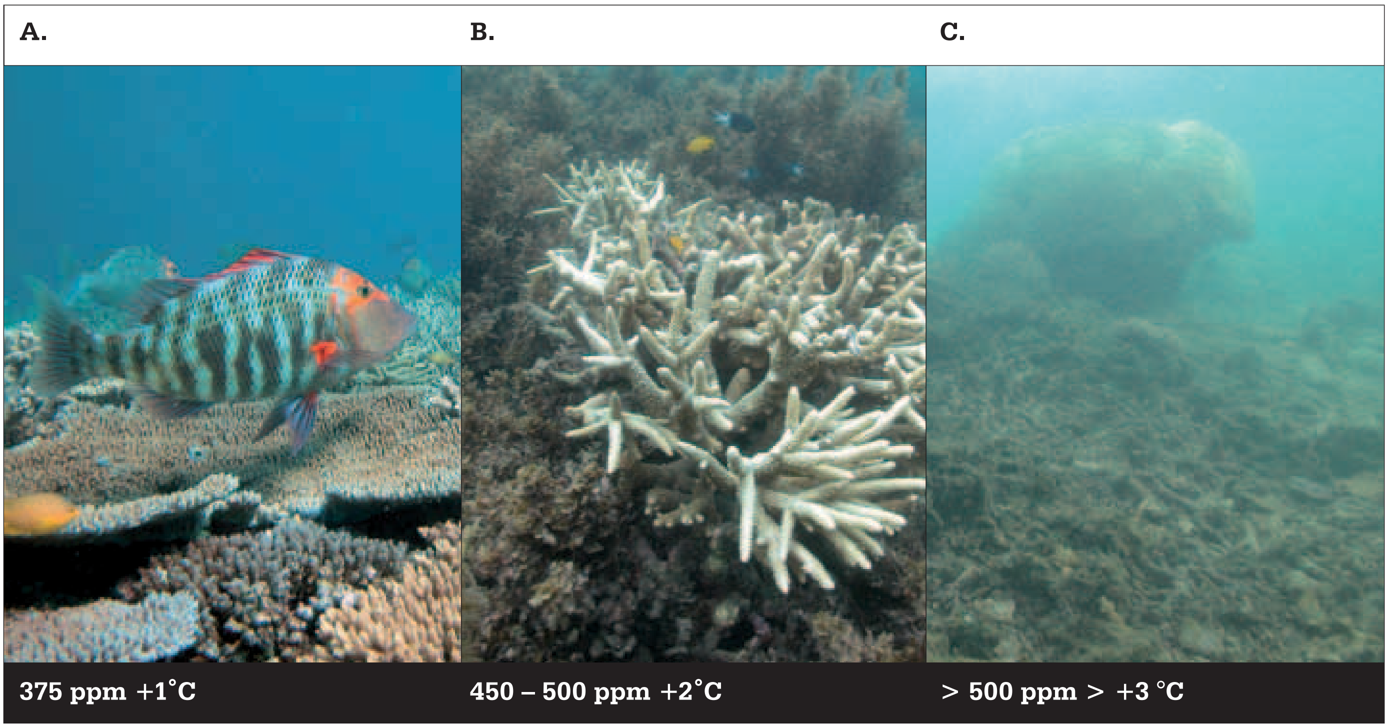
Source: Hoegh-Guldberg et al. (2007), including details of the reconstructions and the location of the photos in part (b).

Corals are also affected by extremes in SSTs (cf. Section 3.4), which can lead to coral bleaching. A 21st century risk analysis for coral reefs emphasises the importance of both SST and acidity/carbonate ion concentration for their future viability. Figure 20 combines the temperature and acidity/carbonate ion concentration influences in a two-dimensional environmental space diagram that contrasts the past, present and future environments for coral reefs (Hoegh-Gulberg et al. 2007).

The cluster of red dots represents the envelope of natural variability that reefs have experienced over the past 420,000 years. Present conditions of carbonate ion concentration – but not temperature – have pushed reefs outside of this envelope.

MOST EMISSIONS AND CLIMATE SCENARIOS FOR THE REST OF THIS CENTURY (IPCC 2007a) PREDICT THE CONVERSION OF CORAL REEFS INTO ALGAE-DOMINATED ECOSYSTEMS (THE UPPER RIGHT QUADRANT OF FIGURE 20a AND THE RIGHT-HAND PANEL OF FIGURE 20b).

Figure 20b. Extant examples from the Great Barrier Reef as analogs for the reef states anticipated for the environmental conditions marked A, B and C in part (a) of the figure.



Source: modified from Hoegh-Guldberg et al. (2007).

2.3 The water cycle

Australia is the driest of the six inhabited continents, and experiences a high degree of natural climatic variability – the proverbial "land of droughts and flooding rains". Thus, the link between climate and water resources has been a dominant theme in the lives of all Australians, from the arrival of the first people about 60,000 years ago to the present. The risks of climate change for water resources, and especially the ways in which the longer term trends of human-induced climate change interact with modes of natural variability, is a hotly debated topic, both within and outside of the research community.

ACHIEVING A BETTER UNDERSTANDING OF THE NATURE OF THIS RISK IS AN URGENT RESEARCH CHALLENGE, THE RESULTS OF WHICH WILL INFORM MANY MANAGEMENT AND POLICY DECISIONS NOW AND INTO THE FUTURE.

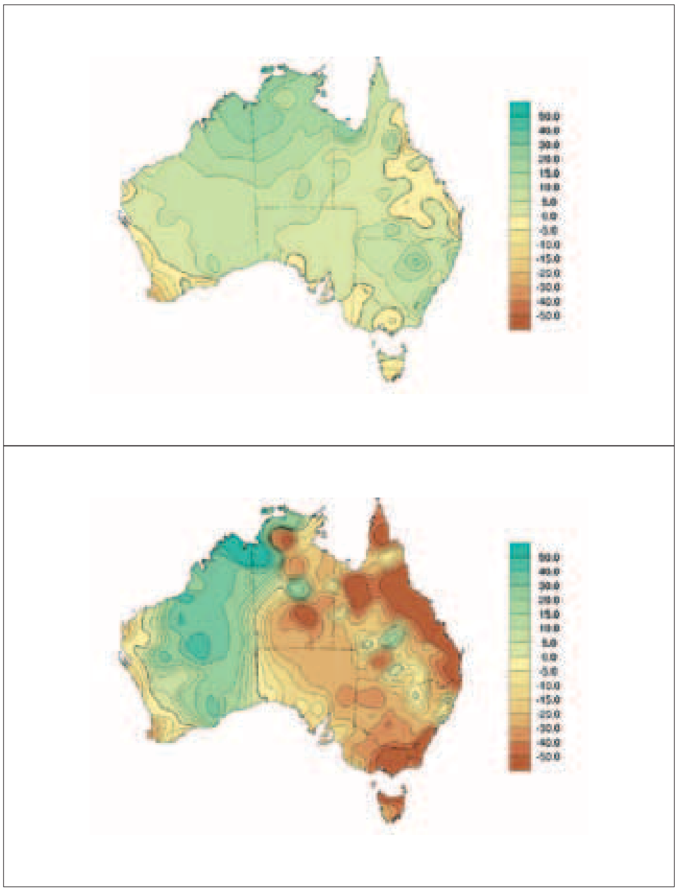
This section explores our current level of knowledge about the climate change-variability relationship and the consequent risks for water resources. The key messages are:

- Observations since 1970 show a drying trend in most of eastern Australia and in southwest Western Australia but a wetting trend for much of the western half of the continent.
- Given the high degree of natural variability of Australia's rainfall, attributing observed changes to climate change is difficult. There is no clear trend, either in observations or model projections, for how the major mode of variability, ENSO, is responding to climate change. Evidence points to a possible climate change link to observed changes in the behaviour of the Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD).
- Improvements in understanding of the climatic processes that influence rainfall suggest a connection to climate change in the observed drying trend in southeast Australia, especially in spring. In southwest Western Australia, climate change is likely to have made a significant contribution to the observed reduction in rainfall.
- The consensus on projected changes in rainfall for the end of this century is (i) high for southwest Western Australia, where almost all models project continuing dry conditions; (ii) moderate for southeast and eastern Australia, where a majority of models project a reduction; and (iii) low across northern Australia. There is a high degree of uncertainty in the projections in (ii) and (iii), however.
- Rainfall is the main driver of runoff, which is the direct link to water availability. Hydrological modelling indicates that water availability will likely decline in southwest Western Australia, and in southeast Australia, with less confidence in projections of the latter. There is considerable uncertainty in the projections of amounts and seasonality of changes in runoff.

Observations of rainfall change

Although the continent of Australia has become slightly wetter in terms of total annual rainfall over the past century, a pronounced pattern has developed since 1970, with drying in much of eastern Australia and in the southwest corner of Western Australia and increasing rainfall in much of the west (Figure 21). The development of this pattern has coincided with the sharp increase in global average temperature, raising the question of possible links with climate change. However, Australia naturally has a high degree of variability in rainfall, with long periods of intense droughts punctuated by heavy rainfall and flooding, so it is difficult from observations alone to unequivocally identify anything that is distinctly unusual about the post-1950 pattern (apart, perhaps, from the drying trend in southwest Western Australia, see below). While the instrumental record goes back little more than a century, not long enough to clearly discern multi-decadal patterns of variability that are repeated on century timescales, palaeo studies could offer some insights into the severity of the recent drought in a longer time perspective. For example, a recent study (Gallant and Gergis 2011) states that the very low streamflow in the River Murray for the 1998-2008 period is very rare – about a 1-in-1500 year event.

Figure 21. Trend in annual total rainfall (mm/10 years) for (a) 1900 – 2010; and (b) 1970 – 2010.



Source: Bureau of Meteorology.

The climate change-variability interaction

Rainfall patterns across Australia are influenced in complex ways by several modes of natural variability, the most important of which are ENSO (El Niño – Southern Oscillation), SAM (Southern Annular Mode) and IOD (Indian Ocean Dipole).

These modes are a manifestation of changes in oceanic and atmospheric circulation and, in particular, their coupling.

Therefore, their behaviour may change as oceanic and atmospheric circulation change in response to the changing energy balance at the Earth's surface. However, for ENSO there is no clear pattern of change in behaviour that can be observed in the observational record over the past several decades and can be linked clearly to climate change, nor is there a strong consensus in climate model projections of the future behaviour of this mode of variability (Collins et al. 2010)

For the IOD, the number of "positive" events, which induce a reduction in rainfall over southern Australia in winter and spring, has been increasing since 1950, reaching a record high frequency over the past decade (Abram et al. 2008; Ihara et al. 2008; Cai et al. 2009a). By contrast, the number of negative IOD events has been decreasing. The majority of climate models assessed by the IPCC in their 20th century simulations produce an upward trend in the frequency of positive IOD events (Cai et al. 2009b). The projected pattern of the mean ocean-atmosphere circulation change in the Indian Ocean in the future is similar to that of a positive IOD phase, implying an increase in positive IOD frequency and/or intensity and thus a reduction in rainfall over southern Australia in winter and spring (Cai et al. 2011a).

The situation is even clearer for the SAM.

THERE IS GOOD EVIDENCE THAT A SOUTHWARD SHIFT OF THE SAM (SOUTHERN ANNULAR MODE), WHICH BRINGS RAIN-BEARING FRONTS IN AUTUMN AND WINTER TO SOUTHWEST WESTERN AUSTRALIA, IS AN IMPORTANT FACTOR IN THE OBSERVED DROP IN RAINFALL THERE OVER THE PAST SEVERAL DECADES (TIMBAL ET AL. 2010; NICHOLLS 2009).

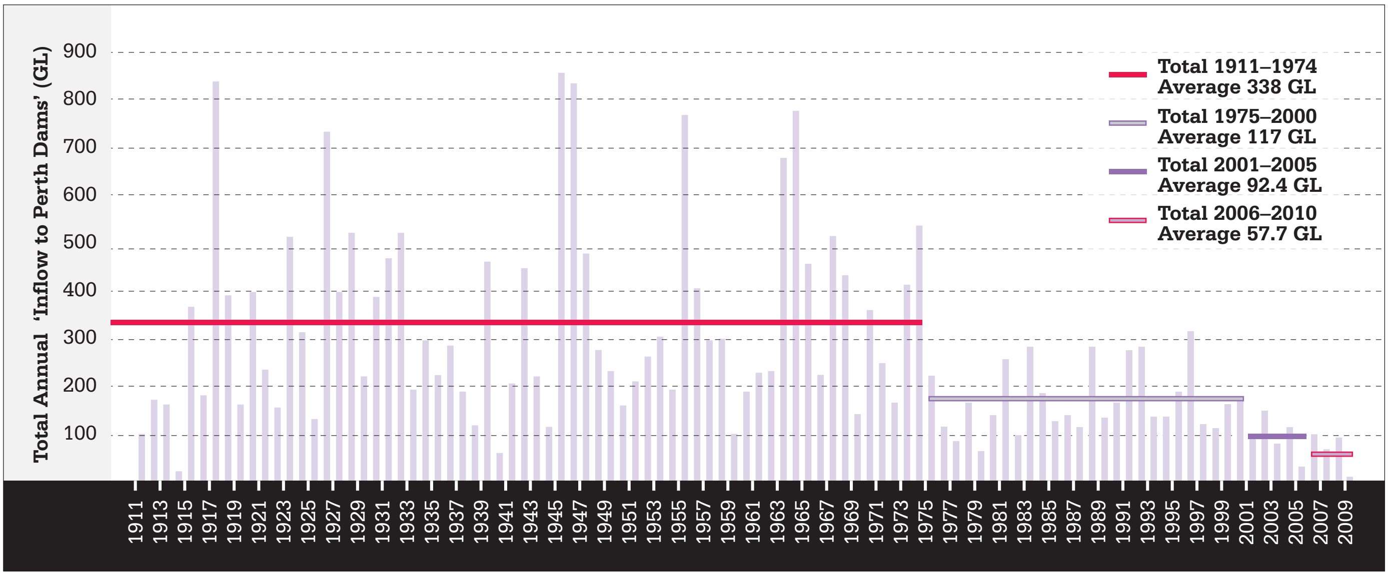
Cai and Cowan (2006) estimate that about 50% of the rainfall reduction is attributable to climate change. This explanation is consistent with our understanding of how atmospheric circulation is changing in response to global warming, and is consistent with model simulations of present climate and of future changes in the SAM (Frederiksen and Frederiksen 2007; Yin 2005; Arblaster et al. 2011).

Furthermore, the drying trend in the southwest has continued into 2011 (Figure 22), consistent with the dominant role of the SAM there, in contrast to the much wetter period in the east, where the other modes of variability are more important.

Understanding hydrometeorological processes

Given the short observational record, the importance of natural variability for Australia's rainfall, and the lack of consensus in climate model simulations at regional scales, a process-level understanding of the factors that influence Australian rainfall patterns offers one way to cut through the complexity and uncertainty and explore possible links between observed changes and climate change. The link between the SAM and the decrease in rainfall in southwest Western Australia, explored in depth by the Indian Ocean Climate Initiative (Cai et al. 2003; Cai and Cowan 2006; Hendon et al. 2007), is an example of the success of this approach.

Figure 22. Trend in total annual stream flow into Perth dams 1911-2010.



Source: Western Australian Water Corporation.

Progress has also been made in understanding recent changes to rainfall in southeast Australia, with the SEACI (South Eastern Australian Climate Initiative, www.seaci.org) playing a major role in this research. Several aspects of the observed decrease in rainfall, especially in Victoria and southern South Australia, are now better understood. First, the proximate cause of the rainfall decline is an increase in the surface atmospheric pressure over much of the continent (Nicholls 2009), although the cause of the rising pressure is not clear. In addition, the subtropical ridge, an east-west zone of high atmospheric pressure that often lies over the southern part of the continent, has strengthened considerably since 1970 (Timbal et al. 2010; Figure 23a). Furthermore, this strengthening of the pressure system correlates very well with the rise in global mean temperature (Timbal et al. 2010; Figure 23b), and is consistent with expectations from the basic physics of the climate system. In another effort to understand changes at the process level, research on changing southern hemisphere circulation patterns, linked to anthropogenic increase in CO_2 concentration, has shown a connection to a reduction in winter storm formation and a consequent reduction in winter rainfall in southern Australia (Frederiksen et al. 2011).

Additional research has shown that, while rainfall variability on year-to-year timescales is strongly associated with changes in tropical SSTs, this relationship explains little of the observed rainfall decline in the southeast (SEACI; Watterson 2010). Furthermore, there is no evidence of a strong land cover-rainfall signal over southeast Australia (Narisma and Pitman 2003), but the methodologies used to explore this relationship are weak and require further development.

Stratifying the observed southeast Australia rainfall changes into seasons, the reduction in autumn is largest (Cai and Cowan 2008), followed by that in spring. Outputs of 20th century simulations by 24 climate models show that only one or two were able to reproduce the observed autumn rainfall reduction. In this season, even the changes in the sub-tropical ridge are unable to account for the rainfall reduction (Cai et al. 2011b). The majority of these models reproduce a reduction in spring rain, as a consequence of an upward trend in the frequency of positive Indian Ocean Dipole events (Cai et al. 2009b).

Figure 23a. Relationship between the May-June-July (MJJ) rainfall in the southwest part of eastern Australia and the sub-tropical ridge intensity during the same three months. The slope of the linear relationship and the amount of explained variance (R^2) is shown in the upper right corner.

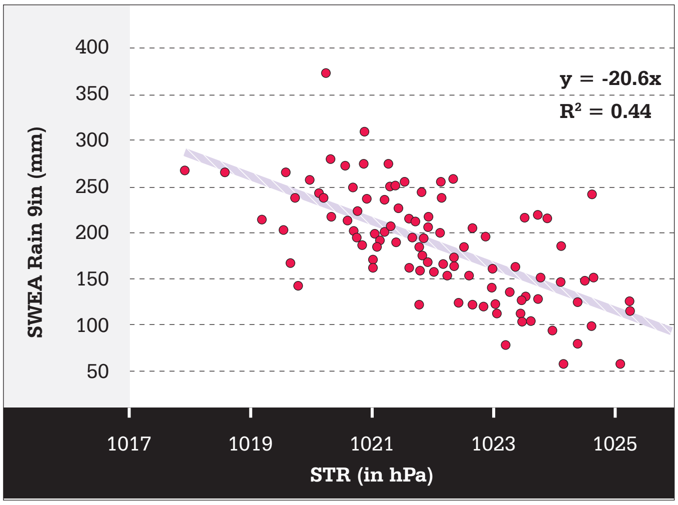
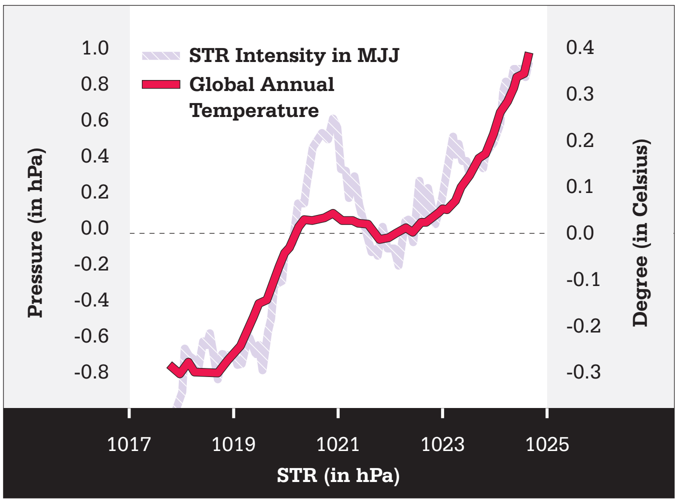


Figure 23b. Long-term (21-year running mean) evolution of the sub-tropical ridge MJJ mean intensity (anomalies in hPa shown on the left-hand Y-axis) compared with the global annual surface temperature.



Source: Timbal et al. (2010), including further details on methodology.

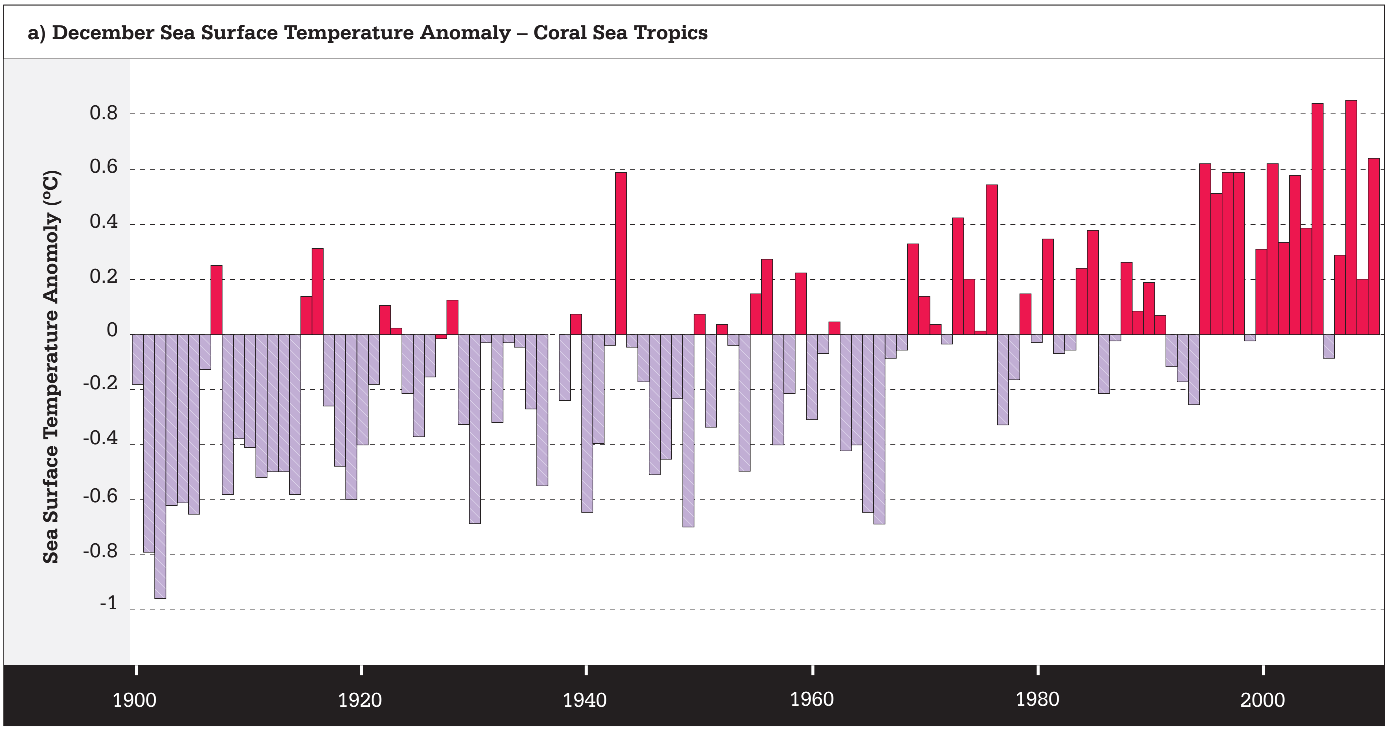
Projecting changes in water availability

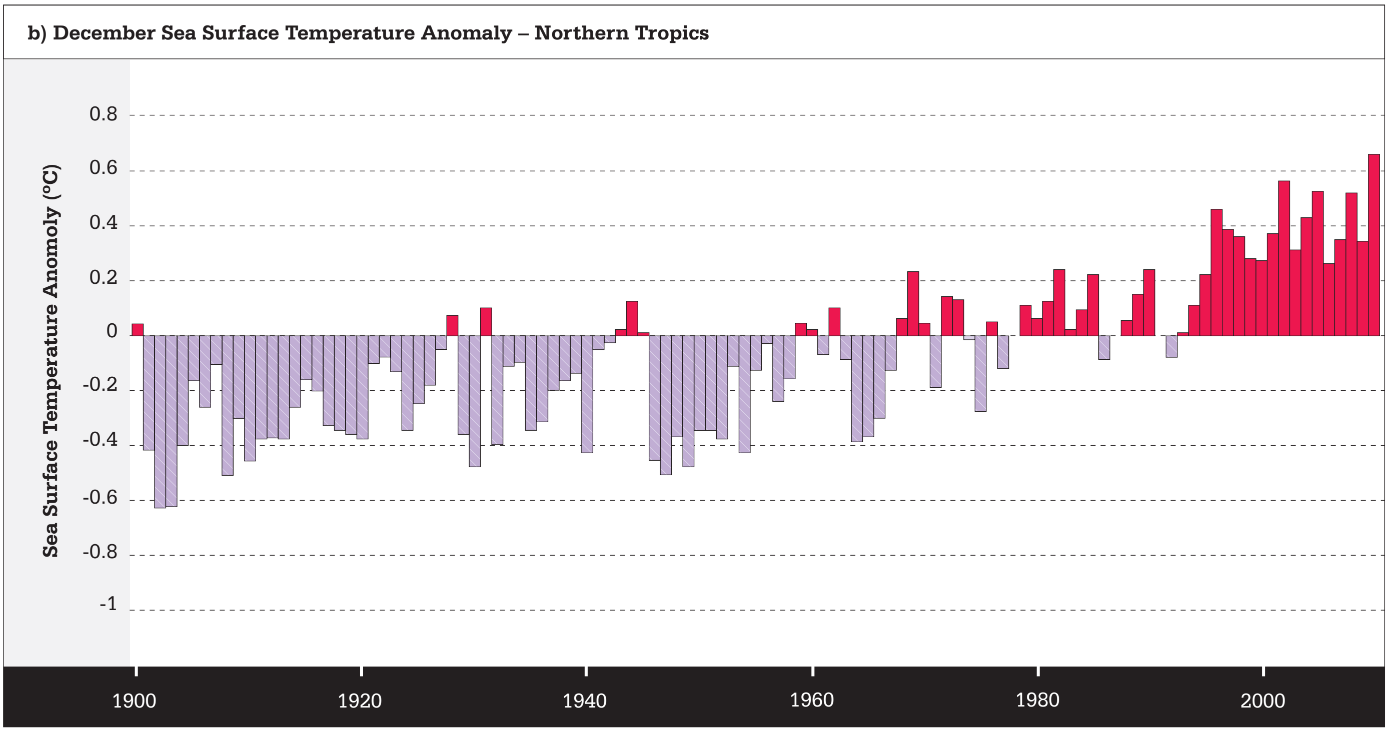
Although there has been progress in unravelling some of the linkages between climate change and observed shifts in rainfall patterns, our capability to project future changes to rainfall patterns, apart from the drying trend in southwest Western Australia, remains uncertain. Does the 2010-2011 extremely wet period across eastern Australia represent a brief interruption in a multi-decadal drying trend, or is it a shift to a multi-decadal wet regime, as one analysis emphasising the Pacific Decadal Oscillation (PDO) asserts (Cai et al. 2010)?

Model projections of future rainfall change do not add much clarity to the situation. Based on the models assessed by the IPCC (2007a), for much of Australia there is no strong consensus across models on the direction of change (increase or decrease in rainfall), or on the magnitude or seasonality. A recent assessment of climate science by the Australian Academy of Science (2010) noted that many aspects of climate change remain difficult to foresee, and, in particular, stated that "how climate change will affect individual regions is very hard to project in detail, particularly future changes in rainfall patterns, and such projections are highly uncertain."

Improving projections of future rainfall patterns is important, as rainfall is the main driver of runoff, which is the link to river flows and water availability. A change in annual rainfall is typically amplified by two or three times in the corresponding change in average annual runoff (Chiew 2006). Downscaled projections of rainfall change from climate models can be translated into changes in water availability through use of hydrological modelling based on point and catchment scale estimates of rainfall and potential evaporation (Chiew et al. 2009). The results of the hydrological modelling reflect the uncertainty in the larger scale rainfall projections by the climate models, but indicate that river flows in southwest Western Australia and in southeast Australia are likely to decline in the future, with higher confidence in the projections for the former. The hydrological models can also project changes in other aspects of water availability that are important for risk assessment, such as variability in reservoir inflows and floods and low flows that affect ecosystems and the environment.

Figure 24. Time series of Sea Surface Temperature (SST) for the month of December from 1900 to 2010 for (a) the Coral Sea and the (b) northern tropical Australian oceanic region.





Source: Bureau of Meteorology.

A possible link between climate change and water availability is via the rise in SST (Figure 24). Based on the strong role of periodic changes in ocean-atmosphere coupling, such as ENSO, for Australia's rainfall, there is a plausible connection between the rising trend in SST and the behaviour of natural modes of variability. As noted in section 3.5 (Figure 32), observations in the eastern Pacific Ocean have shown a link between increasing SSTs, water vapour content in the atmosphere, and heavy precipitation events. The very high temperatures in the Coral Sea and the Northern Tropics in late 2010 (Figure 24) may have contributed to the very strong La Niña event in late 2010 and early 2011 and thus to the record high rainfall across eastern Australia in December 2010 (BoM 2011a). However, the extent of such an influence, and even the direction of the influence (towards stronger or weaker La Niña events) is unknown at this time. No clear trend has been seen in indices of the ENSO, or in eastern Australia rainfall over the past century, suggesting that any link between climate change, ENSO, and Australian rainfall is subtle, at least up to the present time.

The bottom line is that significant uncertainties still surround the relationship between climate change and shifts in Australian rainfall patterns, both in observations over the past several decades and in projections for the future.

It is likely that the drying trend in southwest Western Australia is linked to climate change and will continue. For much of the rest of the country, there is no strong consensus on even the direction of change – more or less – of rainfall. Climate change could, in fact, lead to more extremes in general – both in drought and in rainfall.

APART FROM THESE INSIGHTS, WHAT WE CAN SAY WITH CERTAINTY IS THAT RAINFALL PATTERNS WILL CHANGE AS A RESULT OF CLIMATE CHANGE, AND OFTEN IN UNPREDICTABLE WAYS, CREATING LARGE RISKS FOR WATER AVAILABILITY.

This daunting uncertainty not only challenges attempts at adaptation, but also enhances, not diminishes, the imperative for rapid and vigorous global mitigation of greenhouse gas emissions.

2.4 Extreme events

Many of the impacts of climate change are due to extreme weather events, not changes in average values of climatic parameters. The most important of these are high temperature-related events, such as heatwaves and bushfires; heavy precipitation events; and storms, such as tropical cyclones and hailstorms. The connection between long-term, human-driven climate change and the nature of extreme events is both complex and controversial, leading to intense debate in the scientific community and heated discussion in the public and political arenas.

This section explores our current level of understanding about the relationship between climate change and extreme events, with a focus on types of extreme events that have already occurred in Australia and are likely to occur in future. The key messages are:

- Modest changes in average values of climatic parameters – for example, temperature and rainfall – can lead to disproportionately large changes in the frequency and intensity of extreme events.
- On a global scale and across Australia it is very likely that since about 1950 there has been a decrease in the number of low temperature extremes and an increase in the number of high temperature extremes. In Australia high temperature extremes have increased significantly over the past decade, while the number of low temperature extremes has decreased.
- The seasonality and intensity of large bushfires in southeast Australia is likely changing, with climate change a possible contributing factor. Examples include the 2003 Canberra fires and the 2009 Victoria fires.

- There is little confidence in observed changes in tropical cyclone activity in the past because of problems with the lack of homogeneity of observations over time. The global frequency of tropical cyclones is projected to either stay about the same or even decrease. However a modest increase in intensity of the most intense systems, and in associated heavy rainfall, is projected as the climate warms.
- On a global scale, several analyses point to an increase in heavy precipitation events in many parts of the world, including tropical Australia, consistent with physical theory and with projections of more intense rainfall events as the climate warms.

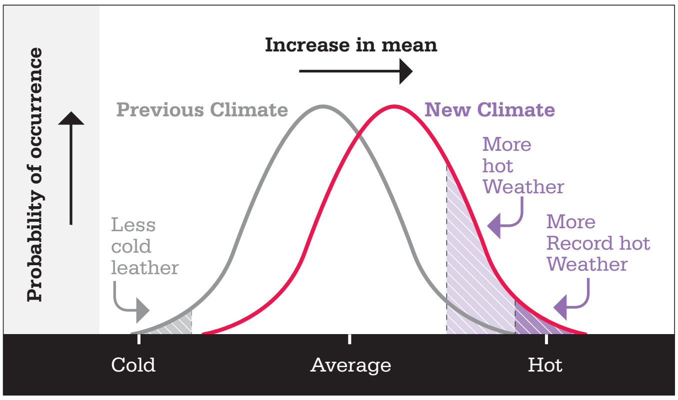
Average-extreme relationship

Temperature increases of 1 or 2 °C, or equivalent changes in other climatic parameters, may seem modest, but they can lead to disproportionately large changes in the frequency and intensity of extreme weather events.

Figure 25 shows the relationship between a change in average temperature and the incidence and severity of extreme events (IPCC 2007a). A modest shift to higher average temperatures leads to a disproportionately large increase in the number of extreme high temperature events, the area under the curve to the right of the dashed vertical line. In addition, the most extreme events become much more intense – the long "tail" at the right of the distribution. Correspondingly, extreme cold events become fewer and less extreme, as shown in the left-side of the figure. This simple picture assumes that there will be no change in the variability of temperature distribution. If variability were also increasing, then this would lead to a much larger impact in the tails.

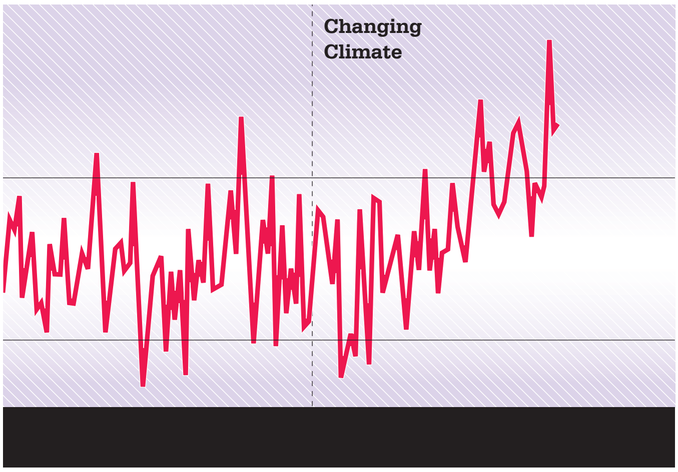
Another way to visualise the relationship between averages and extremes is shown in Figure 26, where the left-hand side of the figure shows variability around a long-term average temperature that does not change. The horizontal lines above and below the long-term average temperature show the limits above and below which extreme events are defined to occur. The right-hand side of the figure shows a rising average temperature with the same shorter-term variability imposed upon it. The figure again shows that the number of extreme high temperature events increases and the intensity of the most extreme of these events also increases.

Figure 25. Relationship between means and extremes, showing the connection between a shifting mean and the proportion of extreme events, when extreme events are defined as some fixed threshold related to a significant impact (e.g., heatwave leading to excess deaths).



Source: IPCC (2007a).

Figure 26. The increase in frequency and intensity of extreme events when an underlying, long-term trend is imposed on an existing pattern of natural variability.



Source: Adapted from Jones and Mearns (2004).

Because extreme events are, by definition, relatively rare, long time series and large spatial areas are required to obtain enough observations to determine statistically whether a change in their frequency and intensity is actually occurring. In most parts of the world, the instrumental record is at most a century or so long, and dense spatial coverage of many areas has only been achieved for a few decades, so determining from observations, with a high degree of confidence, whether any change in the frequency and intensity of extreme events is occurring is very difficult.

Temperature extremes

As described in Section 2.1, the Earth as a whole, including the Australian continent, has been warming strongly since the middle of the 20th century. Thus, it might be possible from observations to discern the beginnings of shifts in extremes that are consistent with what is expected. This is indeed the case for Australian temperature extremes (Alexander et al. 2007).

THE NUMBER OF HIGH TEMPERATURE EXTREMES (E.G. HEATWAVES) IN AUSTRALIA HAS INCREASED SIGNIFICANTLY OVER THE PAST DECADE, WHILE THE NUMBER OF LOW TEMPERATURE EXTREMES HAS DECREASED (FIGURE 27).

An increase in warm nights has also occurred across most of the continent and this is consistent with anthropogenic climate change (Alexander and Arblaster 2009; Figure 27). Changes in Melbourne temperatures provide a good example of the shifts in the frequency and intensity of extremes depicted schematically in Figure 25. The long-term average in the number of days per year 35 °C or above is 10 (BoM 2011c). During the decade 2000-2009, the number of such days per year rose to 13 (BoM 2011c). Furthermore, the increased intensity of extreme events – the long tail to the right in Figure 25 – is clearly evident in Melbourne with the record high temperature of 46.4 °C in February 2009, and the three consecutive days of 43 °C or above in late January.

Sea surface temperature

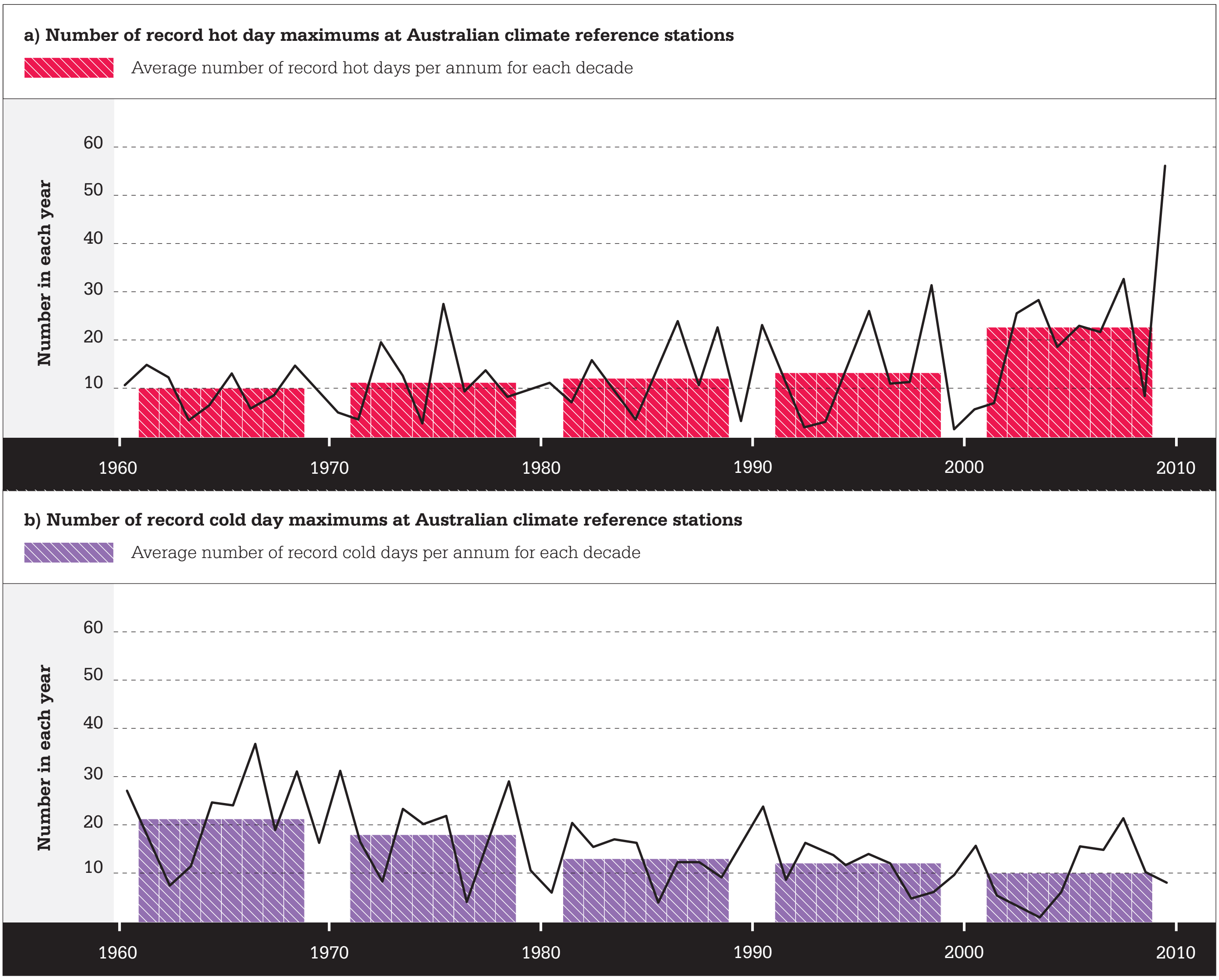
Coral-dominated ecosystems are sensitive to small rises in the temperature of the water in which they reside. This sensitivity results from the breakdown of a symbiosis between corals and tiny organisms called dinoflagellates, which are photosynthetically active and provide corals with organic carbon. When the sea temperature rises 1-2 °C above normal for a six to eight week period, this symbiosis breaks down, the dinoflagellates are expelled, and the corals are "bleached". Corals can recover from a bleaching event, but sustained or repeated bleaching can lead to starvation, disease and death (Hoegh-Guldberg 1999).

Rising sea surface temperature (Figure 24) has increased the number of bleaching events that have been observed on the GBR over the last few decades, consistent with global trends showing increasing incidence of bleaching events since 1979 (Hoegh-Guldberg 1999; Wilkinson 2008). The GBR has fared better than many reefs around the world, although parts of the reef have experienced bleaching events in 1980, 1982, 1983, 1987, 1992, 1994, 1998, 2002 and 2006 – with the 1998 and 2002 events the worst on record for the GBR (Berklemans et al. 2004). In these events over 50% of the GBR bleached in the exceptionally warm conditions, with an estimated loss of 5-10% of corals in each event (GBRMPA 2009).

Bushfire intensity and frequency

Extreme events that are closely related to temperature are also showing changes consistent with what is expected. The intensity and seasonality of large bushfires in southeast Australia appears to be changing, with climate change a possible contributing factor (Cai et al. 2009c). Bushfires have long been a feature of ecosystems in the southeast; the 1939 fires in Victoria are an often-quoted example of large and intensive fires. However, in the first decade of the 21st century, two very large and extremely intense fires occurred – the 2003 Canberra fires, which destroyed 500 houses in suburban Canberra and killed three people, and the 2009 Victoria fires, which killed 173 people in rural areas of the state.

Figure 27. Number of (a) record hot day maximums and (b) record cold day maximums at Australian climate reference stations.



Source: Bureau of Meteorology.

Climate change affects fire regimes in at least three ways (Williams et al. 2009; Lucas et al. 2007). First, changing precipitation patterns, higher temperatures and elevated atmospheric CO_2 concentrations affect the biomass and composition of vegetation, the fuel load for fires. Second, higher temperatures tend to dry the fuel load, making it more susceptible to burning; drought conditions can significantly exacerbate these conditions. Third, climate change increases the probability of extreme fire weather days – conditions with extreme temperature, low humidity and high winds.

The severity of bushfires in southeast Australia is strongly pre-conditioned by low rainfall and high temperature induced by the positive phase of the Indian Ocean Dipole. Since 1950, the majority of large bushfires in southeast Australia, including the Ash Wednesday, Canberra, and Black Saturday bushfires, occurred following a positive IOD event in the preceding spring season, which led to warm and dry conditions (Cai et al. 2009c). Since 2002, the Indian Ocean has experienced five positive IOD events (2002, 2004, 2006, 2007, 2008), with climate change a contributor to the increasing frequency of these events (Cai et al. 2009b).

Tropical cyclones

The relationship between tropical cyclone behaviour and climate change is a particularly complex one, with a high degree of uncertainty in our current understanding. Observational records show no changes beyond natural variability in either the frequency of cyclones or their storm tracks. With the advent of satellite measured intensities of tropical cyclones in 1980, some studies have found a possible link between cyclone intensity and higher sea surface temperatures (e.g. Elsner et al. 2008). However, some of the satellite data is questionable (e.g. over the Indian Ocean), and time period is too short to separate out decadal patterns of natural variability from the underlying trend of rising SST (Knutson et al. 2010). In short, given the short observational period and the changing observational capability through time, it is not yet possible to attribute any aspect of changes in cyclone behaviour (frequency, intensity, rainfall, etc.) to climate change; all observations currently remain within the envelope of natural variability (Knutson et al. 2010).

Heavy precipitation events

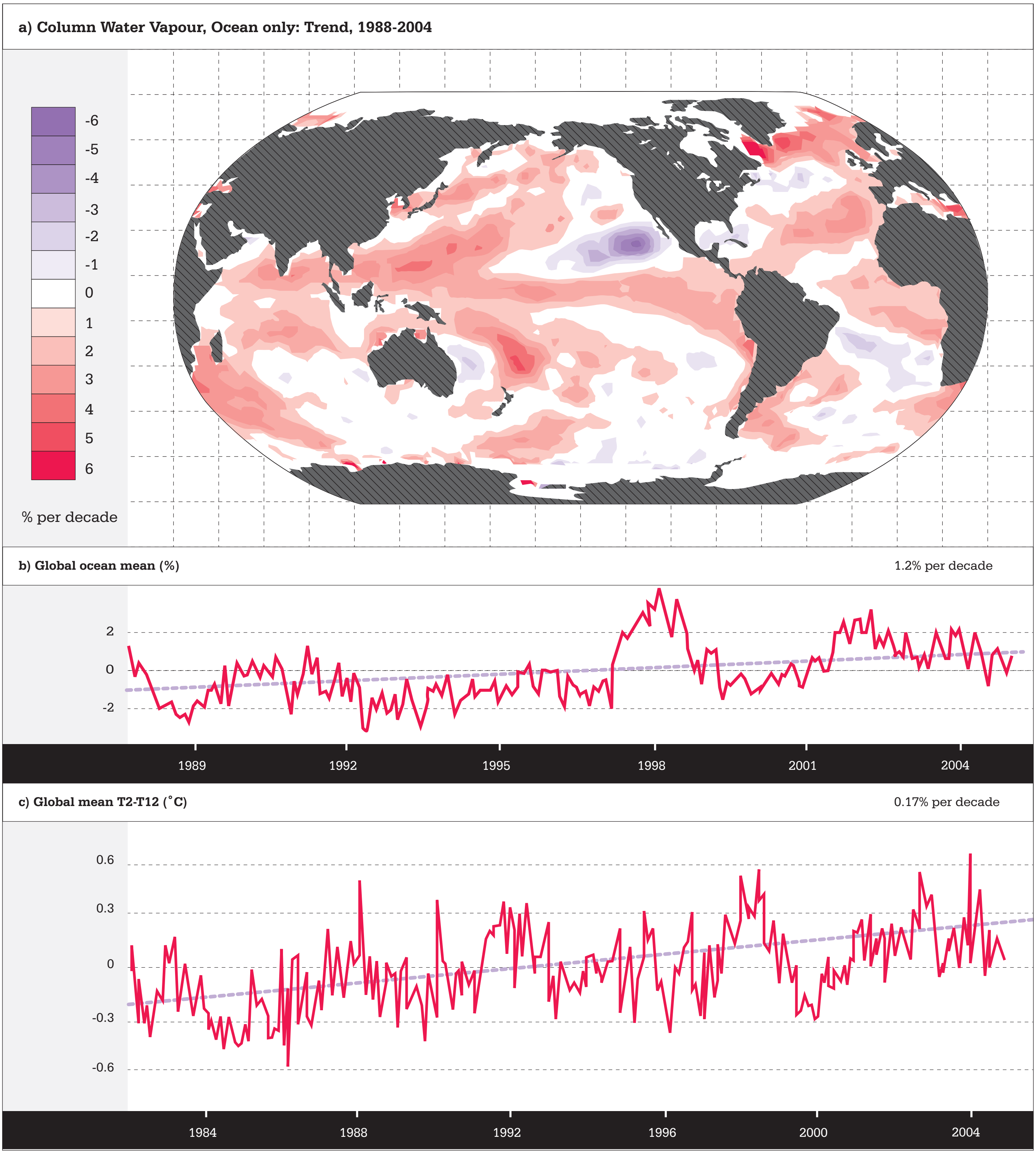
THE SEVERE FLOODING IN QUEENSLAND AND VICTORIA IN EARLY 2011 HAS RAISED THE QUESTION OF A POSSIBLE LINK BETWEEN THE FLOODS AND HUMAN-INDUCED CLIMATE CHANGE.

The severity of the floods is related to several factors, including the intensity of the rainfall event(s) that triggered the floods, the condition of the catchments upstream of and within the flooding area, the effectiveness of structures such as dams designed to ameliorate flooding, and the vulnerability of people and infrastructure to flooding. Here we deal only with the possible connection between climate change and the frequency or severity of extreme rainfall events.

The floods across eastern Australia in 2010 and early 2011 were the consequence of a very strong La Niña event, and not the result of climate change. That is, the underlying cause of the floods is a natural part of climate variability, which is part of the reason why Australia has always been a “land of droughts and flooding rains”. The extent, if any, of the influence of the warming planet on the intensity of these heavy rains and floods is simply unknown at this time. There is no evidence that the strength of La Niña events is increasing due to climate change.

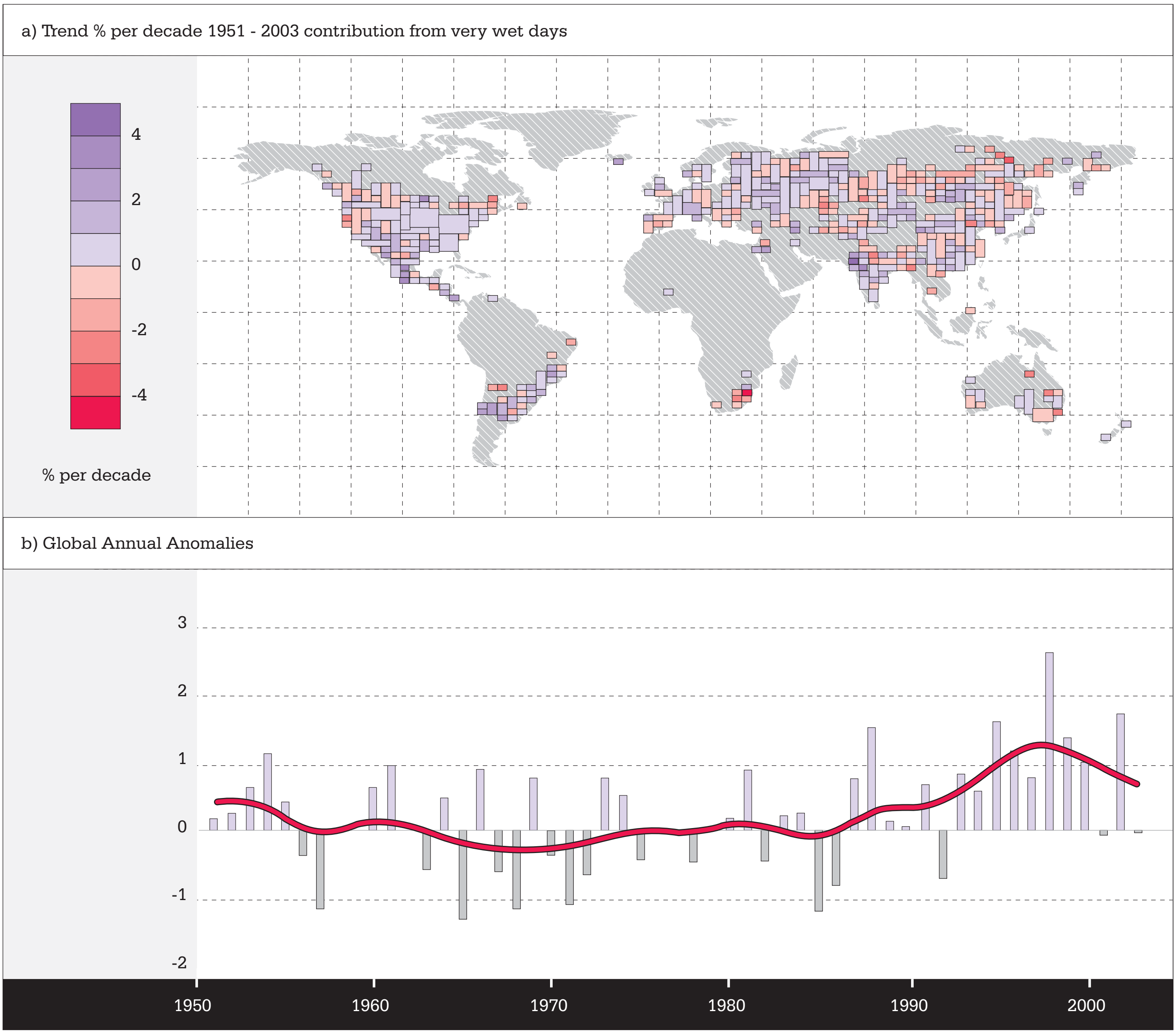
The physical connection between a warming climate and more rainfall is relatively straightforward. Higher temperatures, especially of the surface ocean, lead to more evaporation; this leads to higher water vapour content in a warmer atmosphere (which can hold more water vapour); and this in turn induces more precipitation.

Figure 28. (a) Linear trends in precipitable water (total column water vapour) in % per decade; (b) monthly time series of anomalies relative to the 1988 to 2004 period in % over the global ocean plus linear trend (broken purple line); and (c) monthly time series of global mean (80 °N to 80 °S) anomalies of T2-T12 (an atmospheric radiative signature of upper-trophospheric moistening) relative to 1982 to 2004.



Source: IPCC (2007a), updated from Trenberth et al. (2005) and Soden et al. (2005).

Figure 29. (a) Observed trends (% per decade) for 1951-2003 in the contribution to total annual precipitation from very wet days (95th percentile). Trends were only calculated for grid cells where both the total and the 95th percentile had at least 40 years of data during this period and had data until at least 1999. **(b) Anomalies (%) of the global annual time series (relative to 1961-1990) defined as the percentage change of contributions of very wet days from the base period average (22.5%).** The smooth red curve shows decadal variations.



Source: IPCC (2007a), based on Alexander et al. (2006).

The IPCC assessment (2007a) of observations on a global scale shows an increase in atmospheric water vapour from 1988 to 2004 (Figure 28) as well as increases in precipitation in many parts of the world, with a substantial increase in heavy precipitation events (Figure 29). A recent study (Min et al. 2011) comparing observed and model-simulated patterns of extreme precipitation events found that over the Northern Hemisphere land area with sufficient data coverage (about two-thirds of the total area), human-driven increases in greenhouse gas concentrations have contributed to the observed intensification of heavy precipitation events. However, there is no consistent evidence of an observed increase in heavy precipitation events over most parts of Australia at this time.

At the continental scale a 100-year record from the United States shows a sharp increase in the area of the U.S. experiencing very heavy daily precipitation events (Gleason et al. 2008; Figure 30). A recent analysis of temperature and rainfall extremes in Australia using a combined climate extremes index shows, over the whole continent and for all seasons, an increase in the extent of hot and wet extremes and a decrease in the extent of cold and dry extremes annually from 1911 to 2008 at a rate of between 1% and 2% per decade (Gallant and Karoly 2010). These trends are primarily driven by changes in tropical regions during summer and spring. While such continental-scale analyses in both the U.S. and Australia show trends consistent with a warming planet, it is difficult to attribute them unequivocally to climate change because of the considerable natural variability in rainfall patterns.

Determining a link between climate change and extreme events becomes even more difficult for single extreme events, such as the heavy rainfall event that triggered the floods in southeast Queensland in January 2011. This is especially difficult for eastern Australia in general, where modes of natural variability, such as ENSO and the Indian Ocean Dipole (IOD), play a very important role in influencing rainfall patterns.

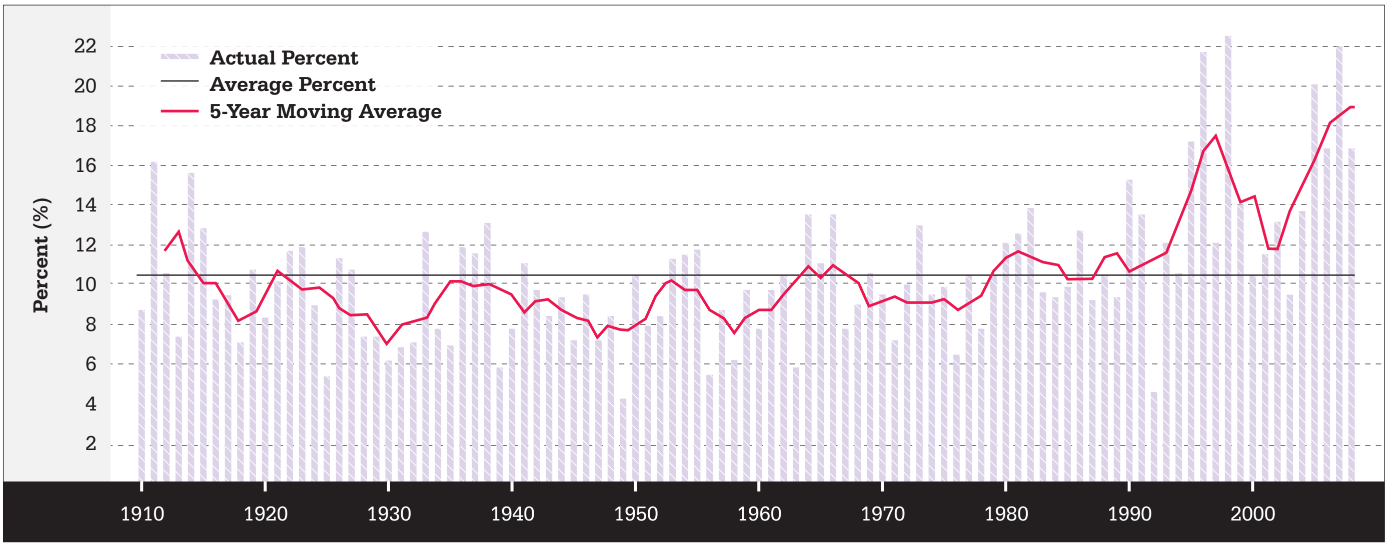
During the second half of 2010 a strong La Niña event developed across the Pacific, with the SOI (Southern Oscillation Index) - an indicator for the state of the ENSO system - showing record positive values for October and December 2010 (BoM 2011b). La Niña events normally bring heavy rainfall to eastern Australia. In the present case the strong La Niña event was accompanied by a positive phase of the IOD, which is associated with unusually warm ocean waters around Indonesia. The combination of a La Niña event and a positive IOD is relatively rare, but they reinforce each other to bring wetter-than-usual conditions across much of Australia. Thus, these two modes of natural variability alone could have generated the heavy precipitation events that occurred in eastern Australia in December 2010 and January 2011.

However, long-term human-induced climate change may also be a factor.

SEA SURFACE TEMPERATURES (SST) HAVE WARMED NEARLY EVERYWHERE OVER THE PAST CENTURY, INCLUDING AROUND AUSTRALIA (FIGURE 31).

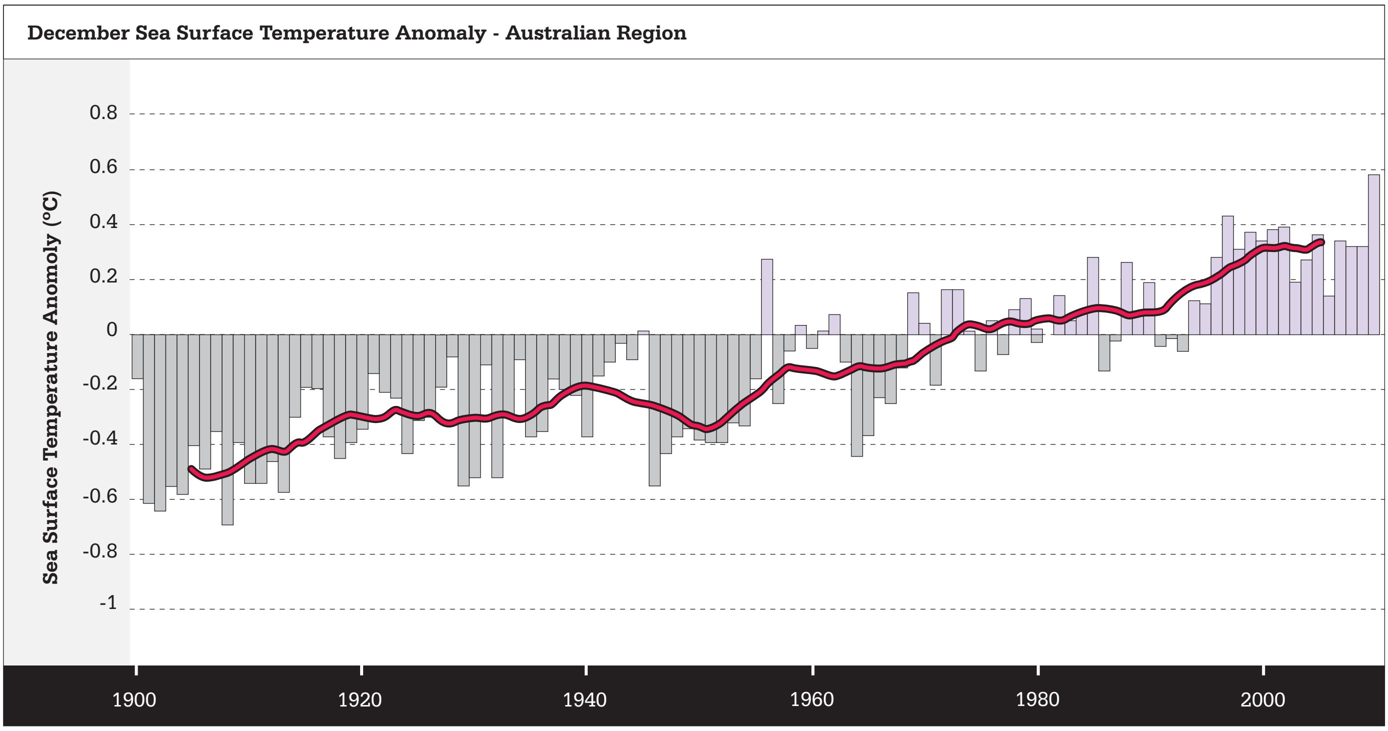
This *additional* warmth in the upper ocean – SSTs in the northern Australian region are currently at or near record levels and are much warmer for this La Niña event than for previous strong La Niña events (Figure 24) – may possibly have enhanced precipitation and led to an even more intense precipitation event than would otherwise have occurred, although such enhancement has yet to be demonstrated.

Figure 30. Time series of the annual values of the percentage area of the United States with a much greater than normal proportion of precipitation originating from very heavy (equivalent to the highest tenth percentile) 1-day precipitation amounts.



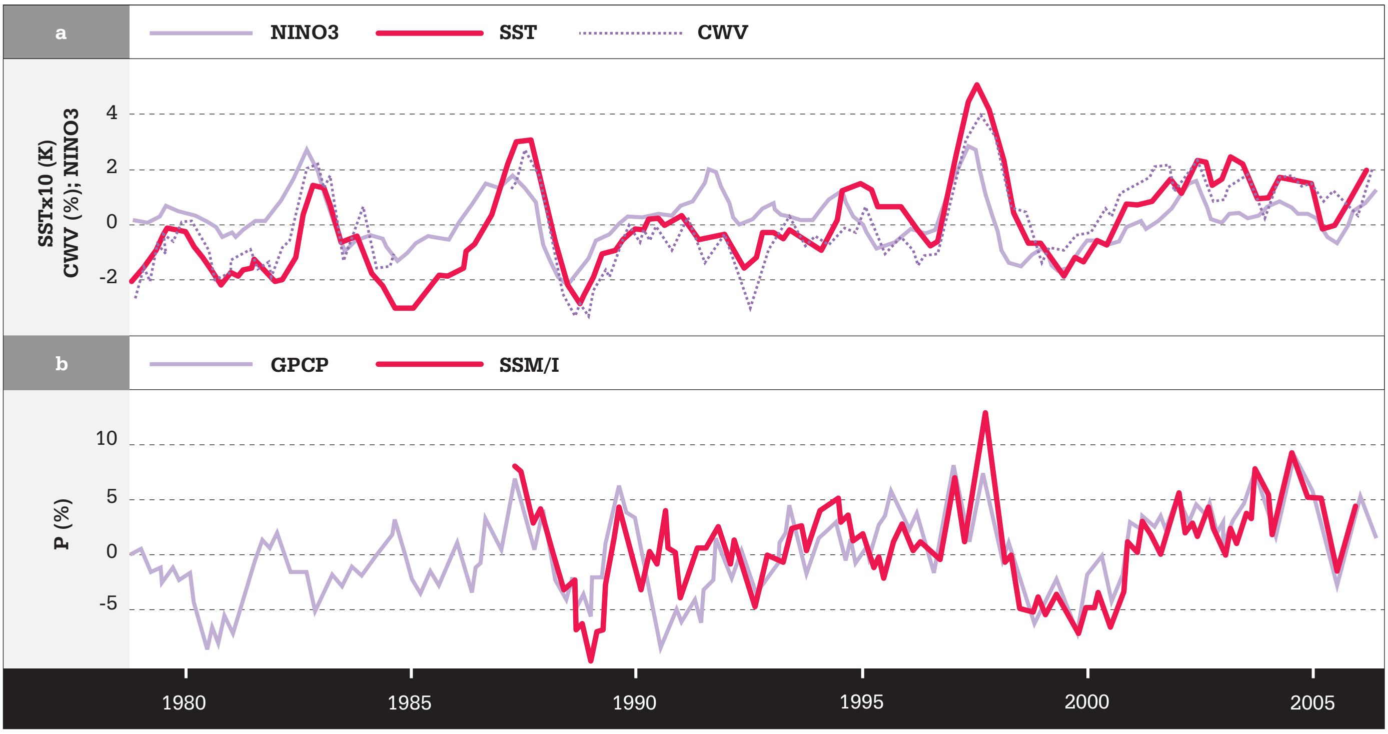
Source: Gleason et al. (2008), updated by NOAA at www.ncdc.noaa.gov/oa/climate/research/cei/cei.html

Figure 31. Times series of SST for the month of December from 1900 to 2010 for the oceanic region around Australia.



Source: Bureau of Meteorology.

Figure 32. Time series of (a) Niño-3 ENSO index (SST anomalies for 90° to 150 °W, 5 °S – 5 °N region, deseasonalised tropical ocean (30 °S to 30 °N) mean anomalies of SST, and column-integrated water vapour (CWV); and (b) precipitation (P).



Source: Allan and Soden (2008).

There is observational evidence that shows a link between SST and rainfall extremes (Figure 32). The top panel of the figure shows a 28-year record of an ENSO index, the sea surface temperature and the column-integrated water vapour in the tropical atmosphere. The three are closely related, with ENSO dominating the interannual variability. The bottom panel shows two observations of precipitation, again showing the prominent ENSO pattern, and also showing the strong correlation between heavy rainfall events and periods of high SSTs. However, despite a substantial warming of the ocean around northern Australia (Figure 24), there is no evidence yet of a trend towards increased precipitation in eastern Australia over the past 50 years, although, as noted above, Gallant and Karoly (2010) found an increase in the extent of hot and wet extremes in the tropical regions of Australia from 1911 to 2008 at a rate of between 1% and 2% per decade.

Looking towards the future, Rafter and Abbs (2009) used extreme value theory to examine changes in the intensity of extreme rainfall as simulated by climate models. Their results showed increases in all regions for 2055 and 2090 for most models considered. The spatial patterns were consistent with previous studies, with smaller increases in the south of Australia and larger increases in the north. Fine-scale regional climate modelling (e.g. Abbs *et al.*, 2007; Abbs and Rafter, 2009) suggests increases in daily precipitation extremes on average, although with large fine-scale spatial variability. The study found short duration (sub-daily) rainfall will change more rapidly than longer duration (daily and multi-day) rainfall.

The bottom line is that although a conclusive link between the southeast Queensland rainfall events and climate change cannot be made, such a link is plausible even if it is not discernible yet. From a risk perspective, this is useful knowledge, and suggests that it would be prudent to factor in a climate change-induced increase in intense rainfall events in urban and regional planning, the design of flood mitigation works, and any reviews of emergency management procedures.

2.5 Abrupt, non-linear and irreversible changes in the climate system

Many projections of future changes in climatic variables are simulated and presented as smooth curves from present values to an altered state at some future point in time. The temperature projections to 2100 highlighted in the IPCC reports are a good example of this. However, smooth changes are not the norm in the climate system. Often the system seems unresponsive to forcing agents until a threshold is reached, after which the system rapidly changes or reorganises into an alternate state. The abrupt drop in rainfall in the mid-1970s in southwest Western Australia is a well-known Australian example. Some changes in the climate system can be irreversible in any timeframe relevant to human affairs, such as the loss of the Greenland ice sheet.

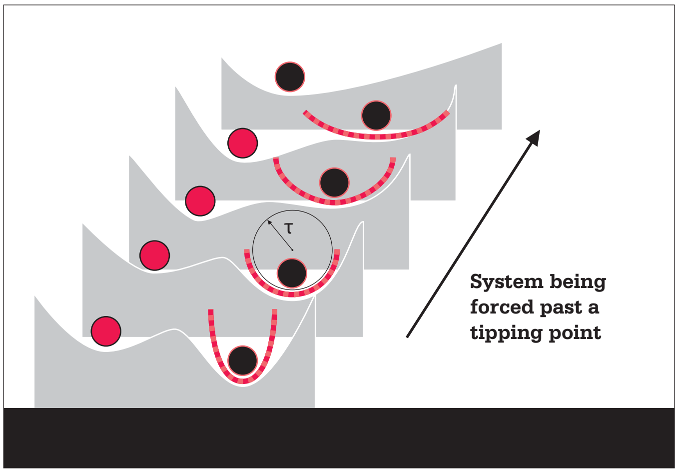
In this section we present a brief summary of the current knowledge base on the potential for abrupt, irreversible changes in the climate system:

- A number of potential abrupt changes in large sub-systems or processes in the climate system – so-called "tipping elements" – have been identified largely through palaeo-climatic research. Many of these, if triggered, would lead to catastrophic impacts on human societies.
- Examples of tipping elements include abrupt changes in the North Atlantic ocean circulation, the switch of the Indian monsoon from a wet to a dry state or vice versa, and the conversion of the Amazon rainforest to a grassland or a savanna.
- Very large uncertainties surround the likelihood, or not, of human-driven climate change triggering any of these abrupt or irreversible changes. Experts agree that the risk of triggering them increases as temperature rises.
- Abrupt shifts in atmospheric circulation can occur very quickly and can have large impacts on regional climates. The recent cold, snowy winters in northern Europe, and their possible link to climate change, comprise a good example of this risk.

The science of abrupt change

While it is common, even in many parts of the scientific community, to employ cause-effect logic and linear thinking (a change in a causal agent drives an appropriately scaled response), the growth of complex system science has brought a new perspective to observing and interpreting changes in the climate system. The phenomenon of abrupt, highly nonlinear changes, which often occur when an apparently small change in a forcing agent triggers an unexpected, large, complex response in the system, has recently been reviewed in the context of the climate system (Lenton et al. 2008; Figure 33).

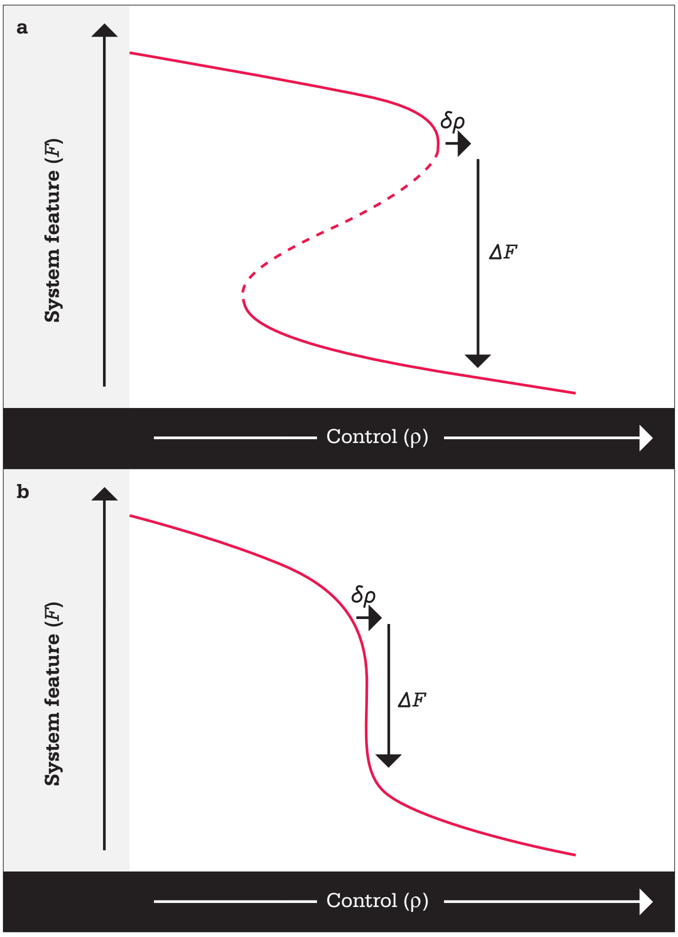
Figure 33. Schematic representation of a system being forced past a tipping point. The system's response time to small perturbations, τ, is related to the growing radius of the potential well.



Source: H. Held, from Lenton et al. (2008).

Figure 34 is a schematic of two types of abrupt change in a complex system such as climate – so-called "tipping elements" – one a mono-stable system showing threshold, abrupt change behaviour and the other showing bistability when a threshold is crossed. An important feature of a tipping element is that it must contain a strong positive (reinforcing) feedback process in its internal dynamics. In addition, tipping elements can have varying degrees of irreversibility. For example, although the large polar ice sheets on Greenland and Antarctica have waxed and waned in geological timescales, they are essentially irreversible on timescales of relevance to human affairs.

Figure 34. Schematic of two types of tipping element that can exhibit a tipping point where a small change in control (δρ) results in a large change in a system feature (ΔF), illustrated here in terms of the time-independent equilibrium solutions of the system: (a) A system with bi-stability passing a true bifurcation point. (b) A mono-stable system exhibiting highly non-linear change.



Source: T.M. Lenton, published in Richardson et al. (2011).

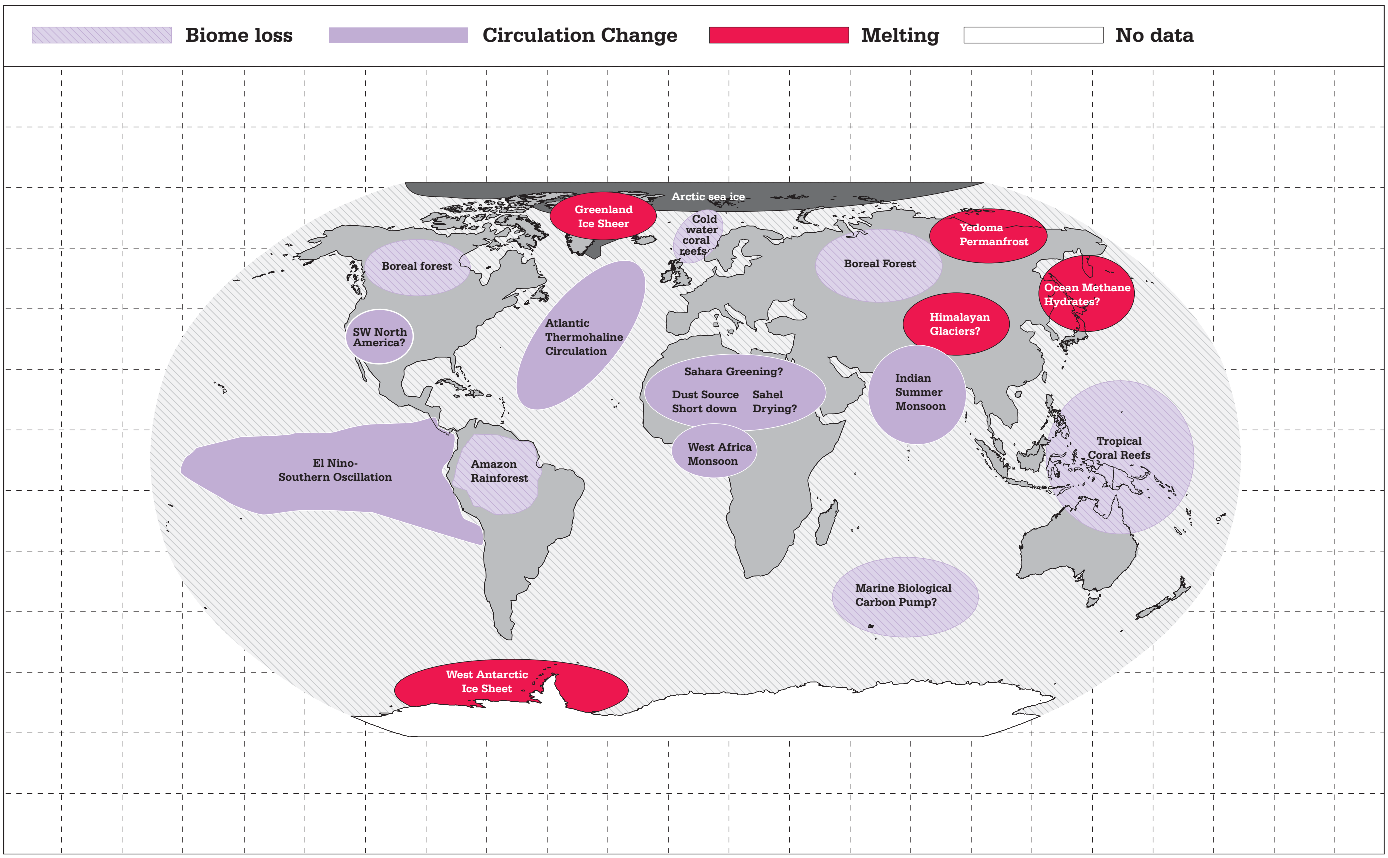
Examples of tipping elements in the climate system

There are many examples of tipping elements in the climate system (Figure 35); it is useful to classify them into those associated with the melting of large masses of ice, those involving significant changes to unique biomes, and those associated with large-scales changes in the circulation of the atmosphere and the ocean (Richardson et al. 2011).

THE GREENLAND AND ANTARCTIC ICE SHEETS MAY NOT SEEM LIKE CANDIDATES FOR TIPPING ELEMENTS AS THEIR RATE OF CHANGE IS NOT "ABRUPT" FROM A HUMAN PERSPECTIVE, BUT THEY ARE DEFINITELY TIPPING ELEMENTS IN THAT BEYOND A RATHER NARROW RANGE OF TEMPERATURE CHANGE, THEY WILL BE COMMITTED TO IRREVERSIBLE MELTDOWN (HUYBRECHTS AND DE WOLDE 1999).

The accelerating downward trend in the loss of Arctic sea ice is indicative of threshold-abrupt change behaviour in which the threshold may already have been crossed (Perovich 2011), although the loss of summer sea ice is not irreversible and could quickly recover with a return to a colder climate.

Figure 35. Map of potential policy-relevant tipping elements, adjusted from Lenton et al. (2008) based on further analysis by T.M. Lenton reported in Richardson et al. (2011). Question marks indicate systems whose status as policy-relevant tipping elements is particularly uncertain.



Source: V. Huber, T.M. Lenton and H.J. Schellnhuber, published in Richardson et al. (2011).

The Amazon rainforest is the most widely quoted example of a large biome at risk of abrupt change from a warming climate. The climate-related forcing factors include both rising temperature and a potential increase in the length of the dry season and the intensity of droughts. A prominent feedback is the way in which a rainforest stores and recycles water. Ecological disturbance processes, such as fires and insect infestations, may also become important feedback processes. Simulations that incorporate these ecological processes suggest that a threshold exists around a 2 °C temperature increase, beyond which the area of the Amazon forests committed to dieback rises rapidly from 20% to over 60% (Jones and Lowe 2011). Severe droughts in the Amazon Basin in 2005 and 2010, along with the observation that such droughts co-occur with peaks of fire activity, support this risk assessment (Lewis et al. 2011).

Perhaps the archetypal example of a tipping element is the Atlantic thermohaline circulation (THC), which in its current mode contributes significantly to the mild climate experienced by western Europe and Scandinavia but which has shown threshold-abrupt change behaviour in the past (e.g., Dansgaard-Oeschger events, Ganopolski and Rahmstorf 2001). A collapse of the THC could lead to a reduced level of warming in the north Atlantic region compared to the global average. Current understanding of the THC system suggests that the threshold for collapse is still rather remote (IPCC 2007a), but that a weakening of the strength of the circulation is likely through this century (Weber and Drijfhout 2011). The THC is an example of a circulation-related tipping element. Others include the El Niño Southern Oscillation (ENSO) and the West African Monsoon, both examples of coupled ocean-atmosphere circulation.

Likelihood of triggering abrupt changes

Much of the interest in tipping elements derives from the very large risks for human well-being associated with activation of many of the tipping elements. For example, loss of significant amounts of the Greenland and Antarctic ice sheets would lead to metres of sea-level rise. The Asian monsoon, or more precisely the Indian Summer Monsoon, is a tipping element whose behaviour is influenced by both the warming of the Indian Ocean and the presence of an "atmospheric brown cloud" over much of the sub-continent. Some models suggest a tipping point related to changes in regional albedo, leading to sudden switches in the strength and location of monsoonal rains (Zickfeld et al. 2005; Levermann et al. 2009). Given that over a billion people directly depend on the reliable behaviour of the Indian Summer Monsoon for their food production, rapid changes in rainfall could have catastrophic consequences for large numbers of people.

Table 1 gives an example of how a risk assessment on tipping elements might be carried out (Richardson et al. 2011). The assessment is based on the combination of the likelihood of the tipping element being activated and the impact on human well-being of a change of state of the tipping element. Of the tipping elements considered, it is interesting that the highest risks are associating with the loss of ice from the large polar ice sheets. Risks associated with the Atlantic thermohaline circulation and the behaviour of ENSO are considered to be rather low primarily because of the small likelihood that a tipping point will be passed.

Abrupt shifts in atmospheric circulation

Tipping elements associated with changes in atmospheric circulation, or coupled ocean-atmosphere circulation, are especially important because of the short time scales on which they can operate. The bi-stability of the Indian Summer Monsoon, noted above, is an example of a large shift in atmospheric circulation that can happen very quickly, even on an annual basis. The recent cold, snowy winters (2005-06, 2009-10, 2010-11) in parts of northern Europe and North America (Figure 2), and their possible link to climate change, comprise another good example of risks associated with this type of tipping element.

Although it sounds counter-intuitive, such cold weather may be linked to the overall warming of the planet. More specifically, a possible link is via the loss of Arctic sea ice in winter and the consequent formation of a high pressure cell over the polar region (Petoukhov and Semenov 2010). This cell changes pressure gradients in the north Atlantic region, rearranging Northern Hemisphere atmospheric circulation and generating cold, easterly airflows over much of western Europe. This change represents an abrupt transition between two states of the circulation. Interestingly, the threshold for the abrupt shift in circulation lies near 40% reduction in sea ice, but another transition, flipping the circulation back to the earlier regime, is projected to exist at about 80% reduction in sea ice.

Table 1. A simple 'straw man' example of tipping element risk assessment, by Timothy M. Lenton

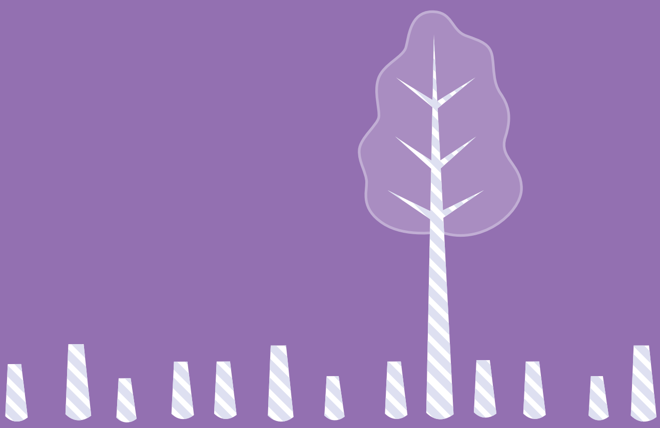
Tipping element	Likelihood of passing a tipping point (by 2100)	Relative impact** of change in state (by 3000)	Risk score (likelihood x impact)	Risk ranking
Arctic summer sea-ice	High	Low	3	4
Greenland ice sheet	Medium-High*	High	7.5	1 (highest)
West Antarctic ice sheet	Medium*	High	6	2
Atlantic THC	Low*	Medium-High	2.5	6
ENSO	Low*	Medium-High	2.5	6
West African monsoon	Low	High	3	4
Amazon rainforest	Medium*	Medium	4	3
Boreal forest	Low	Low-Medium	1.5	8 (lowest)

* Likelihoods informed by expert elicitation

** Initial judgment of relative impacts is the subjective assessment of T.M.L.

CHAPTER 3: IMPLICATIONS OF THE SCIENCE FOR EMISSION REDUCTIONS

DID YOU KNOW...



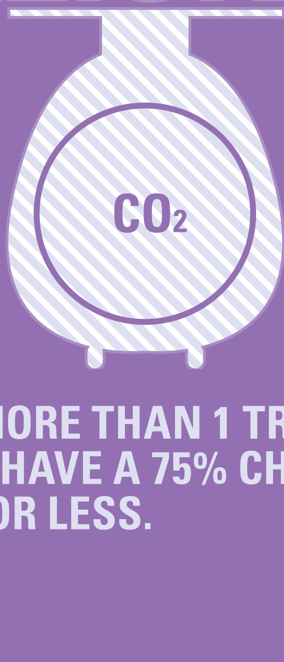
ABOUT 15-20% OF NET CO_2 EMISSIONS GLOBALLY HAVE ORIGINATED FROM LAND ECOSYSTEMS, PRIMARILY FROM DEFORESTATION.

2020

THE PEAKING YEAR FOR EMISSIONS IS VERY IMPORTANT FOR THE RATE OF REDUCTION THEREAFTER. THE DECADE BETWEEN NOW AND 2020 IS CRITICAL.

ONE TRILLION TONNES

2000



2050

HUMANITY CAN EMIT NOT MORE THAN 1 TRILLION TONNES OF CO_2 BETWEEN 2000 AND 2050 TO HAVE A 75% CHANCE OF LIMITING TEMPERATURE RISE TO 2 °C OR LESS.

3.1 The budget approach

Although the targets-and-timetables approach (e.g. an agreed percentage reduction in greenhouse gas emissions by 2020) remains the most common approach to defining trajectories for climate mitigation, the budget, or cumulative emissions, approach is rapidly becoming the favoured approach in analyses in the scientific community. It offers a much simpler, easier-to-understand, transparent and powerful framework to estimate what level of emission reductions is required to meet the 2 °C guardrail.

This section outlines the conceptual framework for the budget approach and its implications for mitigation strategies:

- The budget approach directly links the projected rise in temperature to the aggregated global emissions in Gt CO_2 or Gt C for a specified period, usually 2000 to 2050 or 2100. For example, humanity can emit not more than 1 trillion tonnes of CO_2 between 2000 and 2050 to have a probability of about 75% of limiting temperature rise to 2 °C or less.
- Given an overall carbon budget between 2000 and 2050, the approach does not stipulate any particular trajectory, so long as the overall budget is respected. This allows a strategy that delivers least cost to the economy over time in making the transition to a low- or no-carbon economy.

Conceptual framework.

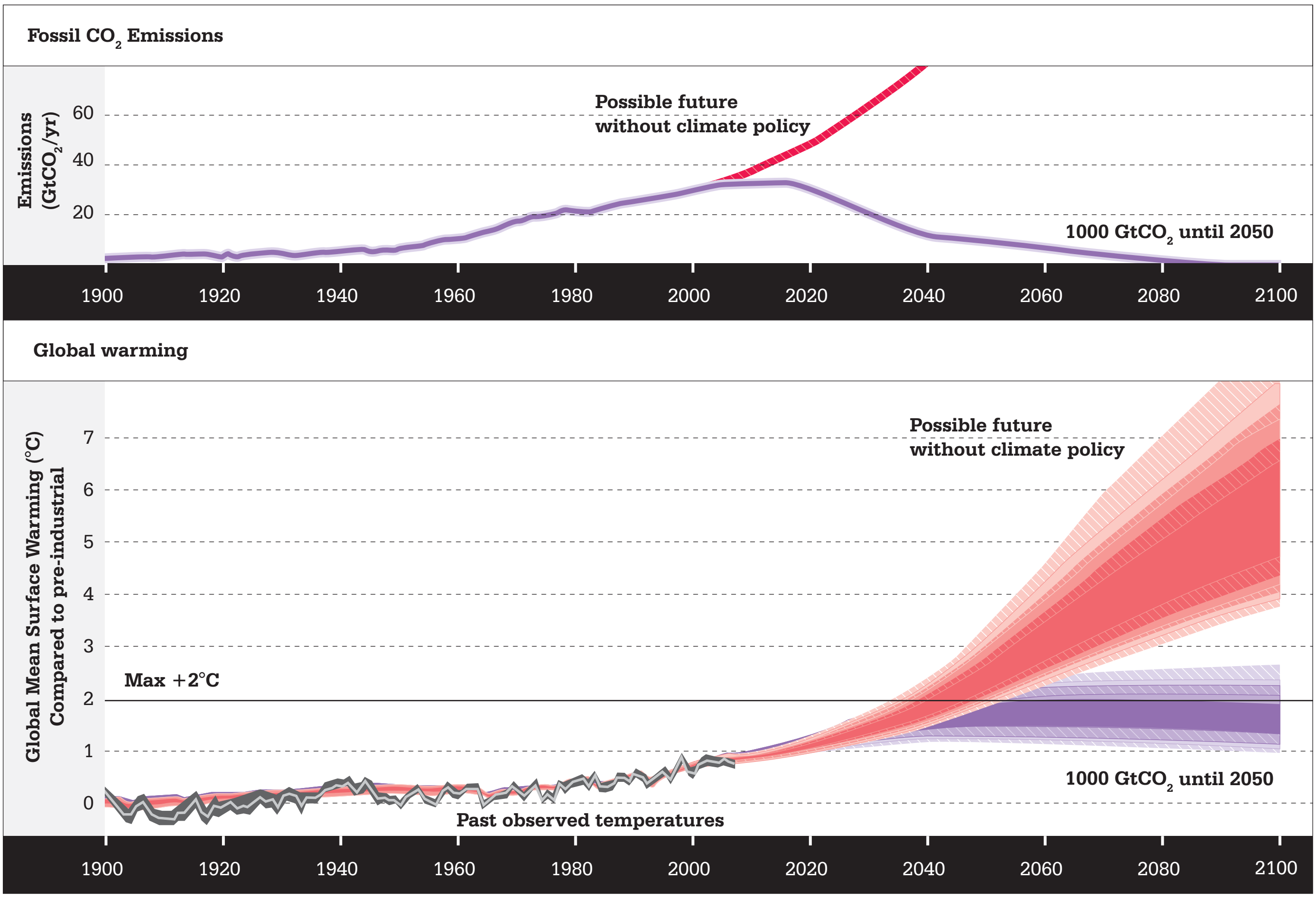
The budget approach avoids the explicit use of targets for the stabilisation of atmospheric CO_2 or CO_2-equivalent concentrations by directly linking the projected rise in temperature to the aggregated global emissions (in Gt CO_2 or Gt C) for a specified period, usually 2000 to 2050 or 2100. That is, it is based on the degree of climate change that we can expect in future estimated directly from the sum of additional greenhouse gases that are emitted to the atmosphere (e.g., Allen et al. 2009; Meinshausen et al. 2009; Figure 36). The relationship is not deterministic but rather probabilistic, given uncertainties in our understanding of the sensitivity of climate to a particular increase in the amount of greenhouse gases in the atmosphere.

To apply the concept, if we wish to have a 75% chance of observing the 2 °C guardrail, we can emit no more than 1000 Gt (one trillion tonnes) of CO_2 in the period from 2000 to 2050. If want to achieve a 50:50 chance of observing the guardrail, then we can emit 1440 Gt in the period. In the first nine years of the period (2000 through 2008), humanity emitted 305 Gt of CO_2, over 30% of the total budget in less than 20% of the time period.

Strategic implications.

Given an overall budget between now and 2050, the approach does not stipulate any particular trajectory, so long as the overall budget is respected. This approach allows, in making the transition to a low- or no-carbon economy, a flexible approach that delivers least cost to the economy, not only across sectors in the economy at any particular time, but also through time from the present to mid-century and beyond. As it is the cumulative emissions over time that must be limited, rather than a series of interim emission reduction targets that must be met, many emission reduction trajectories are possible. However, the later emission reduction trajectories are initiated, the more difficult and costly they become (Garnaut 2008).

Figure 36. Top: Fossil fuel CO_2 emissions for two scenarios: one "business as usual" (red) and the other with net emissions peaking before 2020 and then reducing sharply to near zero emissions by 2100, with the cumulative emission between 2000 and 2050 capped at 1 trillion tonnes of CO_2 (purple). Bottom: Median projections and uncertainties of global-mean surface air temperature based on these two emissions scenarios out to 2100. The darkest shaded range for each scenario indicates the most likely temperature rise (50% of simulations fall within this range).



Source: Australian Academy of Science (2010), adapted from Meinshausen et al. (2009).

3.2 Implications for emission reduction trajectories

Although the budget approach allows more flexibility in the economic and technical pathways to emissions reductions than does a targets-and-timetables approach, the fact that we have already consumed over 30% of our post-2000 budget means that much of that flexibility has been squandered if we wish to avoid the escalating risks associated with temperature rises beyond 2 °C. Thus, there is no room for any further delay in embarking on the transition to a low- or no-carbon economy.

The key messages of this section are:

- Reducing emissions of CO_2 does not reduce or stabilise its concentrations in the atmosphere; it slows the rate of increase of CO_2 concentration. To stabilise the concentration of CO_2 requires emissions to be reduced to very near zero.
- The peaking year for emissions is very important for the rate of reduction thereafter. The decade between now and 2020 is critical.
- Targets and timetables are, in principle, less important in the budget approach, but the urgency of bending emission trajectories downwards this decade implies that more ambitious targets for 2020 are critical in preventing delays in the transition to a low- or no-carbon economy.

Emissions trajectories

Figure 37 (WBGU 2009) shows three of the multitude of trajectories for global emissions that are possible under the budget approach to have a 67% probability of meeting the 2 °C guardrail. It is clear from the figure that global emissions will need to be reduced to very close to zero by 2050 to meet this challenge, that is, to stabilise the CO_2 concentration at a value compatible with the 2 °C guardrail. Less ambitious emission reductions will slow the accumulation of CO_2 in the atmosphere, but its concentration will continue to rise.

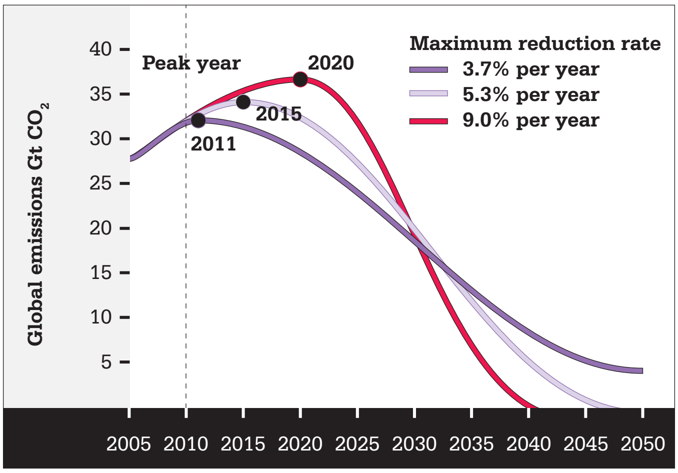
Figure 37 also shows that the peaking year for emissions is especially important for the rate of reduction thereafter. For example, delaying the peaking year by only nine years, from 2011 to 2020, changes the maximum rate of emission reduction from 3.7% per annum, which is very challenging but perhaps achievable, to 9.0% per annum, which is impossible on anything but a wartime footing.

IN SUMMARY, IN TERMS OF MEETING THE 2 °C GUARDRAIL, THE DECADE BETWEEN NOW AND 2020 IS CRITICAL.

Targets and timetables

The more familiar approach of constricting the emissions trajectory to a timetable with a set of interim targets becomes less important in the budget approach. The strategic challenge changes from whether the 2020 target is a 5%, 25% or 40% reduction against a particular baseline to how do we implement the transition to a low- or no-carbon economy by 2050 with the least economic and social cost while staying within the budget? For example, the middle trajectory of Figure 37, with a peaking year of 2015, has a global emissions level for 2020 of about 32 Gt CO_2, which is about the same as for 2010, and much higher than for 1990, the Kyoto baseline. The curves of Figure 37 are for global emissions, though, and industrialised countries would be expected to have much larger emission reductions than the global average.

Figure 37. Three emission trajectories based on the budget approach and giving a 67% probability of meeting the 2 °C guardrail.



Source: WBGU (2009).

The connection between the budget approach and the more familiar targets and timetables approach is clear once a desired trajectory is established based on a nation's overall carbon budget. The trajectory to stay within the budget, in effect, sets a series of targets within a specific timetable that define the trajectory. The flexibility is associated with the determination of the trajectory itself.

THE BUDGET APPROACH ALSO HAS A SUBTLE BUT IMPORTANT PSYCHOLOGICAL ADVANTAGE OVER THE TARGETS-AND-TIMETABLE APPROACH IN THAT IT FOCUSES ATTENTION ON THE END GAME – ESSENTIALLY DECARBONISING THE ECONOMY.

Thus, investment decisions can be taken from a long-term perspective, knowing that a limited budget is most efficiently allocated to invest in new infrastructure that eventually delivers very low or no emissions by mid-century, rather than to invest in shorter-term measures aimed at meeting an interim target that are perhaps less effective in delivering longer-term emission reductions.

Perhaps the biggest challenge to implementing the budget approach is allocating the global budget to individual countries, where equity issues become important. This is a political rather than a scientific question, whereas the overall global budget is more directly related to the science. The problem is not unique to the budget approach, but also bedevils negotiations under the targets-and-timetables approach and has perhaps been the single most difficult issue to resolve to achieve an international agreement on a global emission reduction plan.

3.3 Relationship between fossil and biological carbon emissions and uptake

Carbon "offsets", in which emitters of CO_2 from fossil fuel combustion can meet their emission reduction obligations by buying an equivalent amount of carbon uptake by ecological systems, are often proposed as a way of achieving rapid emission reductions at least cost. However, although the immediate net effect on the atmospheric concentration of CO_2 is the same for both actions, the nature of the carbon cycle means that the uptake of CO_2 from the atmosphere by an ecosystem cannot substitute in the long term for the reduction of an equivalent amount of CO_2 emissions from the combustion of fossil fuels. In fact, the offset approach, if poorly implemented, has the potential to lock in more severe climate change for the future.

Although it is very important to sequester atmospheric CO_2 into land ecosystems, this section outlines the reasons why is not a good idea to consider such biological sequestration as an offset for fossil fuel emissions. The key messages are:

- About 15-20% of net CO_2 emissions globally have originated from land ecosystems, primarily from deforestation. This represents the removal of carbon from a stock in the active atmosphere-land-ocean carbon cycle. It does not introduce any additional carbon into the atmosphere-land-ocean system, but simply redistributes it.
- The combustion of fossil fuels represents the injection of additional carbon from an inert, underground stock into the active atmosphere-land-ocean cycle. This additional carbon is redistributed among the three main stocks in the active carbon cycle, thus adding to the amount of atmospheric CO_2.
- Avoiding emissions by protecting ecosystem carbon stocks is a necessary part of a comprehensive approach to mitigation. Sequestering CO_2 into degraded ecosystems is also an important mitigation activity because it reverses an earlier emission. However, sequestering CO_2 into land ecosystems does not remove it from the active atmosphere-land-ocean cycle. Therefore, the sequestered carbon is vulnerable to human land use and management, which can rapidly deplete carbon stocks, and to major changes in environmental conditions, which can change the amount of carbon stored in the long term.
- The only way that CO_2 sequestered into land ecosystems can permanently "offset" fossil fuel combustion is if the sequestered carbon is subsequently removed from the land ecosystem and stored in an inert state or in a stable geological formation, thus locked away from the active atmosphere-land-ocean cycle. Another approach to offsetting is to replace fossil fuels with biofuels.

Carbon from land ecosystems

Over the past century about 15%-20% of CO_2 emissions globally originate from land ecosystems, primarily from deforestation (Raupach and Canadell 2010). This fraction has decreased over the past decade to about 11% in 2009 (Friedlingstein et al. 2010) due primarily to the large increase in fossil fuel emissions. Emissions from land ecosystems represent the removal of carbon from a stock in the active atmosphere-land-ocean carbon cycle. In essence, deforestation is a human-driven redistribution of carbon among the three active stocks – from land to the atmosphere, and then, in part, to the ocean. It does not introduce any *additional* carbon to the atmosphere-land-ocean cycle. Natural processes such as climate variability also redistribute carbon among these three stocks. A strong La Niña event, for example, redistributes carbon from the atmosphere to the land through increased productivity due to above-average precipitation in some parts of the world. However, averaged over decades, and in the absence of human perturbation or long-term changes in climate, land carbon stocks are relatively stable.

Fossil fuel combustion

The combustion of fossil fuels represents the injection of *additional* carbon from an inert, underground stock into the active atmosphere-land-ocean system. This additional carbon is redistributed among the three main stocks in the active carbon cycle, thus adding to the amount of atmospheric CO_2. A little less than half of the additional, inert carbon activated by the combustion of fossil fuels remains in the atmosphere; the rest is redistributed about equally to the land and ocean (Canadell et al. 2007; Raupach et al. 2007). So the combustion of fossil fuel is fundamentally different from deforestation because fossil fuel combustion introduces additional carbon to the active cycle, rather than redistributing the existing amount of carbon in the active cycle among the three major stocks.

Replacing the legacy carbon on land

Sequestering CO_2 into land ecosystems does not remove it from the active atmosphere-land-ocean system. It returns the original carbon, sometimes called "legacy carbon", lost from land-use change back into the land stock, and the amount that can be sequestered is limited by the prevailing environmental conditions. That is, atmospheric carbon cannot be sequestered into land ecosystems indefinitely.

However, it is very important that this legacy carbon be returned to land ecosystems as soon as possible for a number of reasons. First, such sequestration is indeed a rapid way to begin reducing the anthropogenic burden of CO_2 in the atmosphere. Thus, it yields some quick gains while the slower process of transforming energy and transport systems unfolds.

FURTHERMORE, IF DONE CAREFULLY, SEQUESTRATION OF CARBON INTO LAND ECOSYSTEMS CAN LEAD TO MANY OTHER CO-BENEFITS, SUCH AS ENHANCED SOIL CONDITION, MORE PRODUCTIVE AGRICULTURAL SYSTEMS, AND BETTER BIODIVERSITY OUTCOMES.

Some general principles provide a guide for designing and implementing an appropriate land carbon mitigation scheme:

1. The size of the stock is the important factor in the carbon cycle, not the rate of flux from one compartment (e.g. atmosphere) to another (e.g. a land ecosystem). These two different aspects of the carbon cycle are often confused. Although a fast-growing, mono-culture plantation forest may have a rapid rate of carbon uptake for the years of vigorous growth, it will store less carbon in the long term that an old growth forest or a secondary regrowth forest on the same site (Diochon et al. 2009; Brown et al. 1997; Nepstad et al. 1999; Costa and Wilson 2000; Thornley and Cannell 2000).

2. Natural ecosystems tend to maximise carbon storage, that is, they store more carbon than the ecosystems that replace them after they are converted or actively managed for production (Diochon et al. 2009; Brown et al. 1997; Nepstad et al. 1999). An observational study of temperate moist forests in southeast Australia identified the world's most carbon dense forest and developed a framework for identifying the forests that are the most important for carbon storage (Keith et al. 2009). In general, forests with high carbon storage capacities are those in relatively cool, moist climates that have fast growth coupled with low decomposition rates, and older, complex, multi-aged and layered forests with minimal human disturbance. This framework underscores the importance of eliminating harvesting of old-growth forests as perhaps the most important policy measure that can be taken to reduce emissions from land ecosystems. Recognition of the need to protect primary forests has helped to catalyse formulation of the REDD (Reduction of Emissions from Deforestation and forest Degradation) agenda item under the UNFCCC negotiations (http://unfccc.int/methodsandscience/lulucf/items/4123.php).

3. If designed carefully, a bio-sequestration approach can yield significant co-benefits. These are especially important for deforested, degraded and intensively cropped lands where the potential for sequestering carbon is large. Well-conceived and implemented bio-sequestration schemes in these landscapes can improve the productivity of cropping systems through the replacement of soil carbon that was lost in tillage, can deliver additional ecosystem services such as improved water quality on landscapes, and can maintain or enhance biodiversity. The relationship between bio-sequestration and biodiversity is particularly important, as well-designed sequestration schemes have the potential to yield positive outcomes for biodiversity (Steffen et al. 2009). In fact, a synthesis of the interplay among forest biodiversity, productivity and resilience argues that more diverse forests have higher productivity, store more carbon, and are more resilient towards disturbance than those with impoverished biodiversity (Thompson et al. 2009).

There are some cautions associated with bio-sequestration into land ecosystems, however. As shown in Figure 12, the land sink is highly variable on time scales of a few years, varying by as much as 2-3 Pg C in those timeframes. The strong fluctuations are driven largely by modes of climate variability such as ENSO and by volcanic activity, which induce rapid changes in soil respiration and plant growth through changes in solar radiation, rainfall/drought and temperature (Raupach and Canadell 2010; Kirschbaum et al. 2007).

IN THE LONGER TERM, CLIMATE CHANGE CAN SIGNIFICANTLY WEAKEN OR EVEN REVERSE THE LAND SINK THROUGH DROUGHTS, INCREASED SOIL RESPIRATION AND DISTURBANCES SUCH AS FIRE AND INSECT OUTBREAKS.

Simulations by dynamic global vegetation models using the IPCC IS92a emissions scenario show a levelling off of the land sink in the second half of the century with two models showing a significant weakening (Cramer et al. 2001). When coupled to a climate model in interactive mode, all vegetation models show a weakening of the land sink by 2100 with a net release of carbon back to the atmosphere corresponding to an additional rise in concentration from 20 to 200 ppm CO_2 (Friedlingtstein et al. 2006).

There are already several observations of the processes in the models that weaken the land sink and ultimately threaten to reduce the size of the land stock. The 2003 drought and heatwave in central Europe triggered a 30% reduction in gross primary productivity over the region, which resulted in a strong net source of 0.5 Pg C yr^{-1} to the atmosphere, undoing four years of a net carbon sink for the region (Ciais et al. 2005). A multi-decadal study of the carbon balance of Canadian forests has demonstrated that since 1970 they have become a weaker carbon sink despite a longer growing season, owing to a sharp increase in disturbances such as fire and insect outbreaks triggered by a warming climate (Kurz and Apps 1999). As cited earlier, the Amazon rainforest, an important stock of carbon on a global level, has suffered severe droughts and fires in 2005 and 2010, leading to estimated losses in carbon storage of 2.2 and 1.6 Pg C for the two drought events, respectively (Lewis et al. 2011). This analysis suggests that the two droughts have offset a decade of carbon sink activity, estimated to be about 0.4 Pg C uptake per annum; such observations support the assessment that, at temperatures above the 2 °C guardrail, the Amazon rainforest is at risk of extensive dieback and conversion to a savanna, with consequent loss of carbon to the atmosphere (cf. Section 2.5). If this occurs, then Amazonian ecosystems will continue to hold significant carbon stocks but at lower than current levels.

In summary, for many reasons increasing carbon storage in land ecosystems is a necessary and desirable component of a comprehensive approach to greenhouse gas mitigation. However, it is not equivalent to storing carbon in a secure geological formation, locked away from the influences of climate variability and change or from the direct impacts of human management. The relative vulnerability of carbon stored in land ecosystems to perturbations compared to inert geological fossil fuel is sometimes called the "permanence" issue in the design of economic instruments to reduce emissions.

Geosequestration as an offset

In principle, CO_2 sequestered into land ecosystems can fully offset the emissions of CO_2 from fossil fuel combustion if the sequestered carbon is subsequently made inert to the impacts of human land management, environmental disturbances or changing environmental conditions. It is theoretically conceivable that bio-sequestered carbon could be removed and stored in a stable geological formation, locked away from the active atmosphere-land-ocean system.

Another approach, equivalent to geosequestration, is to replace fossil fuel combustion with biofuel combustion to produce energy. The growth and then combustion of biofuels is potentially carbon-neutral as it represents a cyclical processes of shifting carbon between the land and the atmospheric compartments in the fast atmosphere-land-ocean carbon cycle. The fossil fuels thus replaced would leave the carbon in fossil fuels in the ground and thus away from the atmosphere.

Care must be taken, however, in the generation of the biofuels to limit the emissions associated with the production process to low levels relative to the amount of energy produced, and avoid undesired side effects such as competition with food production, loss of natural ecosystems and thus generation of large carbon emissions (see point 2 on page 60) and losses of biodiversity. In general, biofuels made from 'waste' biomass from plantation forests or from perennial vegetation grown on abandoned agricultural land offer the most advantages and avoid the undesirable side effects.

Focussing on the end game

The budget approach to mitigation described above, which is becoming more widely used for analyses in the research community, offers some scientifically based insights into mitigation approaches. Perhaps most importantly, it focuses strongly on the "end game" rather than interim targets.

PUT SIMPLY, IF THE 2 °C GUARDRAIL IS TO BE ACHIEVED, THEN THERE IS NO TIME FOR DELAY IN INVESTING IN LOW AND NO-CARBON TECHNOLOGIES FOR ENERGY GENERATION, BUILT INFRASTRUCTURE AND TRANSPORT.

Responsibly implemented bio-sequestration schemes offer some early gains; they can remove carbon quickly from the atmosphere and also offer a number of important co-benefits. The challenge is to ensure that linking bio-sequestration to the fossil fuel emissions sectors does not lead to any delays in the investment or deployment of low- or no-carbon technologies in those sectors.

As you've read in this report, we know beyond reasonable doubt that the world is warming and that human emissions of greenhouse gases are the primary cause. The impacts of climate change are already being felt in Australia and around the world with less than 1 degree of warming globally. The risks of future climate change – to our economy, society and environment – are serious, and grow rapidly with each degree of further temperature rise. Minimising these risks requires rapid, deep and ongoing reductions to global greenhouse gas emissions. We must begin now if we are to decarbonise our economy and move to clean energy sources by 2050. This decade is the critical decade.

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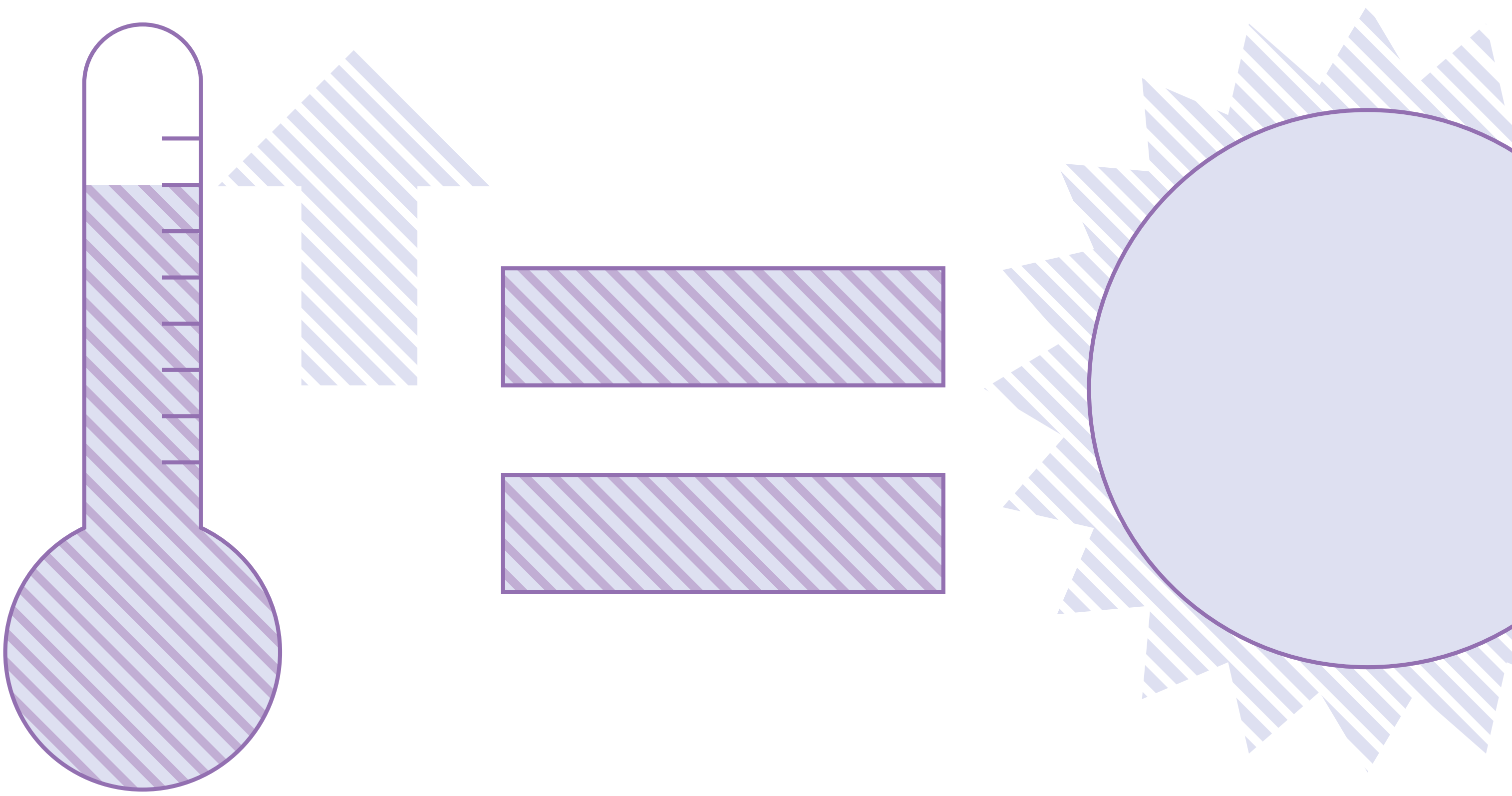

NATIONAL CARBON OFFSET STANDARD CONSUMER

The Climate Commission uses **National Carbon Offset Standard** certified Tudor RP Carbon Neutral paper
An Australian Government Initiative

APPENDIX 6 – BEYOND ZERO EMISSIONS –

ZERO CARBON AUSTRALIA STATIONARY ENERGY PLAN

THE UNIVERSITY OF MELBOURNE

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A research collaboration


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Australian Sustainable Energy

Zero Carbon Australia Stationary Energy Plan

> A ten year roadmap for 100% renewable energy
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beyond ZERO emissions

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As the IEA has shown in its research, solar energy is now a serious global player for providing the world's energy. Australia has one of the world's best solar energy resource, especially suited for concentrating solar thermal power plants, which can dispatch electricity when it is needed. The Zero Carbon Australia Plan is based on up-to-date and sound information and provides quality insights on how a country well-endowed in renewable resources can transition to a solar and wind economy.

CÉDRIC PHILIBERT
RENEWABLE ENERGY DIVISION
INTERNATIONAL ENERGY AGENCY

With our natural advantage Australia can and should be positioning itself as a global renewable super power for future prosperity. This report will help shift the climate debate to focus on energy, security, affordability, export and of course opportunity. Beyond Zero Emissions offers a new and invigorating message that is much needed.

ROBIN BATTERHAM
KERNOT PROFESSOR OF ENGINEERING, UNIVERSITY OF MELBOURNE
PRESIDENT, AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING
FORMERLY CHIEF SCIENTIST OF AUSTRALIA

The Zero Carbon Australia 2020 plan shows that it is technically feasible and affordable to replace all fossil fuel electricity with 100% renewable energy given the willpower and commitment to do so. This is a cutting-edge science-based plan that should be read by every energy decision maker and politician in Australia.

MARK Z. JACOBSON
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The management of BrightSource Energy have had a long and extensive involvement in the solar thermal industry. At BrightSource's predecessor, Luz, they designed, developed, built and operated the nine SEGS parabolic trough plants in California that still operate today. Built in the 1980's, these plants were the best that could be built with the available technology at the time and certainly proved beyond any doubt that one could capture the sun's energy and convert it into steam for large scale electricity generation on a scale never before contemplated.

But, there were limits to this technology which resulted in low efficiencies and capacity factors, and high capital costs. Our team at BrightSource has now completely re-engineered the whole approach to solar thermal, utilising a centralised tower to effect a direct solar to steam design. By using flat glass mirrors that track the sun all day and through the seasons, our tower plants generate steam at 550°C and higher, allowing us to use standard Rankine cycle generation power blocks that are dry cooled. With far greater efficiencies, higher capacity factors, lower capital costs and the ability to operate the plant in hybrid mode and/or with storage, the BrightSource Luz Power Tower is the proven technology of today and well into the future for delivering firm, renewable power.

I certainly encourage and endorse the need for a holistic plan being developed for our generation portfolio in Australia going forward – one that properly takes into consideration our targets and desire to substantially increase the proportion of renewable generation capacity. The plan requires careful consideration of our "as is" situation, the desired "to be" at future dates such as 2020 and beyond, and a migration plan that will transform our generation portfolio over time to meet our renewable targets and achieve security of supply. Solar thermal power, as a firm, dispatchable power generation source, will be an integral and significant component of this plan and its deployment.

— ANDREW DYER, DIRECTOR, BRIGHTSOURCE ENERGY AUSTRALIA

As the IEA has shown in its research, solar energy is now a serious global player for providing the world's energy. Australia has one of the world's best solar energy resource, especially suited for concentrating solar thermal power plants, which can dispatch electricity when it is needed. The Zero Carbon Australia Plan is based on up-to-date and sound information and provides quality insights on how a country well-endowed in renewable resources can transition to a solar and wind economy.

— **CÉDRIC PHILIBERT**
RENEWABLE ENERGY DIVISION, INTERNATIONAL ENERGY AGENCY

With our natural advantage Australia can and should be positioning itself as a global renewable Super Power for future prosperity. This report will help shift the climate debate to focus on energy; security; affordability; export and of course opportunity. Beyond Zero Emissions offers a new and invigorating message that is much needed.

— **PROFESSOR ROBIN BATTERHAM**
KERNOT PROFESSOR OF ENGINEERING, UNIVERSITY OF MELBOURNE
PRESIDENT, AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING
FORMERLY CHIEF SCIENTIST OF AUSTRALIA

The Zero Carbon Australia 2020 plan shows that it is technically feasible and affordable to replace all fossil fuel electricity with 100% renewable energy given the willpower and commitment to do so. This is a cutting-edge science-based plan that should be read by every energy decision maker and politician in Australia.

— **MARK Z. JACOBSON**
PROFESSOR OF CIVIL AND ENVIRONMENTAL ENGINEERING
PROFESSOR BY COURTESY OF ENERGY RESOURCES ENGINEERING
DIRECTOR, ATMOSPHERE/ENERGY PROGRAM,
STANFORD UNIVERSITY, USA

No doubt improved technologies for tapping usable energy from the sun, the winds, the tides, and the hot core of our planet will emerge as time goes by. But this report shows clearly that the solutions available now are, with our small population and enormous landmass, sufficient for Australia to move forward very quickly to tap renewable energy sources and minimize greenhouse gas emissions. We have the resources. We need the will.

— **PETER DOHERTY**
NOBEL LAUREATE, SCHOOL OF MEDICINE, UNIVERSITY OF MELBOURNE

This is an ambitious, technically feasible plan that should be looked at seriously.

— **TIM FLANNERY**
PROFESSOR FACULTY OF SCIENCE, MACQUARIE UNIVERSITY
AUSTRALIAN OF THE YEAR 2007

100 % renewable energy with zero emissions is achievable in Australia in about a decade if politics takes concerted actions... Moreover, Australia can become the initiator for a serious attempt to shift the world to a solar economy. This is the only promising strategy for climate protection and would provide societies around the world with solutions for climate protection, economic development, poverty reduction and conflict resolution. We need action now!

— **HANS-JOSEF FELL**
MEMBER OF THE GERMAN PARLIAMENT ALLIANCE 90
THE GREENS SPOKESMAN FOR ENERGY

To achieve a safe climate future we need an urgent, large-scale transition. The work of Beyond Zero Emissions shows that the technical transition is affordable and achievable. Now we need a social and political transition to get behind it.

— PROFESSOR CARMEN LAWRENCE
SCHOOL OF PSYCHOLOGY, UNIVERSITY OF WESTERN AUSTRALIA
FORMER PREMIER OF WESTERN AUSTRALIA

Over the past few decades the community in general and all sides of politics have come to accept the significance of the threat that greenhouse gas emissions from fossil fuel use has given rise to. Serious concrete action on changing our energy mix is all too slow in coming.

One of the challenges that those of us promoting a renewable energy future face, is that in the community and amongst decision makers, whilst there is widespread support for the idea of the renewable energy solutions, there is a lack of information on their level of technical and commercial maturity and their ability to deliver in short time frames. This is the information gap that the Beyond Zero Emissions study helps to fill in a very significant way.

The ZCA report analyses one particular scenario of renewable energy technology choice based on available solutions, in considerable depth. It successfully shows in detail that 100% renewable energy is both technically possible and economically affordable. Clearly other renewable energy technology scenarios are also possible, that only serves to strengthen the overall conclusion about viability. The group is to be congratulated for their efforts.

— ASSOCIATE PROFESSOR KEITH LOVEGROVE
HIGH TEMPERATURE SOLAR THERMAL GROUP,
AUSTRALIAN NATIONAL UNIVERSITY

The chips are down - there is no longer any doubt about our need to rapidly transition to a zero emission economy. The fate of Australia and the world depend on it. The Zero Carbon Australia strategy being launched by Beyond Zero Emissions provides the roadmap to the solutions. Let's hope it is adopted by responsible governments everywhere.

— PROFESSOR OVE HOEGH-GOLDBERG
DIRECTOR, GLOBAL CHANGE INSTITUTE, THE UNIVERSITY OF QUEENSLAND

"This is a bold and ground-breaking piece of work which should be a wake-up call to all those in government and industry who refuse to see beyond coal.

This is a very exciting report. It has academic rigour; it has also the hope of a generation and it has thousands of jobs waiting to happen.

We can and must aim to power Australia with 100% renewable energy as soon as possible if we are to truly tackle the climate crisis - and the great news is, that will bring huge benefits to us all, cleaning the air and creating jobs and investment from the suburbs to the farmlands.

This Zero Carbon Australia plan is an extremely valuable contribution which all in the parliament should be looking at very seriously"

— CHRISTINE MILNE
SENATOR FOR TASMANIA

"It's not the five per cent cut project or the 20 per cent cut project with a bunch of unachievable caveats. It's a zero carbon project and I think people actually want to be told a narrative, a story which is ambitious, which is aspirational, but also practical and I think that is what this project is about."

— NICK XENOPHON
SENATOR FOR SOUTH AUSTRALIA

It is difficult to imagine the Zero Carbon Australia plan being adopted in the context of Australia's current political and commercial culture and power cost structure. However, as an examination of the technical feasibility of achieving its goals as it seeks to shift this culture, it offers an interesting challenge for the imagination of policymakers and power suppliers feeling their way in to an uncertain future.

— KEITH ORCHISON, DIRECTOR, COOLIBAH PTY LTD
FORMER MANAGING DIRECTOR, ELECTRICITY SUPPLY ASSOCIATION OF AUSTRALIA

Every nation in the world should make a plan like this. If one can get a 100% renewable, zero carbon electricity system by investing 3% of GDP (and 10% of gross investment) for ten years, there is no good reason not to do it. Except, maybe, the straitjacket of old ways of thinking and doing.

This plan lays out a high solar-wind renewable future and then does more. It looks carefully at the materials requirements of such a future, an aspect of the matter too often left unaddressed.

Australia could be the first large economy to show the way.

— JOHN O. BLACKBURN
PROFESSOR EMERITUS OF ECONOMICS,
DUKE UNIVERSITY, USA

I strongly endorse the broad concept of such a solar and wind plan and applaud the work of the University of Melbourne and Beyond Zero Emissions. Our own work underway to calculate the feasibility of a 100% solar - wind plan for the United States has so far had the aim of testing technical feasibility, and the match seems to be 99-100%. We have considered the biomass backup options as well for CST plants but increased thermal storage also seems to work for a 100% solar - wind system for the USA. I have some differences in the discussion of CST technology used as an example, but the study is at an initial stage. The advent of such a comprehensive study in Australia will assist recognition of our own work directed to the USA case, and speed the market development of the CST and wind technologies to supply economical solar energy both day and night.

— DR DAVID MILLS
FOUNDER AND PAST CEO
SOLAR THERMAL POWER COMPANY AUSRA

Wind Power is now a serious player in international energy. Installing 8,000 megawatt-class turbines along with smaller wind turbines and other renewables where appropriate is achievable at a price the community can afford. Direct drive turbines such as the Enercon turbines are very suitable for a modern electricity grid where wind will be relied upon for a large proportion of overall electricity demand.

— DAVID WOOD
ENMAX/SCHULICH PROFESSOR OF RENEWABLE ENERGY
DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING
UNIVERSITY OF CALGARY, CANADA

That Australia enjoys an abundance of renewable energy resources is beyond question. The Zero Carbon Australia 2020 plan demonstrates that it is both technically feasible and economically affordable for Australia to realise the benefit of these resources and transition to a 100% renewable energy future. Australian politicians and decision makers with the vision and commitment to embrace this new path have the opportunity to play an important role in leading Australia to a sustainable low carbon future.

— SHARON MASCHER, ASSOCIATE PROFESSOR, CENTRE FOR MINING,
ENERGY AND RESOURCES LAW UNIVERSITY OF WESTERN AUSTRALIA

For decades, those opposing the transition to clean energy have claimed that it is not technically feasible. This report puts that argument convincingly to bed. There is no longer an excuse for inaction. Starting the transition now is our responsibility to future generations.

— PROFESSOR IAN LOWE
PRESIDENT OF THE AUSTRALIAN CONSERVATION FOUNDATION
EMERITUS PROFESSOR GRIFFITH UNIVERSITY

Beyond Zero Emissions have been in my building, Kindness House, for five years. The dedication of this remarkable team of individuals is astonishing. Most of all, I am impressed by their relentless pursuit of the truth, wherever it may lead. They have built their strategies cautiously, never letting the enthusiasm distract them from the goal of getting the right answers by asking the right questions.

They are a welcoming organization, drawing experts from a variety of disciplines, methodically searching for practical solutions to the challenges of reducing our massive carbon footprint. I am personally delighted to see the tens of thousands of hours they have invested in this important project, never once complaining about the lack of financial resources at their disposal. They have focussed their attention heavily on the carbon costs of stationary power, transport and building. I look forward to the time when they devote their formidable intellect and energy to the Livestock industry, where so much of our carbon share is squandered and emissions ignored. Beyond Zero Emissions is one organization I am proud to say I helped to incubate.

I urge every serious institution to listen to them attentively. These are serious people for serious times.

— PHILIP WOLLEN OAM
AUSTRALIAN OF THE YEAR VICTORIA 2007

Australians are capable of rapid change when the historical circumstances call for it. Indeed, we pride ourselves on being a resourceful people. The Beyond Zero Emissions team show how inventive and resourceful we can be. Their plan for a transition to 100% renewables is a powerful and cogent response to those who claim it can't be done. The reception this report receives will be a sign of how much Australians believe in their future and how much they take refuge in the thinking of the past.

— CLIVE HAMILTON
PROFESSOR OF PUBLIC ETHICS AND
AUTHOR OF REQUIEM FOR A SPECIES

The Zero Carbon Australia Stationary Energy Plan is a provocative and timely contribution to the climate change debate, and it deserves attention both here and abroad. The Plan demolishes a pile of conventional wisdom that Australian policymakers still seem unable to get past. The sorry history of Australian climate policy procrastination is littered with polluter-friendly analyses conducted by economic hired guns. Their work has been used to argue against action, or for illusory schemes that price carbon without reducing the greenhouse pollution billowing from Australian smokestacks and tailpipes. The effect has been to constrain debate and obscure from our view a very different vision—a rapid switch from fossil to renewable energy that makes economic and environmental sense. By highlighting one of many pathways to achieving that vision, the ZCA report sheds light where it is desperately needed.

— DR GUY PEARSE
RESEARCH FELLOW, GLOBAL CHANGE INSTITUTE, UNIVERSITY OF QUEENSLAND
AUTHOR OF HIGH & DRY AND QUARRY VISION

I get to work with people all over the world in the fight against global warming, a fight growing increasingly desperate as temperatures climb and rainfall patterns shift. Since Australia leads the world in per capita emissions, it makes sense that its transition planners would be thinking big. This transition obviously won't be easy or simple or cost-free, but given the alternatives it's very nice to know it's technically feasible!

— BILL MCKIBBEN
SCHOLAR IN RESIDENCE AT MIDDLEBURY COLLEGE, AUTHOR AND FOUNDER 350.ORG

This is exactly the type of initiative that we, the solar power industry, needs to propel our technology into the energy markets of Australia. SolarReserve's concentrated solar power towers with molten salt storage are the most reliable, stable form of clean, renewable energy, which is exactly what's needed to achieve the safe climate future proposed in BZE's Zero Carbon Australia roadmap. SolarReserve's solar thermal technology with molten salt storage; proven at Solar Two, the US Department of Energy's 10 MW pilot plant that operated for over 3 years in the 1990's, will not only aid in meeting Australia's renewable energy and carbon reduction objectives, but also have significant economic benefits, bringing green jobs and cutting edge technology.

Solar Reserve is willing, ready and able to deploy our molten salt power towers and fully supports the Zero Carbon Australia project.

— TOM GEORGIS
VICE PRESIDENT, SOLARRESERVE

The twin threats of peak oil and climate change are now real and escalating rapidly. They demand a radical re-think of our approach to energy, ending our fossil-fuel dependence and moving to sustainable solutions before oil scarcity and climate change impact cut off our options - and it has to happen far faster than our leaders are prepared to acknowledge.

Zero Carbon Australia 2020 is exactly the type of positive, rigorous technical analysis that is urgently needed to chart our path to a sustainable future - and convince Australia that there are far better alternatives to the complacent assumption that our high-carbon lifestyle can continue ad infinitum.

— IAN DUNLOP
FORMER CEO, AUSTRALIAN INSTITUTE OF COMPANY DIRECTORS
FORMER EXECUTIVE DIRECTOR OF THE AUSTRALIAN COAL ASSOCIATION

Renewable energy is the only way to go in the future. Enercon wind energy converters are designed to the newest standards to integrate with the modern high flexibility demands of electricity grids, providing sustainable reliable power to keep the wheels of daily life, household and industry turning. The Zero Carbon Plan outlines a technically achievable plan for generating all of Australia's energy from the wind and the sun. It can be a realistic goal if Australia gets immediately seriously committed with decision making from industry and government. We hope that its recommendations are taken up so that Australia can also be a player in the renewable energy economy that is already booming around the world.

— ENERCON GMBH

Success in restoring a safe climate depends on transforming the global economy by 2020. Every nation and every economy needs to act. The Beyond Zero Emissions group shows in their Zero Carbon Australia 2020 report how this can be done for Australia. The report charts a practical path—using only commercially available technology—to a zero emissions stationary energy sector. Let's hope that, very soon, every country has such a plan.

— LESTER R. BROWN, PRESIDENT OF EARTH POLICY INSTITUTE
AUTHOR OF PLAN B 4.0: MOBILIZING TO SAVE CIVILISATION

As a company involved in the development of solar plants all over the world, at Torresol Energy we support the Zero Carbon Australia Plan that sets the path for a future with clean, renewable energy.

Australia is one of the areas with better solar radiation and forms part of the international 'sun belt'. Besides, the country has excellent conditions for profiting from that solar radiation: large low-populated areas to build the plants and an industry that can support the technological development in the solar generation sector. In that sense, each of Torresol Energy's new projects introduces technologically advanced improvements to make Concentrated Solar Energy a manageable, economically competitive option and a real, viable, ecological and sustainable alternative to traditional energy sources.

Torresol Energy has three plants currently under construction. Among them, Gemasolar, with an innovative technology of central tower with molten salt receiver and thermal storage system, is the first commercial plant in the world of its kind. Due to this, the project has achieved considerable importance in the field of renewable energies as it opens the path to a new solar thermal power generation. Today, all of the analyses that have been carried out either by ourselves or by major international institutions show that tower plants with thermal storage is the type of technology that will be capable of generating reliable, manageable and renewable energy at the lowest costs. Therefore Australia could adapt this kind of technology in its renewable energy development plan that will allow the country to conserve the environment for future generations with a reliable energy source through utility scale baseload CSP plants.

— SANTIAGO ARIAS
CHIEF INFRASTRUCTURE OFFICER,
TORRESOL ENERGY

From the other side of the globe Protermosolar fully shares the vision of the realistic and feasible Zero Carbon Australia Plan. Spain is currently the country with the most intensive deployment of CST plants and their contribution to the grid stability and to the dispatchability of power supply has been fully demonstrated. Molten salt storage systems have been implemented in many Spanish plants providing predictable and reliable operation after sunset. Thus CST technologies could be considered as a real alternative to cover even the base load requirements of the electricity system.

Australia must profit from its high solar resource, the sooner the better. An effective boost to CST and to the other renewable technologies - as presented in this plan – will not only go in the right direction in terms of the transition to a new energy mix but it will also result in an excellent business for the Australian economy.

— DR. LUIS CRESPO
GENERAL-SECRETARY PROTERMOSOLAR
SPANISH ASSOCIATION OF CST INDUSTRIES

Australian Sustainable Energy
Zero Carbon Australia
Stationary Energy Plan

> A ten year roadmap for 100% renewable energy

> Baseload energy supplied by renewable sources

> Affordable at $8 per household per week

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Foreword

Twenty-eight billion is a big number. Measured in tonnes it is a very heavy load. This figure is the amount of sediment eroded each year from all our mountains and carried by all our rivers to all our seas. And it is the amount of carbon dioxide (CO_2) we pump into the atmosphere each year from burning fossil fuels globally – enough to cover Australia in a blanket two metres thick. In dollars, it is just a little more than the extra annual investment needed to reconfigure Australia's stationary energy system to have zero emissions in just 10 years time.

Each year the 28 billion tonnes of CO_2 we make induces heating. The oceans are now heating at the phenomenal rate of 300 trillion watts. In frighteningly human terms that is equivalent to detonating five Hiroshima sized A-bombs every second, every day of every year.

To make 28 billion tonnes of CO_2 we dig 7 billion tonnes of coal and suck countless gallons of oil and gas from the ground. In total we already excavate more rock from the Earth than nature does. With peak oil rapidly approaching, if not passed, BP's Deepwater Horizon catastrophe attests to the huge risks entailed in maintaining production.

The rate we consume energy to emit that CO_2 is 16 trillion watts. That is already about 1/3 of the energy released by plate tectonics - the process that pushes continents around the globe over geological time making mountains and earthquakes as it goes. On current growth trajectories we are set to surpass this amount of energy by 2060.

Each year we are adding a bit under 1% to the atmospheric CO_2 load, enhancing the greenhouse effect by a small fraction of a percent. By trapping just a tiny extra fraction of the incoming solar energy, we are heating not only the atmosphere, but also the oceans and land.

Such numbers give a very real sense that we humans are now operating as a geological change agent. But the scary thing is we have only just begun. Energy use is increasing exponentially, doubling every 34 years so that it will increase by 800% in a century. Curtailing energy growth will not be easy with 2 billion people already in energy poverty and 2 billion more added to the human number by mid century.

So how will we cater for our future energy needs?

One answer stares us in the face. Effectively converting about 0.06% of the solar energy that hits the land would meet the entire global energy demand.

But aren't there problems with renewable energy? Isn't it too expensive and unreliable? After all, the wind doesn't blow all the time and the sun doesn't shine at night.

Currently, advanced solar thermal power with molten salt storage, capable of producing power on demand day or night, is about four times more expensive than the cheapest coal fired power plants. But the cost of new technologies always reduces with large-scale rollout. The 2003 US-based Sargent & Lundy report anticipated solar thermal electricity costs would reach parity with coal fired power once 8.7 GW of capacity was installed – just a bit under Victoria's stationary energy capacity today.

So far, there has not even been modest stimulus for solar thermal power. The Global Financial Crisis is partly to blame, but political will is the resource in shortest supply. The BP Deepwater Horizon oil spill may have changed that.

So what if we were to try to build a 100% renewable energy system to power the Australian economy in just 10 years? How could we possibly do that, and what would it cost?

That is the challenge outlined in Australian Sustainable Energy – Zero Carbon Australia Stationary Energy Plan.

Zero Carbon Australia outlines a coherent and thoroughly researched blueprint showing how 100% renewable energy is achievable using technologies that are commercially available today: wind power and concentrating solar thermal with molten salt storage. It goes through the options, costs and benefits, confirming that a 10 year transformation of the stationary energy sector is achievable and affordable. This will also add huge stimulus to the new green economy and create jobs.

Zero Carbon Australia demonstrates that both cost and variability can be readily addressed, and exposes as myth the frequent argument that we need coal, gas or nuclear to provide baseload electricity. This is achieved by first smoothing power output across the grid via geographically dispersed production, and secondly providing dispatchable "back up" power from the molten salt storage at solar thermal power plants. Our nation continent, stretching across climate and time zones, appears ready made for this.

Zero Carbon Australia provides a big vision - Australia as a renewable energy powerhouse. But 28 billion tonnes of CO_2 is a big load, and getting bigger. Therefore a big vision for an alternative energy system is precisely what is needed.

Zero Carbon Australia is an extraordinary and pragmatic roadmap to a new and more sustainable energy system in Australia, and ultimately our region. I recommend it to all who are truly interested in securing Australia's energy future.

Mike Sandiford

Professor of Geology
Director, Melbourne Energy Institute
University of Melbourne

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Executive Summary

The Zero Carbon Australia 2020 Stationary Energy Plan (ZCA2020 Plan) is a detailed and practical roadmap to decarbonise the Australian stationary energy sector within a decade.

Current levels of greenhouse gases in the atmosphere are already sufficiently high to carry the climate system past significant tipping points. They pose an unacceptable risk of dangerous and irreversible changes to the world's climate, to biodiversity, and therefore to human civilisation. These changes directly affect Australia's food and water security, and increase the risk of regional instability.

Using a global carbon budget approach, recent work by the German Advisory Council on Global Change demonstrates that, to have a two-in-three chance of keeping global warming to less than 2°C above pre-industrial temperatures, developed nations with the highest per capita rates of emissions, such as the United States and Australia, would need to decarbonise their economies by 2020. There is increasing consensus that the 2°C threshold is too high and beyond a 'safe boundary', and that atmospheric carbon dioxide must be reduced from the current level of around 390 parts per million (ppm) into the range of 300 to 350 ppm.

For these reasons a timeline of ten years is recommended. Ten years is a meaningful timeframe for planning purposes, as it requires immediate action, whereas longer and less ambitious goals lead to half-responses and delay. Over this ten year period, fossil fuel generating assets will be retired as new renewable energy infrastructure is brought on line and securely integrated into the electricity supply system.

A group of dedicated individuals with experience and expertise in relevant energy industry disciplines, many of whom work in the fossil fuel energy industry, collaborated to develop the Zero Carbon Australia 2020 Stationary Energy Plan.

Only proven and costed technologies are used in the ZCA2020 Plan. Wind power and concentrating solar thermal (CST) with molten salt storage are the two primary technologies used, providing approximately 40% and 60% of the energy mix respectively. These key energy sources are backed up by a 2% annual contribution from crop waste biomass and hydroelectricity. Detailed modelling was undertaken to ensure that the new renewable energy supply can meet all demand projected under the ZCA2020 Plan, 24 hours a day, 7 days a week, 365 days a year.

When compared to other nations, Australia's renewable energy resources are amongst the best and the most profitable to develop. Thus, these resources offer a strategic advantage for all Australians as we prepare to compete in the future carbon-constrained global economy. The investment required to transition Australia's stationary energy sector to renewables is a stimulus equivalent to just 3% of GDP over ten years, to build a zero-emissions energy system that will last for at least 30-40 years.

The ZCA2020 research team also found that moving to 100% renewable energy by 2020 is well within the financial and industrial capability of Australia's economy. The raw materials, and manufacturing and construction labour needed to implement the transition are small when compared with those employed every day within Australian industry. For example, 80,000 construction jobs will be required at the peak of the ZCA2020 Plan installation, equivalent to only 8% of Australia's present construction workforce. This is easily achievable given that in the period immediately prior to the Global Financial Crisis, new construction jobs were increasing at a rate of around 50,000 per year. Furthermore, the jobs created by the new renewable energy economy will more than offset job losses in the fossil fuel industries.

In narrow economic terms the ZCA2020 Stationary Energy Plan does not impose a long-term cost on the economy above business-as-usual. That is, the net present costs for both scenarios calculated for the period 2010-2040 are approximately equal, at roughly $AU500 billion. This calculation ignores savings from transport fuel costs and possible carbon pricing. The ZCA2020 Plan is able to achieve this low cost, because the pipeline of renewable energy projects in the plan contributes to the rapid reduction in the cost of renewable energy. Cost reductions from increased cumulative capacity of these technologies are realised, as well as avoiding future rising costs of fossil fuels for power stations. Adoption of the full ZCA2020 Plan provides significant economic benefits, eliminates all dependence on foreign energy sources, and positions Australia to lead in the 21st century renewable energy economy.

Decisive leadership is now needed from government, business, academia and the wider community for this transition to begin.

The Stationary Energy Plan is the first in a series of six plans making up the ZCA2020 Project. Future reports will cover the sectors of Transport, Buildings, Land Use and Agriculture, Industrial Processes and Replacing Fossil-Fuel Export Revenue.

ZCA2020 Stationary Energy Plan Detail

The stationary energy sector accounts for almost 55% of Australia's CO_2 equivalent emissions, with all fossil fuels accounting for over 70% of Australia's emissions.

The ZCA2020 Stationary Energy Plan describes how to repower Australia's stationary energy sector using 100% renewable sources by 2020. The authors acknowledge that the Plan detailed herein is not the only way that Australia could achieve zero emissions from the stationary energy sector. While ongoing innovation will indeed make it even easier and cheaper to meet the zero emissions target, the option presented here is available right now.

Enercon E-126 turbines in Belgium. Image: Steenki

The ten-year timeframe has been mapped out taking into account the need for initial growth of the renewable energy industry. The timeframe could be accelerated with continued growth in later years or delayed if policy action is too slow However the report demonstrates that such a rapid transition is within Australia's capacity.

There are a variety of policy mechanisms that could facilitate implementation of the ZCA2020 Plan, with funding provided from any mixture of public and private sources. It is beyond the scope of this report to recommend any particular financing or policy mechanism.

Key features of the Plan include:

Increased Electricity Use

Australia's annual electricity demand increases by over 40%, from 822 PJ/yr (228 TWh/yr) in 2008 to 1,170 PJ/yr (325 TWh/yr) in 2020. While this is more electricity demand than would be required under business-as-usual demand growth, it is demonstrated that with a combination of energy efficiency and fuel-switching measures, this is in fact sufficient to replace all fossil fuel use, including transport and heating.

Reduced Overall Energy Requirements

Total delivered energy use under the plan is reduced by more than half, from 3,915 PJ/yr (2008) to 1,660 PJ/yr (2020), while maintaining the same level of energy services, including transport, heating and cooling, industrial energy use and so on.

This is achieved through a combination of energy efficiency measures, and by switching energy services currently provided with oil and natural gas, mostly for transport and heating, with far more efficient electrical systems.

For instance, due to the inefficiency of internal combustion engines, less than 20% of the fossil fuel energy consumed by the transport sector is actually converted into useful vehicular motion, once stop-start inefficiencies are factored in. On the other hand, electric rail and electric cars convert 80-90% of electrical energy into motion.

Similarly, space heating with efficient heat pump systems uses a small amount of electricity to "pump" ambient heat - a renewable resource - from outside. Typically, heat pump systems for domestic and commercial buildings will use between one quarter and one third of the energy used by natural gas or resistive electrical heating systems to provide the same amount of heat.

A minor allowance is made for biogas and biofuels to meet energy demands that cannot be electrified, though this is kept to a minimum.

Flatter Electricity-Use Profile

Australian electricity and natural gas usage fluctuates considerably from day to day and between seasons. This means that at present the energy generation and distribution infrastructure is under-utilised. The ZCA2020 Plan employs measures to flatten this profile on both a daily and seasonal basis so that infrastructure is more effectively used and infrastructure investors can achieve suitable economic returns.

Proven and Costed Renewable Energy Technologies

The Plan relies only on existing, proven, commercially available and costed technologies. The Plan found that wind and concentrating solar thermal (CST) power with molten salt heat storage are the most appropriate, cost effective, commercially available, and scalable technologies for deployment in Australia.

"Better-than-Baseload" Electricity Generation

Storing the sun's energy as heat in the form of hot molten salt allows CST plants to provide power that is "better-than-baseload". Similar to a hydroelectricity dam, CST plants with heat storage can dispatch electricity as needed at very short notice. This is achieved by using the heat from the stored molten salt to produce steam as necessary.

Achievability

The Plan examines the achievability of the required transformation, including labour and resource requirements and manufacturing capacity, and concludes that there are no resource constraints that prevent the transition to 100% renewable energy.

Electricity Generation Technology Details

The Plan provides 100% of Australia's electricity needs using the following renewable energy sources geographically dispersed around an improved national grid. This geographic diversity is a major contributor to the consistency of the ZCA2020 power supply. Detailed modelling using real-world data on a half-hourly timescale has shown that the proposed generation mix is capable of meeting 100% of electricity demand. The system is in fact able to generate at least 25% *more* power than the projected 325TWh/yr demand.

Concentrating Solar Thermal (CST) Power with Molten Salt Storage supplies 60% of Electricity Demand

Enviably, Australia has the best solar resource of any developed country, and concentrating solar thermal power is recognised as the optimal technology to exploit this. The Plan provides CST power towers with molten salt storage, such as those available from Torresol and Solar Reserve. Power towers offer the dual advantage of continued high performance in winter, and higher operating temperatures year-round. With fully integrated molten salt heat storage, from which steam can be produced on demand, these plants provide 24-hour electricity production. Crop-waste biomass firing is used during extended periods of concurrent low solar and wind availability, as described below. Industry scale-up and cost reduction trajectories have been detailed by the U.S. Department of Energy and Sargent & Lundy Consulting LLC. Consistent with these, after a capacity of 8,700 MWe is installed globally, solar thermal power towers will provide electricity at a cost that is competitive with conventional coal power at 5-6 $AU cents/kWh.

Proposed National Renewable Grid - see Part 5 for detail

One ZCA2020 CST module consists of a net 217 MWe turbine, with a mirror field and molten salt system sized to provide thermal energy for 17 hours of storage. Air-cooling of the power cycle is used instead of water cooling in order to minimise water requirements. These solar thermal plants are capable of running at a 72% annual capacity factor - more than the annual operating capacity of most large black coal power plants operating in Australia today. Twelve solar sites around Australia were chosen, each with installed capacity of 3,500MW per site.

Wind Supplies 40% of Electricity Demand

Wind power is generally the cheapest renewable energy source to deploy and is technologically mature. Australia however, currently has less than 2,000 MWe of wind turbine capacity installed. The Plan provides 48,000 MWe of new installed turbine capacity running at an average annual capacity factor of 30%. This consists of 6,400 7.5 MW wind turbines spread out over 23 geographically diverse locations. Detailed simulations have shown that 40% wind power can be readily integrated with the CST-based electricity supply grid. For example, during periods of high wind speeds, wind generated electricity is dispatched to the grid first, while the sun's energy is used mainly to heat salt for storage. Conversely, when wind speeds are low, the hot molten salt at CST plants is used to produce extra steam for the turbines and hence make up for the lull in wind generation. Based on detailed studies from the U.S.A., it is projected that at least 15% of the installed wind capacity will always be producing power, with the same reliability as conventional 'baseload' power.

Biomass and Hydroelectricity Backup

Biomass and hydroelectricity are used as contingency backup for up to 2% of annual demand. Pelletised crop waste biomass is provided as a backup heat source for the CST plants to accommodate periods of extended cloud cover in winter. This is similar to the way in which natural gas is used to backup some existing CST plants. In both cases, the steam system and other power generation infrastructure of the CST plants function without regard to the source of heat: sun, combusted biomass, or combusted natural gas. Adequate backup can be provided by processing just 13% of waste straw residue from Australia's annual wheat crop. Pelletisation increases the energy density and cost effectiveness of the transport of the biomass. Australia's existing hydroelectricity systems have also been factored in to provide backup, though at a discounted rate to account for future drought periods.

Electricity Transmission Infrastructure

The ZCA2020 Plan provides upgraded electricity grid infrastructure connected to an optimal selection of renewable energy plant sites. Sites for wind and solar power generation were chosen on the basis of data available from NASA and Australian Government bodies. Emphasis was placed on selecting sites with high year-round energy availability so that both winter and summer peak electricity demands are met.

Electrical transmission links are upgraded in order to strengthen the Australian grid and connect the new renewable energy installations. New interstate connections enable greater import and export capability between the geographically diverse renewable energy resources. The Plan provides 500kV alternating current links to connect new power stations near populated regions where the power is to be used locally. Meanwhile efficient High Voltage Direct Current (HVDC) links are provided for low-loss long-distance transmission to connect specified solar installations and for interstate connections to areas of high electricity demand. The Plan costings also allow for supply of 4,475 MW of offgrid electricity to load centres without grid access.

Achievability and Employment

Implementation of the plan would require a rapid ramp-up of projects and industry. The ten year timeframe takes into account that this will not happen overnight, and would see most of the proposed infrastructure completed in the second half of the decade. Mid-term goals are to have 15,000 MW of wind and 5,000 MW of CST operational by 2015. This requires fast-tracking existing projects and putting in place the right policies to stimulate new projects.

The labour resource requirements for the implementation are dwarfed by Australia's existing industrial capacity. The Plan would require a peak of 80,000 construction workers by 2016, out of an existing workforce of almost one million. Prior to the Global Financial Crisis of 2008, the construction workforce was growing at the rate of 50,000 new jobs per year. Similarly in manufacturing, modelling has allowed for 50% of the manufacturing of wind turbine components and CST heliostat mirrors to be done onshore. This would create up to 30,000 new jobs, out of Australia's existing manufacturing workforce of one million which is projected to decline under business-as-usual. The Plan would create a further 45,000 ongoing jobs in operations and maintenance of the renewable energy infrastructure, which would more than offset the loss of around 20,000 jobs in the domestic fossil energy supply sector.

The raw materials required by the Plan are primarily concrete, steel and glass, none of which are constrained by supply. The Plan would require the equivalent of only 7% of Australia's current concrete production, while sourcing steel and glass would require some increase in either domestic production or imports. The manufacturing of heliostats and wind turbine components would require the setting up of several new factories of a similar size to ones that already exist overseas. For example, it is feasible that the production of 600,000 heliostats per year could be done in a single factory, as there are already car factories in Australia and overseas with the capability of producing 300,000 to 500,000 cars per year.

Required Investment and Economics compared to Business-As-Usual

The ZCA2020 plan requires a total investment of $AU370 billion over the period 2011-2020. Annual investment, averaging $AU37 billion per year, will be lower in initial years and higher as the pace of construction ramps up. Importantly, the up-front annual costs of construction need only be paid by investors, not by the Australian public. As with any energy infrastructure project, up-front capital costs will be paid back over time through energy sales. Therefore the figure of $370 billion is not an expense to the economy without return. Rather it is a strategic investment that secures Australia's zero-emission future and results in significant savings in future years.

Compared to Australia's annual GDP of $AU1.2 trillion, the investment for ZCA2020 represents 3% of GDP over the ten years. Though the up-front investment required by the Plan is significant, maintaining business-as-usual (BAU) is not without its costs either. BAU requires $AU135 billion for ongoing capital investments in energy infrastructure for the period 2011 to 2020, and then continues to pay for increasingly expensive fossil fuels in later years, with $AU300 billion in fuel costs. Although the ZCA2020 Plan's up-front investment is substantially higher than BAU, the Plan's low ongoing costs result in dramatically reduced expenditures over the long-term. Calculating net present costs on a longer timeframe (2011-2040) demonstrates that the ZCA2020 Stationary Energy Plan is about the same cost as the BAU scenario.

These savings expand when the broader economic benefits of the Plan are included. The use of electricity to power transport instead of oil realises fuel cost savings of nearly $AU1,170 billion. Lastly, in the event that a carbon price is implemented, an estimate of the savings made by avoiding potential CO_2 emission charges shows that the Plan avoids an additional $AU370 billion, raising total savings to $AU1,550 billion. Taking these costs into account realises a very rapid economic payback of only a few years.

This report also compares the ZCA2020 Plan costs to other public and private expenditures – for example, the annual ZCA2020 investment is equal to what Australians spend each year on insurance. This demonstrates that the scale of the projects described within this report are well within the capacity and capability of the Australian economy. More detailed economic modelling and policy recommendations are beyond the scope of the ZCA2020 Stationary Energy Report. Future work will include a separate financing and policy document to be produced at a later date.

As a benchmark for gauging the economic impact of the Plan, a preliminary analysis has been done based on one possible funding scenario where the investment is paid for solely through electricity retail revenue. If the proposed

BrightSource Solar Thermal Power Tower

infrastructure was funded with revenue from electricity prices at a standard rate of return for regulated assets, it would require a price rise of around 6.5c/kWh by 2020, equivalent to the existing premium for GreenPower today. This should not be taken as a recommendation of the ZCA2020 Plan, but it does provide a useful indication of the costs involved. This price increase would cost approximately $AU420 per household per year, or $AU8 per household per week, by 2020, and is a similar electricity price rise to what may be expected in Australia's business-as-usual electricity market. There are of course various policy options that could fund the Plan in different ways and would not require electricity price increases. Also, further detailed design to the Plan in later versions may decrease this price, as more detailed modelling and information comes to hand.

Summary

The following chapters show in detail how the transition to a Zero Carbon Australian economy can be achieved using technology that is commercially available today. There are no technical barriers to this deployment. Implementing the proposed infrastructure in ten years is well within the capability of Australia's existing industrial capacity. ZCA2020 outlines a decisive and achievable transition blueprint for a 100% renewable energy future which would position Australia as a leader in the emerging global renewable energy economy. What is required to make this happen is leadership through action from policymakers and society, with firm decisions made quickly that will allow this transition to occur.

Part 1

Introduction and Overview

Contents

The Zero Carbon Australia 2020 Stationary Energy Plan outlines a technically feasible, practical, and economically attractive transition to 100% renewable energy in Australia in ten years. The plan is a rational and necessary response to the risk of major climate change.

As governments continue to grapple with the problem of how to shift to low-carbon societies, the evidence mounts that only a rapid transition to a zero-carbon economy can ensure climate and energy security for us all. Mitigating climate change in an incremental manner ignores the potentially catastrophic effects we face if global warming "tipping points" are passed. Moving to a zero-carbon economy requires concerted efforts across all national governments and across multiple sectors including Stationary Energy, Transport, Building Efficiency, Industrial Processes and Land Use.

Many different factors shape action to mitigate climate change. Societal and political barriers are quite different from technical barriers. This report is aimed at demonstrating the technical and financial feasibility of rolling out a 100% renewable energy system in Australia over the next ten years. Importantly, only commercially available technology is specified, to show that such a roll-out could start today. This report does not address the political and social impediments to beginning such a Plan. It is aimed at concluding the debate about whether renewable energy has the capability to keep the wheels of industry turning, in order to enable the social and political changes that will lead to the transition to 100% renewable energy. The 2020 timeframe is motivated by the best available climate science. While any delay to the roll-out of such a ten-year 'decadal plan' could still see a 100% renewable sector achieved at a later date, this comes with greater risk of exceeding safe limits within the Earth's climate system.

This report focuses on the Stationary Energy sector in Australia. Subsequent reports will address the other carbon emitting sectors of the economy. The ZCA2020 Stationary Energy Plan allows Australia to play a responsible, constructive and leading role in promoting decisive action for climate protection around the world. For the remainder of this document, unless otherwise defined, the ZCA2020 Stationary Energy Plan will be referred to as "the Plan" or the "ZCA2020 Plan".

There are a number of potential paths to a zero-emissions stationary energy system. This Plan offers one possible solution based on renewable resources, using existing proven and reliable technologies, such that the costs and liabilities of the Plan can be rigorously assessed. In this regard, the Plan concords with an emerging view that national scale renewable systems are not only technically and economically viable, but are likely to accrue significant benefits to the nations that first implement them.

"[t]his goal is achievable, affordable and transformative."
U.S. VICE PRESIDENT AL GORE, ANNOUNCING HIS PROPOSAL TO RE-POWER AMERICA WITH CLEAN ELECTRICITY IN TEN YEARS[1]

"We know the country that harnesses the power of clean, renewable energy will lead the 21st century"
U.S. PRESIDENT OBAMA[2]

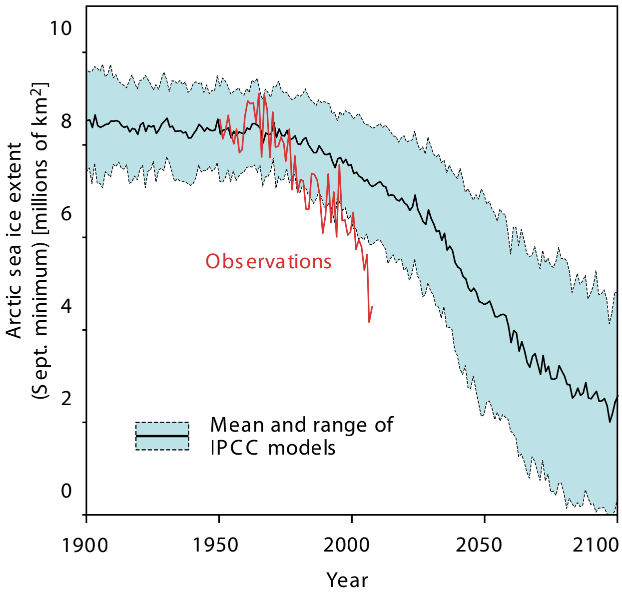
1.1 Why Zero Emissions?

Present atmospheric levels of CO_2 are at 390ppm[3], well above the pre-industrial levels of 275 to 285 ppm (AD 1000-1750)[4]. Furthermore, atmospheric CO_2 concentration has been growing rapidly for the last 40 years [note 1]. Many climate scientists now believe that CO_2 levels must be reduced from today's concentrations to avoid triggering dangerous "tipping point" mechanisms[6,7] [note 2].

Tipping points are serious because once they are passed, a return to a normal climate situation may be impossible. For example, if global average temperatures increase by 4°C , the huge carbon stores in the northern circumpolar permafrost zone (estimated at 1,672 gigatonnes) may be vulnerable to irreversible release[8]. Figure 1.1 shows that the current rate of loss of summer arctic sea ice is exceeding worst-case IPCC predictions.

Many scientists have stated that the maximum safe level of atmospheric CO_2 concentration is 350 ppm or less—a level significantly below the present atmospheric concentration of 390 ppm[note 3]. It is not too late—a rapid and decisive reduction in CO_2 emissions can return us to safe atmospheric levels with a reasonable probability of avoiding dangerous tipping points. However, this can only be

FIGURE 1.1
Arctic Sea Ice Extent—observed loss versus IPCC forecasts [9]



achieved through the implementation of urgent, purposeful action by governments to quickly reduce anthropogenic carbon emissions to zero.

"If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted .... CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm."

HANSEN ET AL, 2008[6]

"... any reasonably comprehensive and up-to-date look at the evidence makes clear that civilization has already generated dangerous anthropogenic interference in the climate system. What keeps me going is my belief that there is still a chance of avoiding catastrophe."

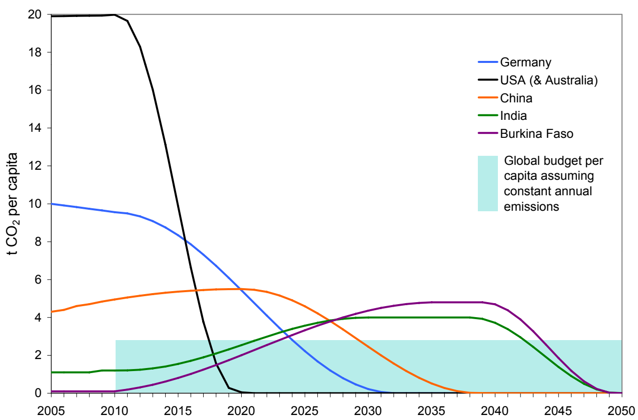
JOHN P. HOLDREN, ENERGY AND ENVIRONMENT EXPERT AT HARVARD UNIVERSITY, PRESIDENT OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE, AND PRESIDENTIAL SCIENCE ADVISOR TO BARACK OBAMA[10]

1.2 Why Ten Years?

The Plan looks not only at how to implement a zero-greenhouse gas emission energy sector, but also how to achieve this within a ten year timeframe, from a technical perspective. It is recognised that this is needed to properly address the threat of severe and potentially irreversible climate change.

The premise of a ten year timeframe to achieve zero emissions echoes several leading academics and public figures. In a recent report from the German Advisory Council on Global Change (WBGU), Prof. Hans Joachim Schellnhuber (Director of the Potsdam Institute for Climate Impact Research) indicated that, in order to have a two-in-three chance of keeping global warming below 2°C over pre-industrial levels, and using a global per-capita carbon budget approach, it would be necessary for the USA to reduce emissions to zero by 2020[9]. An extension to this would be that other rich countries, with the highest per-capita emissions, such as Australia[12], would need to pursue the same goal. As Figure 1.2 depicts, the "global budget per-capita" (the blue block in the background) shows that the maximum per-capita emissions allowed across all populations of the world would need to be limited to around 110 tonnes of CO_2 per-capita (2.75 tonnes per-capita per annum over a period of 40 years).

FIGURE 1.2
Carbon budget 2010—2050: Emissions paths per capita for selected countries (adapted)[11]



As such, countries with high per-capita emissions (such as the USA or Australia [note 4]) have less than ten years to cut their emissions to zero. At the current Australian emissions rate of about 20 tonnes per-capita per annum, our emissions budget would run out in five years. If instead we begin reducing emissions sooner, we could extend the budget to ten years. As a country with high per-capita emissions, Australia has the opportunity to be a catalyst for other countries (particularly countries with high total emissions but low per-capita emissions, such as China and India) by inspiring action on climate change and developing renewable energy industries.

A transition in ten years may seem challenging, but the world has seen remarkably fast economic transitions in the past; the restructuring of the United States economy during the Second World War is a notable example[13]. A ten year transformation period has also been nominated by Al Gore[14]. In his 2008 speech calling for America to move to 100% renewable energy within ten years , Al Gore said: "To those who say ten years is not enough time, I respectfully ask them to consider what the world's scientists are telling us about the risks we face if we don't act in ten years. Ten years is about the maximum time that we as a nation can hold a steady aim and hit our target."[14]

There are many additional reasons for Australia planning immediate and deep cuts to emissions. Global warming has the potential to create irreversible ecological change, and Australia is at particular risk of biodiversity reduction[15]. With our agricultural and water systems also at particular risk, climate change threatens our national security.

"Global average temperature increases of 1.5 or 2.0°C above pre-industrial levels will likely lead to a massive loss of biodiversity worldwide. ... The more effectively the rate of climate change can be slowed and the sooner climate can be stabilised, the better are the prospects that biodiversity loss will be lessened."

SUMMARY OF A REPORT TO THE NATURAL RESOURCE MANAGEMENT MINISTERIAL COUNCIL COMMISSIONED BY THE AUSTRALIAN GOVERNMENT, 2009[16]

There is widespread recognition that those who lead the renewable energy race will reap significant economic benefits. Already, several Australian renewable energy technology firms have moved offshore to take advantage of more supportive and forward-looking regulatory environments. These include the now multi-million dollar corporations Ausra (now French-owned) and Suntech (now China-based). The DESERTEC program is pressing ahead with plans to build a vast network of solar thermal plants across North Africa, the Middle East and Europe[17] while Spain will have 2.5 gigawatts (GW) of solar thermal power connected to the grid by 2013.[18] In terms of renewable resources, Australia has all the natural advantages of the DESERTEC proposal, with none of its multi-national political impediments.

China has begun to invest heavily in renewable energy, doubling its wind power capacity every year for the last 5 years, now having 25 GW as of 2009. China has a target of 150 GW of wind by 2020, but if it continues its current rate of installation it will reach 150 GW by 2015—five years ahead of schedule. This scale of growth is impressive and actually accounts for one third of the total global wind power growth[19,20].

As these and other countries take actions which reduce their reliance on coal, Australia has the opportunity to move beyond its 'quarry vision',[21] which sees the success of our economy strongly tied to fossil fuel exports, and look instead to reap the economic benefits of being among the leaders in zero emissions technology innovation.

"The credit crunch has been brutal for solar start-ups in the West, but not for Chinese firms with access to almost free finance from the state banking system. They have taken advantage of the moment to flood the world with solar panels, driving down the retail price from $4.20 per watt last year to nearer $2 in what some say is a cut-throat drive for market share ... We may soon be moving into a phase of history when ill-prepared countries cannot be sure of obtaining energy—whatever the price."

AMBROSE EVANS-PRITCHARD [22]

By choosing to become a leader in the race towards zero emissions, Australia has the opportunity to secure its food, water and energy supplies for the future, and build a new and robust economy as a global renewable powerhouse. These arguments all promote the case for immediate action.

"I think that the word "now" has to creep into the vocabulary of people in public policy."

S DAVID FREEMAN, US ENERGY ADVISOR AND FORMER HEAD OF TENESSEE VALLEY AUTHORITY [23]

1.3 Guiding Principles, Assumptions and Project Methodology

A zero emissions target—not a low emissions target. The ZCA2020 Project is based on a zero emissions methodology underpinned by a set of guiding principles. These principles relate to the use of proven technology solutions and the achievement of social equity goals with minimal disruption to food, water and energy supplies.

The Plan differs from other emissions reductions plans in that, from the outset, it seeks a target of zero emissions within ten years. Most other transition plans aim to move towards a low emissions economy over a period of indeterminate length. A zero emissions plan is not simply an accelerated low emissions strategy. *The point of a rapid transition to a zero emissions economy is not to just proceed further along the same path that will take us to a low emissions economy over 50 years or so.*

With this in mind, the ZCA2020 working group has framed the development of the whole Project within the following set of guiding principles to provide clarity of direction and transparency of purpose.

- **Proven and Reliable Solutions**. A plan for transition to a zero emissions economy beginning now requires us to use the best of what is now available. There have been major advances in renewable energy technology over recent years, and it is possible to move to a zero emissions economy without waiting for further technologies to be developed[22]. Consequently, the Plan considers only technological solutions that are already commercially available from existing companies which offer the technology at a multi-megawatt scale, and have moved beyond small-scale demonstration and pilot projects.
- **Implementation Flexibility**. While the Plan only considers commercially proven technologies at the outset, the ZCA2020 working group leaves open the option of subsequent incorporation of new and innovative technologies as they become commercially available, if they will reduce the cost of the transition and/or they have fewer associated environmental or social impacts. Example technologies that the ZCA2020 working group anticipates may become commercially available during the 10 year transition period include arrays of Australian National Universities' 500 m^2 SG4 concentrating solar thermal Big Dishes,[24] and Carnegie Corporation's CETO III Wave Technology[25,26].
- **A Socially Equitable Solution.** The ZCA2020 Project will seek to ensure that social equity in Australia is maintained or enhanced during the transition to a zero emissions economy. In particular, this solution will continue to provide equitable access to energy for all Australians today, while ensuring that the costs and burdens are not deferred to future generations.
- **Transition Fuels.** Whereas a long-term low emissions plan may recommend the use of natural (or petroleum) gas as a transition fuel, such a 'double transition' is not considered because it necessarily ties Australia to continued fossil fuel emissions beyond the Plan's timeframe, and would see money that could otherwise be spent on renewable generation capacity diverted into fossil fuel infrastructure.
- **Technology Sequencing.** As with the idea of transition fuels, investment in so-called 'transition technologies' will only serve to divert funding and attention from developing true zero emissions solutions. An example would be the development of more efficient petrol driven cars at the expense of investing in an electrified transport system that can be powered from a renewable energy grid.

- **Minimal Impact on Food, Water and Energy Supplies.** The transition to a zero emissions economy should aim to do so without compromising Australia's food, water and energy security.

1.4 Summary of Technology Choices

While the choices of energy technologies are detailed with references in Part 2 of the report, they are summarised here to aid the reader in understanding why the guiding principles outlined above led to the chosen technology mix. There are commonly held perceptions that renewable energy has a limited future because "the wind doesn't always blow and the sun doesn't shine at night". The aim and scope of this report is to show that this is not an issue, and to demonstrate the feasibility of 100% renewable energy in Australia within the next ten years. Instead of focusing on various negative aspects of the technologies we have not chosen, the authors wish to show the positive aspects of the renewable technologies that are already available to replace fossil fuels.

The conclusions relating to technology choices are as follows:

- Wind, solar photovoltaics and concentrating solar thermal with storage are commercially proven, scaleable solutions that together can ensure reliable, 24-hour renewable energy supply.
- Biomass and hydro are commercial renewable options that are limited in their scaleability due to other environmental considerations. They are better suited to supplying backup and balancing power to wind and solar. Biomass is also needed for its carbon content to replace non-energy-related chemical carbon requirements.
- Wave, tidal and enhanced geothermal power are technologies that are on the horizon, but as yet have not overcome all technical hurdles nor have they been demonstrated at scale.
- Carbon capture and storage (CCS) is similarly an unproven technology, that is not expected to be commercially available within the ZCA2020 timeframe. It is also not a zero-emissions solution, as even should it be demonstrated at scale, proposed projects are not expected to capture 100% of fossil fuel plant emissions.
- Nuclear power is highly unlikely to be viable in Australia over a ten-year period, as countries that already have a nuclear power industry experience implementation times for nuclear plants in the order of 10-19 years for single reactors.

1.5 The ZCA2020 Project and the Stationary Energy Plan

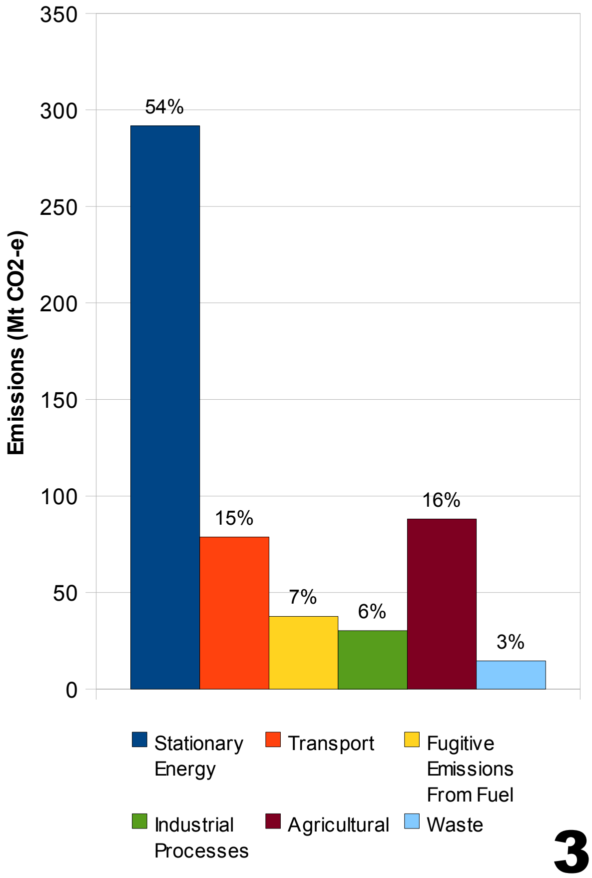
The ZCA2020 Project consists of six inter-related reports, each addressing a specific Plan. The ZCA2020 Stationary Energy Plan is the first and most urgent of these, since 50% of Australia's emissions are generated by the stationary energy sector.

The complete set of ZCA2020 reports to be produced are:

- Report 1: The ZCA2020 Stationary Energy Plan addresses the re-powering of Australia's stationary energy sector with zero emissions technology
- Report 2: The ZCA2020 Buildings Plan considers measures to improve energy efficiency, and hence reduce the demand for stationary energy
- Report 3: The ZCA2020 Transport Plan is concerned with powering private and public transportation with renewable electricity
- Report 4: The ZCA2020 Industrial Processes Plan addresses measures to reduce emissions from industry
- Report 5: The ZCA2020 Land Use Plan considers changes to agriculture, forestry and other land use practices to minimise emissions
- Report 6: The ZCA2020 Plan for Replacing Coal Export Revenue focuses on Australia's large fossil fuel exports.

The reports will be inter-related and complementary. As an example, the design of the stationary energy supply

FIGURE 1.3
Australian Greenhouse Gas Inventory 2007[27]



system (Report 1) must include projections of demand and efficiencies from Reports 2, 3 and 4. Furthermore, emissions reductions achieved in the stationary energy sector will have flow on effects in other sectors (Reports 2, 3 and 4) because, for example, electricity will become a low emissions energy source relative to gas. The Stationary Energy Plan is released in Version 1.0 form prior to the release of the other five components of the final report, in order to allow for discussion and feedback at the earliest opportunity. The remaining five reports of the ZCA2020 Project will be completed following the release of this report. Ultimately, each report will be combined into a single document to form a comprehensive Plan for reaching zero emissions in Australia over a ten year period.

1.6 Structure of the Stationary Energy Plan Report

The structure of the Plan is as follows:

- **Part 2** describes the design of the proposed stationary energy system (including the implications of the size and pattern of projected demand), an overview of the available zero-emissions technologies, and the rationale for the choice and weighting of these technologies.
- **Part 3** provides a blueprint for the installation of the 100% renewable electricity infrastructure, including specifications, proposed locations, costs and installation timelines.
- **Part 4** shows energy modelling on real-time meteorological data that demonstrates the reliability of the Plan's specified grid.
- **Part 5** shows how the new renewable energy infrastructure integrates into an upgraded grid to ensure reliable supply of electricity. It addresses the significant upgrades to transmission networks that will be required in order to transition to 100% renewable energy.
- **Part 6** describes the resourcing of the transition, in terms of mobilising the material and human resources required within the ten-year timeline.
- **Part 7** compares the investment for the Stationary Energy Plan with the Business-as-Usual case, putting the scale of the financial investment into context with Australia's other present day expenditures.

The basis for the energy demand estimates used within the Stationary Energy Plan are derived from work already undertaken on the remaining ZCA2020 reports. These remaining five reports are currently in development and therefore it is possible that the projected stationary energy demand may change from the estimates in this initial version of the Plan. Nevertheless, the same design principles would apply to the proposed stationary energy system when updated demand figures become available. Similarly, although the current figures for costing are well-informed estimates, it is feasible that the figures in later versions of the Plan may be higher or lower, depending on updates relating to technologies and proposed efficiencies.

1.7 The ZCA2020 Working Group

The concept of a plan to achieve zero-emissions energy in ten years originally came from Beyond Zero Emissions, motivated by the scientific evidence that atmospheric concentrations of greenhouse gases are already too high. BZE put together an enthusiastic expert team of engineers and scientists with relevant industry and academic backgrounds who worked pro-bono to develop the plan.

As one of the project leaders Patrick Hearps, from The University of Melbourne's Energy Institute, recruited a team of University researchers and alumni, doubling the capacity of the project. The Melbourne Energy Research Institute has reviewed the plan, and publishes it as part of its "Australian Sustainable Energy" series.

1.7.1 The Future of ZCA2020

The ZCA2020 project is an ongoing initiative. It is a collaboration of pro bono contributors, and more people with relevant expertise and interests are welcome to contribute. The current publication is Version 1.0 of the Stationary Energy Plan. Future work includes not only the other ZCA2020 reports, but updated versions of the Stationary Energy Plan that take into account more in-depth analysis, updated figures on energy projections, modelling with improved data, and any new technological developments.

In the meantime, updates to the Plan will be available online.

It is not the intent of the ZCA2020 Stationary Energy Plan to comment or recommend any particular financial or policy mechanisms that would lead to the roll-out of the proposed transition. There are a range of policy instruments that can be used, which should all be judged by their effectiveness in achieving a desired outcome. The Plan demonstrates one potential outcome. However, future work will also involve a separate publication discussing financial and economic policies in the context of the ZCA2020 plan.

Footnotes

1. *The absolute growth rate of CO_2 in the atmosphere has increased substantially: the first 50 ppm increase above the pre-industrial value was reached in the 1970s after more than 200 years, whereas the second 50 ppm occurred in about 30 years. In the 10 years from 1995 to 2005, atmospheric CO_2 increased by about 19 ppm; the highest average growth rate recorded for any decade since direct atmospheric CO_2 measurements began in the 1950s[5].*
2. *While we normally tend to think of climate as having its own inherent equilibrium, the concept of a "tipping point" mechanism[7] breaks this rule, creating a situation where large scale climate systems can finally switch into a different state, which is qualitatively different from past history, and recovery may be impossible. "Tipping point" mechanisms include positive feedback, phase transitions with hysteresis, and bifurcations.*
3. *Hansen recommends that atmospheric CO_2 concentration be reduced to 350 ppm at most (but preferably less) to preserve a planet similar to that on which civilisation developed, and to which life is adapted[6]. Schellnhuber et al base their strategy on keeping temperature rise below a "guardrail" of 2°C rise above 1990 levels[9]. They do not specify a particular concentration of atmospheric CO_2, but strongly suggest that we should return to pre-industrial levels of atmospheric CO_2 (280 ppm) to avoid the risks of untested long term climate conditions.*
4. *Australia and USA have virtually the same per capita emissions—Australia 19.00 tonnes per capita per annum, USA 19.7 tonnes per capita per annum (2006 data)[12].*

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Part 2

Designing the ZCA2020 Stationary Energy Plan Supply System

Contents

2.1 Overview of the ZCA2020 Stationary Energy Plan Supply System

Part 2 presents a broad overview of the design of the ZCA2020 Stationary Energy Plan (the Plan). It begins with a description of Australia's current stationary energy sector, then outlines what Australia's energy demand will look like in 2020 under the Plan's implementation of efficiency upgrades and fuel-switching. Strategies for flattening demand peaks are discussed, and, finally, the commercially available renewable technologies that will meet this demand are introduced.

The renewable energy infrastructure proposed (further detailed and costed in Part 3) will be sized to supply a 2020 grid electricity demand of 325TWh/yr, more than 40% higher than today's electricity consumption. This is greater than would be expected under Business-As-Usual growth, and is more than capable of meeting future electricity needs. However, with further investment in energy efficiency and fuel-switching, to be detailed and costed in future ZCA2020 reports, it is projected that this will be sufficient to replace not only current electricity, but oil and gas that is currently used for transport and direct heating, thereby replacing all fossil fuel use.

Australia's current energy consumption is approximately 3,915 PJ/yr, while the grid electricity component of this is 228 TWh/yr (822 PJ/yr). Under the Plan, total energy consumption will halve by 2020 without reducing the provision of energy services. To achieve this, grid electricity requirements will increase to 325TWh/yr. This new requirement has two major parts:

- improved energy efficiency technologies reduce the electricity requirements for current services by one third across the residential, commercial and industrial sectors. This brings Australia energy efficiency into line with other modern, developed economies.;
- a fuel-switch from transport oil, heating gas, and industrial use of fossil fuels to highly efficient renewably-sourced electricity. This reduces Australian consumption of *energy* dramatically, though of course leads to an increase in *electricity* demand.

Seasonal energy demand variation, and ways of flattening demand curves, are also examined in detail. In particular, the strong peaking influence of Victorian cold weather gas demand can be mitigated through a large-scale rollout of building insulation and integrated photovoltaic technology in Victoria.

In order to meet the new demand curves, the ZCA2020 Plan recommends the following commercially-available generation technologies:

- **Concentrated Solar Thermal (CST) Power Towers with molten salt heat storage**: meeting 60% of electricity demand throughout the year;
- **Wind power**: meeting the remaining 40% of demand;
- **Crop-waste biomass and hydroelectricity**: providing backup for 2% of the demand, when simultaneous lulls in solar and wind cause shortfalls in supply;
- **National Grid**: flattening demand peaks and integrating CST, wind and backup energy sources, to provide reliable supply.

Concentrating solar thermal with molten-salt-heat-storage technology provides the capability to store the sun's energy as heat, rather than as electricity. Electricity can then be generated either at a constant rate ('baseload') or as required to meet peak demand. Cost-effective storage of the sun's energy as heat means that CST can reliably provide electricity during cloudy periods and at night. Overseas, Concentrating Solar Thermal electricity generation already operates at utility scale, providing efficient energy storage and 24-hour electricity supply.

In Australia, a wide geographical distribution of generation assets under the Plan allows lower-cost wind power to be integrated with CST.

In rare extended periods of low sun and wind across Australia, crop waste biomass-firing provides an additional source of heat at the CST plant sites, and/or existing hydro is used. Historical system performance and weather forecasts are used as tools to manage the system during such periods.

Lastly, solar PV is likely to reach "grid parity" between 2015-2020, and an allowance is made for small scale solar PV and solar hot water to provide 10% of energy by 2020.

A life-cycle emissions analysis of this system demonstrates that wind and CST have rapid energy pay-back periods, and vastly superior emissions profiles compared with alternative technologies such as carbon capture and storage (CCS). Moreover, unlike technologies such as enhanced geothermal and CCS, all the technologies relied upon in the Plan are commercially available today.

2.2 Analysis of Current Australian Emissions and Energy-Use Trends

2.2.1 Australian Greenhouse Gas Emissions

Australia currently generates the highest per-capita emissions of greenhouse gases amongst OECD countries[1] As shown by Figure 2.1, approximately two-thirds of Australia's total greenhouse gas emissions result from fossil fuel combustion in the stationary energy and transport sectors.

As shown by Figure 2.2, close to 90% of the emissions from the Stationary Energy Sector arise from the combustion of coal. Other emissions associated with the use of fossil fuels in the Stationary Energy Sector are related to industrial processes and fugitive emissions, including leakage from natural gas distribution networks and methane released during coal mining[1].

Treasury modelling predicts that under Business As Usual (BAU), Australia's greenhouse gas emissions will continue to rise[2]. The same modelling also predicts that any reductions in greenhouse gas emissions under CPRS type legislation (5-15% reductions), will depend substantially on importing permits from other countries. Given this predicted dependence on exporting Australian carbon emissions offshore, it is difficult to see when and how, under current government policies, the Australian economy will make any significant move away from its reliance on fossil fuels.

FIGURE 2.1
Australia's projected cumulative emissions by sector 2005 to 2050

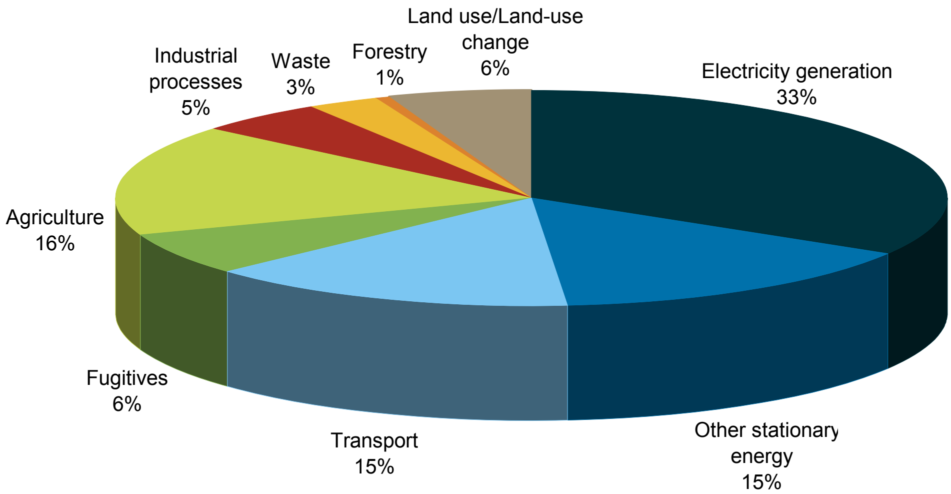
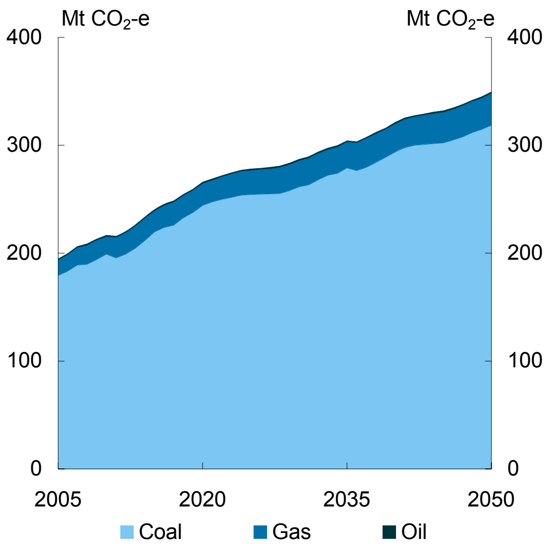


FIGURE 2.2
Australia's projected stationary energy emissions by fuel source[2]



Source: Treasury estimates from MMRF and MMA (2008).

2.2.2 Current Australian Energy Consumption

Figure 2.3, sourced from Geoscience Australia, reveals important relationships between Australian energy supply and utilisation. The relative width of the lines represents the size of the energy flows.

Coal (shown in blue in Figure 2.3) is an inefficiently-used fuel. 2,050 PJ/yr of coal is burned in Australia to produce only 750 PJ/yr of electricity[3]. Even then, about 7% of this is "parasitic" consumption used onsite by the power stations themselves[4]. This means that only 700 PJ of useful, end-user coal-fired electricity makes it to consumers. The remaining 1,350 PJ/yr, or 66% of the resource[3], is lost in the electricity generation process. This lost energy is rejected into the environment via vaporisation of cooling water or when coal-fired power stations 'blow steam' at periods of low demand. Water used in the coal-fired generation of electricity is unavailable for other uses such as for growing food. A typical 500 MW coal-fired power station requires around 8.3 billion litres of water per year[5].

In Australia, natural gas (shown in pink in Figure 2.3) currently supplies more end-use energy than any other fuel used in the Stationary Energy Sector, even coal. This energy is largely consumed for industrial and residential heating.

Australian passenger and freight movements are currently powered primarily by the burning of 300 million barrels per year of oil and LPG[3] in inefficient internal combustion engines. Oil (shown in black in Figure 2.3) is a growing expense which, under BAU, will cost the Australian economy ~$1.3 trillion (2010 dollars) between 2010 and 2040 (see Part 7—Economics). Oil imports have grown since Australian domestic oil production peaked in 2000. Domestic oil production is now in decline and this is projected to continue. Forty percent of the crude oil consumed in Australia is imported, adding $15.7 billion to the 2007/2008 current account deficit[6].

FIGURE 2.4
Australia's projected oil supply-demand balance [8]

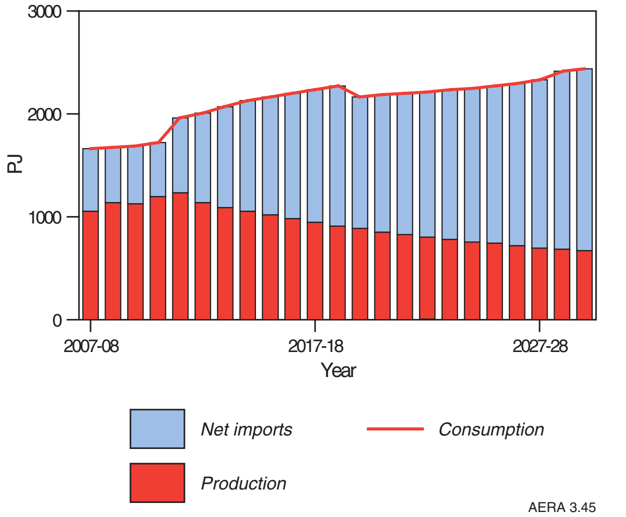


FIGURE 2.3
Australian Energy Flows 2006-2007[3]

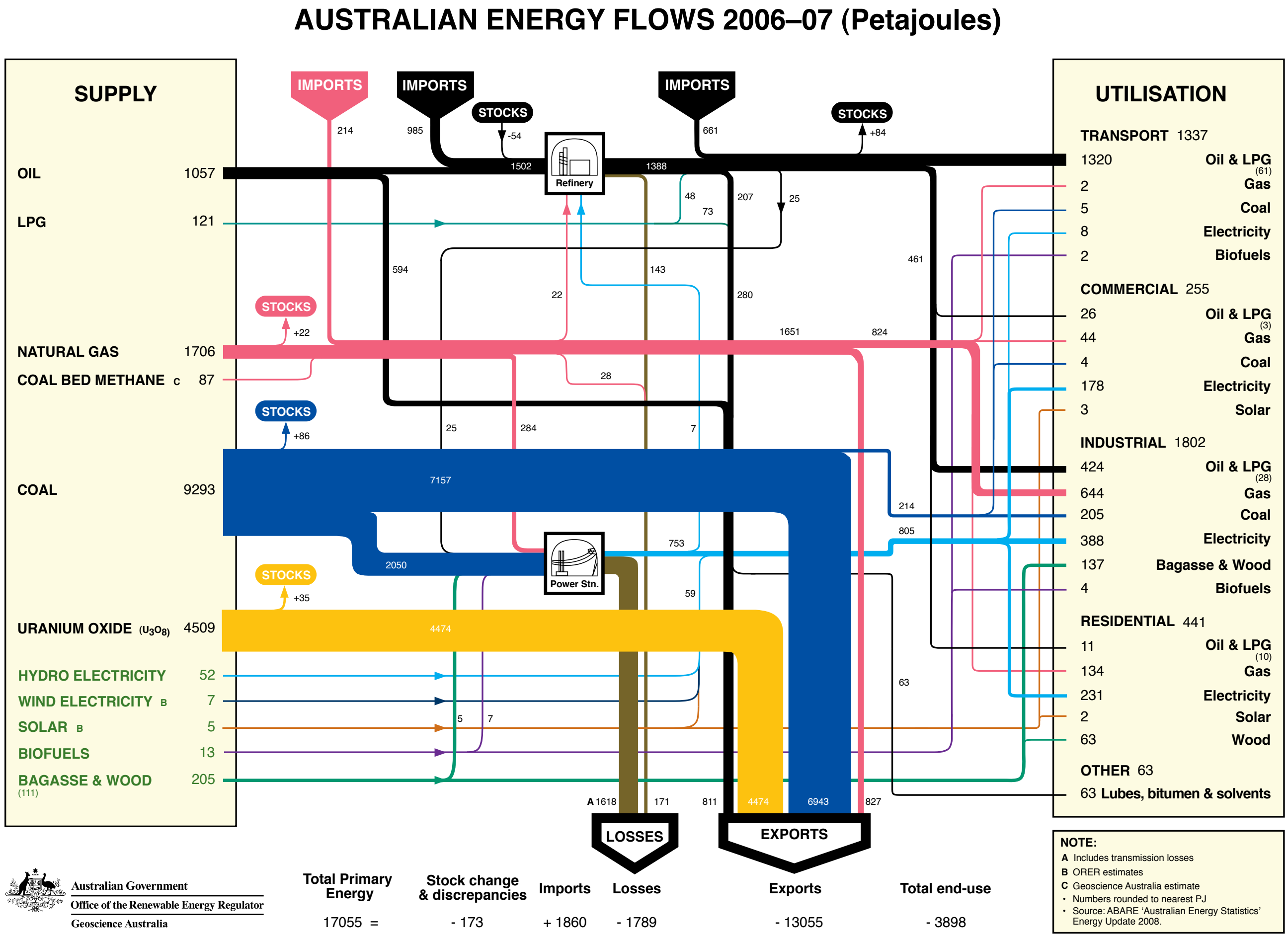
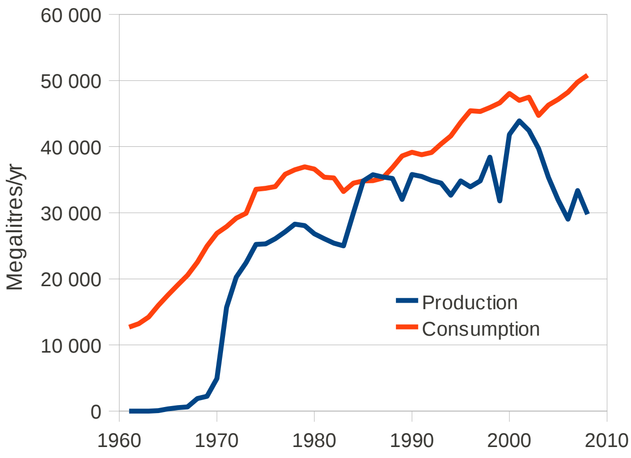


FIGURE 2.5
Australia's Oil Production and Consumption 1961-2008. Data from ABARE[7]



Moving away from oil as a transport fuel has the additional benefit of improving Australia's energy security. A number of studies support the conclusion that global oil production is currently peaking, leading to supply/demand price spikes in the near future[9,10,11].

Due to the inefficiency of the internal combustion engine, less than 20% of the fossil fuel energy consumed by the Transport Sector is actually converted into useful vehicular motion, once stop-start ineffiencies are factored in. On the other hand, electric rail and electric cars convert 80-90% of electrical energy into motion—and the electrical energy can be derived from 100% renewable sources. This presents a massive opportunity to improve energy-use efficiency, eliminate the vast cost of oil imports, and reduce the carbon-intensity of Australia's transport system to zero.

2.3 Australian Energy Demand in 2020 under the Plan

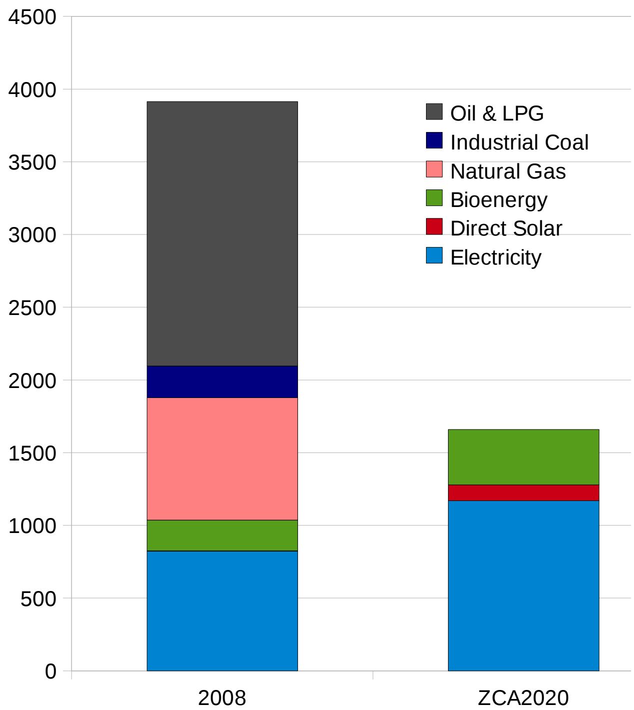
The ZCA2020 Plan proposes a complete phase-out of all fossil fuels (natural gas, oil and coal), starting from 2011. By 2020, total Australian energy consumption is reduced to less than half of Business As Usual (BAU) projections. This is the result of moving to a higher efficiency, zero carbon, electricity-based energy system that applies negative pressure on energy costs in the long term[12]. Detailed modelling of this energy transition can be found in Appendix 1, though a short summary is presented in the following text.

Figure 2.6 illustrates the impact of the transition from present-day energy sources to ZCA2020 Plan sources.

Under the ZCA2020 Plan, total energy consumption is reduced to less than half of BAU, from 3,915 PJ/yr (2008) to only 1,660 PJ/yr (2020). How is such a dramatic fall possible?

Under the Plan, oil and LPG production ceases and the inefficient internal combustion engine is replaced with a combination of electrified heavy and light rail, electric vehicles, and some range-extending biofueled hybrid-electric vehicles. These efficiency improvements mean that the 1,217 PJ/yr currently used in transport, primarily oil-

FIGURE 2.6
Australian Energy Sources: Present and Under ZCA2020



(Note: In Figure 2.6, "End-use" coal shown on the chart represents coal that is used only for metallurgical smelting and process heat. Coal currently used for electricity production falls into the "electricity" section of this barchart.)

fuelled, can be replaced with two far smaller energy inputs: first, 180PJ/yr (50TWh) of additional renewable electricity generation capacity for electrified transport, and secondly, just over 50PJ/yr of liquid biofuel to support non-electrified transport services (approximately 5% of the total).

Natural gas is completely phased out and replaced with efficient electrically-driven devices. Natural gas space-heating, for example, is replaced with high efficiency electric heat pumps. As with oil, natural gas consumed for transportation is replaced by additional electricity generation capacity. Certain industrial applications, however, cannot be electrified. Methane, for example, is used directly as a feedstock for the production of chemicals such as methanol and ammonia-based fertiliser. For these purposes, the plan proposes 50 PJ/yr of biogas.

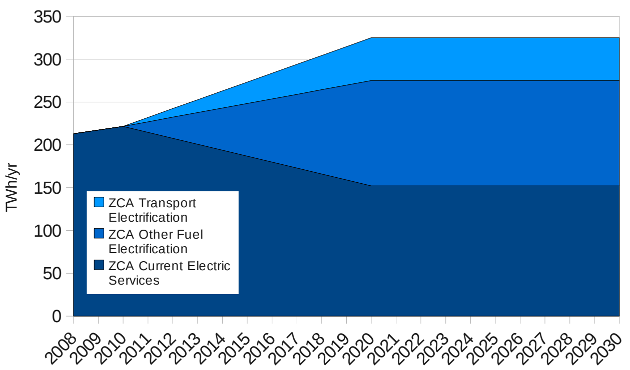
Energy used in the refining of petrol, mining of coal and in the manufacture of liquefied natural gas (LNG), is excluded from the total future energy requirements. This is because the ZCA2020 Plan assumes zero domestic demand for fossil fuels, and assumes that Australia will not be servicing overseas demand for any LNG, petrol, or other fossil fuels.

Locally-collected solar energy for heating water, indoor spaces, and other purposes increases from 3 PJ/yr (currently) to 110 PJ/yr. This includes household solar hot water systems and the use of direct solar energy for industrial processes and other commercial consumption. Onsite solar energy use is modelled by reducing the requirements for grid-delivered electricity.

Lastly, the deployment of energy efficiency programs reduces the end-use energy demanded by traditional services (i.e. not including newly electrified transport and space heating/cooling) in the commercial, industrial, and residential sectors by 20% over the period 2011—2020. This translates to a 33% reduction in per-capita electricity use for these services when population growth is taken into account. This 20% reduction in demand has been modelled conservatively, and deeper analysis in later reports is likely to identify greater energy savings within each sector.

In summary, and as shown by Figure 2.7, though total *energy* demand is reduced by 50% under the Plan, total *electricity* demand increases by 42% from 2008-2020 because of the electrification of transport as well as residential, commercial, and industrial heating. This increased electricity demand is supplied through the renewable generation system that forms the centerpiece of the Plan.

FIGURE 2.7
Total electricity demand including fuel switch and transport electrification



Under the ZCA2020 Plan, total annual grid electricity demand is 325 TWh.

- 152 TWh/year is required for the continuation of current end-use electricity functions (after a 20% reduction from current levels due to efficiency, and other reductions outlined in Appendix 1 such as onsite solar).
- 123 TWh/year is required after the shift from gas to electricity for heating. Improved insulation minimises the winter peaking effect of this shift.
- 50 TWh/year is required for the electrification of transport. The transport component is inherently less volatile than current end-use functions, and in fact can contribute to load levelling due to EV smart charging capability.
- Onsite solar PV and solar hotwater displaces 30TWh/year that would otherwise be required from the grid.

FIGURE 2.8
International comparison of primary energy consumption per capita (GJ, 2007).

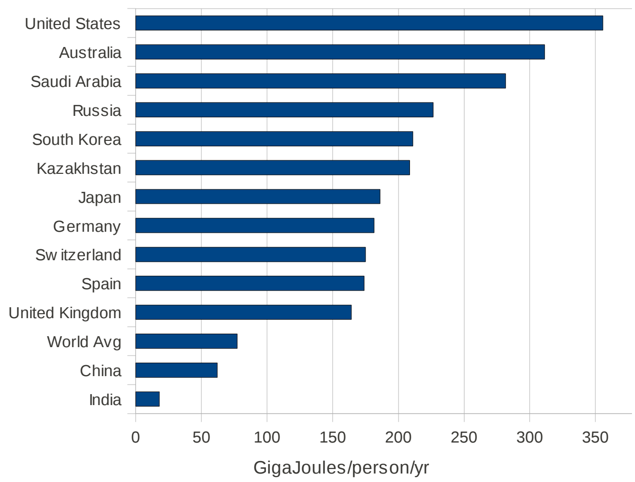
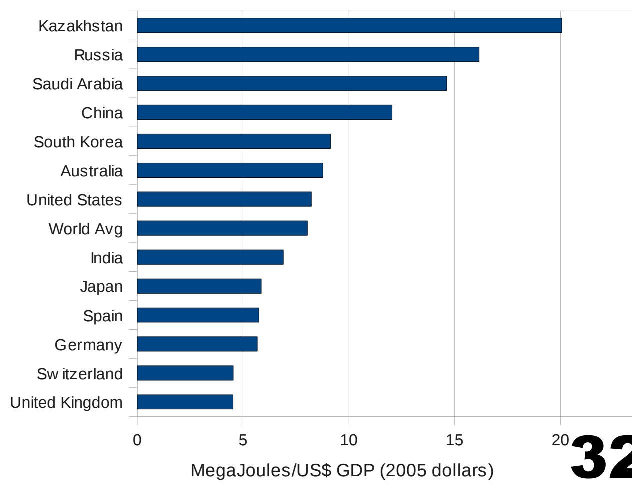


FIGURE 2.9
World energy intensity (MJ / $US GDP, 2005).



2.3.1 Energy Efficiency Measures Employed to Reduce Overall Energy Demand

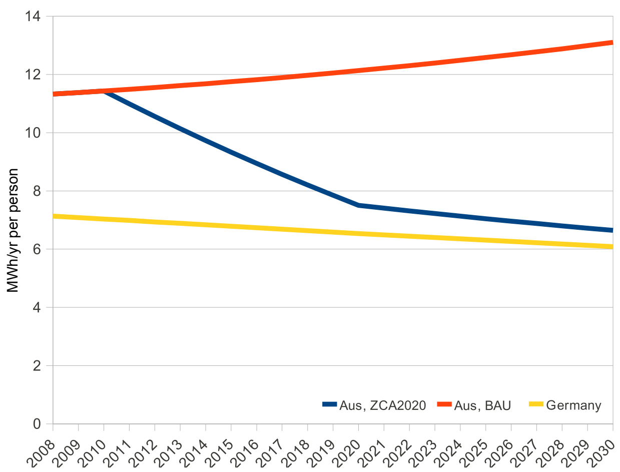
Australia has an energy intensive economy compared to other modern economies worldwide. Many European countries have significantly lower per capita primary energy consumption (Figure 2.8). High energy consumption is not necessarily linked to higher wealth or quality of life. Countries like Kazakhstan and China have a higher energy intensity (MJ/$GDP) than Australia and are poorer countries with lower living standards.

Increasing energy efficiency, and thereby reducing overall demand, is the most cost-effective way to reduce carbon dioxide emissions in Australia. Our current per-capita energy consumption is significantly higher than energy-efficient countries such as Germany. In fact, even after the Plan's 20% improvement in commercial, residential and industrial energy efficiency, Australian per-capita electricity consumption is still above that of Germany (Figure 2.10), not inclusive of the extra electricity for oil and gas replacement. Ongoing per-capita efficiency gains of 1-1.3% per year after 2020 keep total demand steady at least to 2040, while allowing for population growth.

This 20% improvement in energy efficiency can be achieved largely through targeting 'low-hanging fruit': technologies that are easily implemented with rapid payback periods. Examples include upgrades to the latest appliances and machinery, and measures as basic as insulation of buildings and piping. These 'low-hanging fruit' improvements can be implemented without negative effects on service levels or quality of life, and can realise per-capita efficiency gains of 3.5-4% per year.

As shown in Figure 2.7, total electricity demand will continue to rise as electricity steadily replaces oil and gas. This will in fact result in higher total per-capita electricity consumption than even the Business-As-Usual scenario of 2% growth per year. From 2020 to 2040, the Plan caps total electricity consumption at 325TWh/yr by continuously deploying ever-improving efficiency measures.

FIGURE 2.10
Per capita electricity consumption



Such improvements in energy efficiency appear realistic and achievable when compared with experiences in other developed economies—such as the aforementioned Germany. Germany is a comparable modern economy with car manufacturing and energy-intensive metal refining industries, including five aluminium smelters[14]. It provides a good example of what can be achieved through strong energy efficiency measures: Germany and Australia have similar per capita GDP[15], but Germans currently use about 36% less end-use delivered electricity than Australians (7.2 MWh of electricity per capita is used in Germany compared to 11.2 MWh per capita in Australia)[16].

Germany plans to improve its use of energy still further, with an additional absolute cut of 8% from current net energy levels between 2010 and 2020 and a further 9% cut during the decade after that[17]. This will be achieved through the implementation of Germany's National Energy Efficiency Action Plan which includes such measures as:

- rapid implementation of smart metering;
- increased investment in energy efficiency for public buildings;
- new guidelines emphasising energy efficiency in government procurement processes;
- long-term, low-interest loans for retrofitting of old residential buildings;
- subsidies for new low energy houses;
- employment of specialised energy managers within municipal governments;
- demand management projects to foster energy saving actions by consumers;
- improved energy consumption labelling on motor vehicles, equipment and products in general[18].

Australia's record on energy efficiency is poor, as shown in Figure 2.8. This has resulted from the absence of effective government policies to provide incentives for investment in energy efficiency. Consequently, there is room for dramatic improvement in energy efficiency in Australia[13].

Given Germany's plans for the future, and Australia's current laggardly performance in energy efficiency, rapid improvements are feasible and will be cost-effective. Coordinated measures and policies can ensure both short-term and long-term gains in efficiency, and prevent negative rebound effects[19].

2.3.2 Buildings: Energy Efficiency and Retrofitting

The cost of electricity in Australia has historically been low compared to other developed nations, allowing lowest-initial-cost building practices and inefficient design to persist as the norm. Given a growing awareness that these practices are unsustainable, the ZCA2020 Sector Report 2—"Buildings" will be developed to correct this. It will include detailed and costed proposals for:

- a building efficiency retrofitting program, including insulation, double glazing and draught-proofing;

- phasing out the use of gas for domestic, commercial and industrial space and water heating, by moving to electric heat pumps and solar water heating. (Heat pumps use around one third of the energy of other forms of space heating);
- the phased replacement of gas used in cookery with induction cooking and high efficiency electric ovens (gas stove tops are 30-40% efficient[20] at heating food while induction cooktops are generally 80-90% efficient[21] at heating food).

For the purposes of the ZCA Stationary Energy Plan, a projection of a 20% improvement in energy efficiency (i.e. 20% reduction in total energy use) for the buildings sector is modelled. Preliminary work analysing the retrofitting Australia's existing housing stock indicates that this is likely to prove conservative. The preliminary Residential Retrofit report, a prelude to a full Building sector analysis, shows that total energy use could be reduced by 60%, and grid electricity consumption by 36%, through the measures outlined above.

Up to four and a half million homes would be fitted with rooftop mounted solar photovoltaic systems, reducing the requirements for grid electricity. Solar PV systems in this analysis are considered similar to a form of energy efficiency, by offsetting grid demand and reducing daytime peak power requirements.

There is ample evidence that many simple initiatives to reduce energy consumption are cost negative in the short term[22]. iGrid, a collaboration of leading Australian research institutes including the CSIRO, recently pointed to energy efficiency as the most economical method of reducing power consumption, with an effective energy "cost" that is substantially below that of conventional power sources[23]. Despite their higher construction expenses, energy efficient buildings more than pay for themselves in both cost and energy savings over their lifetime [24 25]. Analysis undertaken by the Australian federal government also supports this finding[26].

The Empire State Building in New York provides a compelling case for retrofits in the commercial sector. It is currently undergoing a comprehensive retrofit program to reduce energy consumption by 38%. It will require a $13.2 million incremental investment, but will save $4.4 million per year in energy bills. Measures include retrofitting 6,514 individual glass windows with triple-glazing, inserting an inert gas in between glazing panels, as well as upgrading the heating and cooling equipment and introducing more effective energy management systems. Once complete, peak electricity requirements will be reduced by 3.5MW[27].

2.3.3 Transport Electrification and Mode Shift to Public Transport

The ZCA2020 Sector Report: Transport will include detailed costings of:

- replacement of the present petroleum-fuelled fleet with electric vehicles, comprising 'plug-in, battery swap' models and plug-in hybrid-electric vehicles, using liquid biofuels to extend the driving range;
- the design of future personal transport vehicles, fostering and encouraging development and roll-out of a range of lower cost zero-emission electric vehicles;
- a general shift from private cars and trucks to electric passenger trains, passenger trams, freight trains and cargo trams;
- additional energy savings from reductions in average

FIGURE 2.11
Residential energy efficiency, based on preliminary analysis from ZCA2020 Buildings sector report.

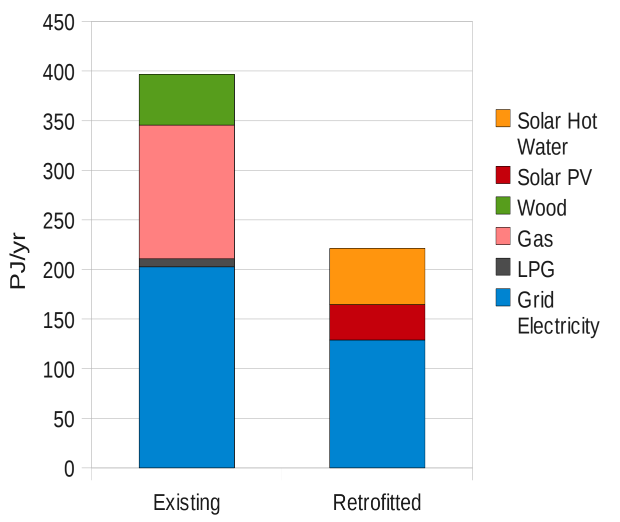
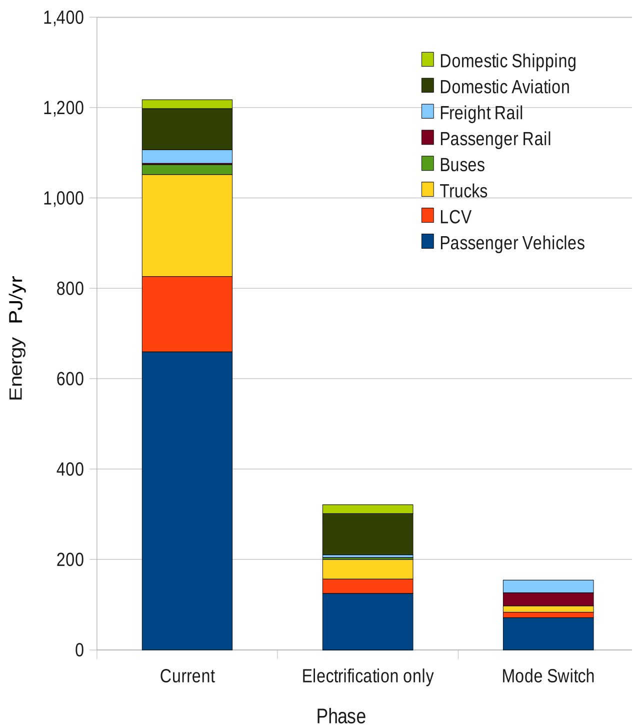


FIGURE 2.12
Energy savings from comprehensive transport electrification and modal shift. Data in Appendix 1



High-speed train in Shenzhen, China[28]

distances travelled, achieved through better urban planning, localised access to services and a range of other policy settings.

Figure 2.12 shows the reduction in energy consumed by the transport sector upon completion of the electric conversion in 2020.

Current annual domestic transport energy consumption is 1217PJ, mainly oil (international transport not included). Analysis indicates that this can be reduced to 320PJ by electrifying 95% of land-based modes of transport, both passenger and freight. A further modal switch to electric light & heavy rail would reduce this to 160PJ, just under 45 TWh/yr of electricity. Allowing for population growth, 50TWh has been allocated for electric transport in 2020 (See Appendix 1 for details).

These figures are based on a switch to efficient, electric light & heavy rail of

- 50% of urban passenger-kilometres
- 25% of non-urban passenger-kilometres
- 50% of urban freight tonne-kilometres
- 80% of non-urban freight tonne-kilometres
- all domestic passenger and freight air and shipping

International air & shipping is beyond the scope of this analysis for Australia.

The Plan proposes a large scale upgrade of public transport services, supplemented with a smaller-than-current private vehicle fleet, consisting of electric, battery swap and plug-in hybrid electric vehicles. Where plug-in hybrid vehicles exist in the fleet, The Plan proposes that they use green biofuels instead of petrol or diesel fuel. However, The Plan recommends a focus on development and rollout of zero-emission electric vehicles, rather than that of low emission fossil-fuel-powered vehicles. Additional energy savings can be accessed by reducing average distances travelled through better urban planning and localised access to services. A renewed emphasis on cycling infrastructure will encourage the use of bicycles in urban areas.

The modal shift from private passenger vehicles to shared electric rail vehicles has the capacity to reduce the private car fleet by around 50%. The average car will travel 8000km p.a. instead of the 15,000km travelled today. ZCA2020 aims for Australia to have six million pure electric, plug-in hybrid electric and battery swap electric vehicles by 2020.

Electric Car Production Capacity and Jobs

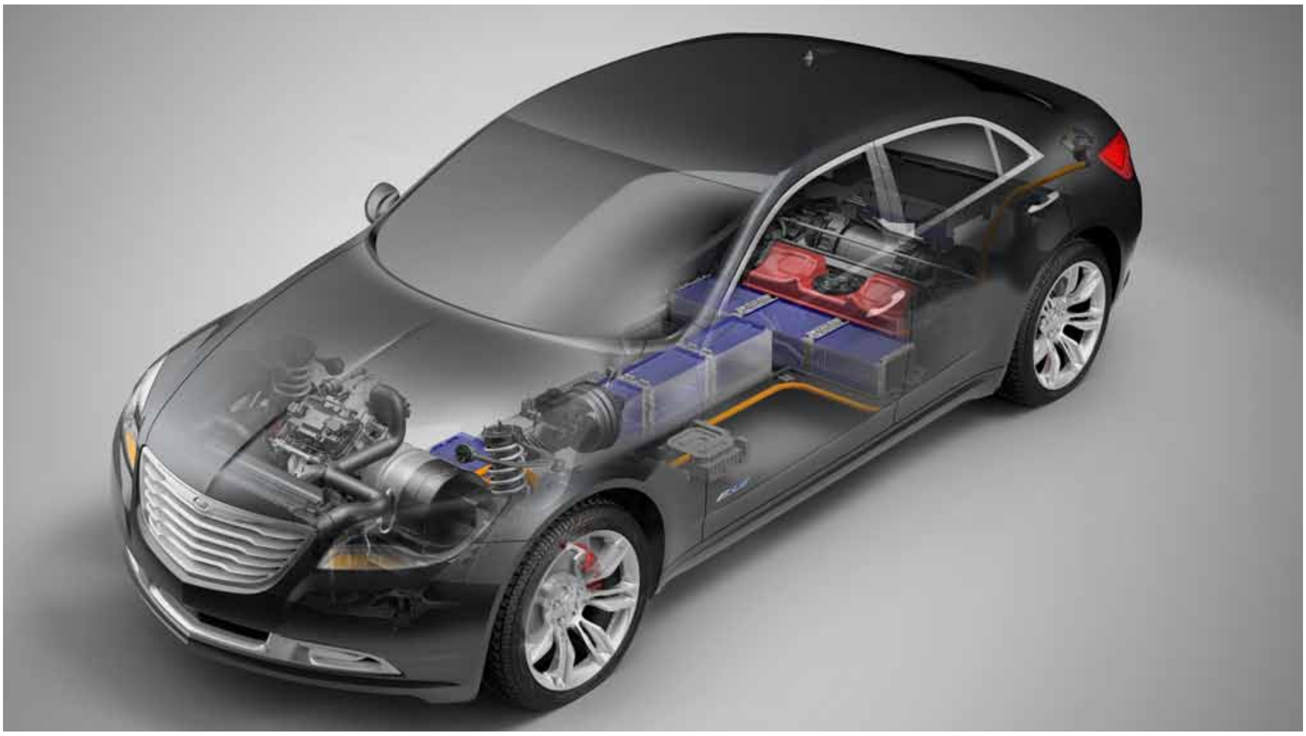
The introduction of 6 million new vehicles in 10 years may seem a challenge, but Australians currently purchases around 1 million new vehicles every year[29]. Demand for new vehicles is therefore strong enough to drive the introduction of appropriately-priced zero emission vehicles. The Australian fleet currently numbers some 12 million private vehicles. The Plan does not attempt to replace all 12 million vehicles, as it anticipates vast improvements to public transport, higher fuel prices, and hence reduced demand for private vehicles. Nevertheless, the capacity exists to deploy 10 million electric cars over the 10 year implementation period. Whether these are sourced from overseas or domestic manufacturing is an economic matter for which the Plan does not recommend any particular solution. An example is given below of the capability of Australia's domestic car manufacturing capacity, to demonstrate the feasibility of the transport shift.

Mass car manufacturing has been a prominent industry in Australia since 1931, beginning with General Motors and Ford, then Toyota, Nissan and Mitsubishi. Three domestic manufacturers remain. As of December 2009, none of their plants were running at full capacity. Toyota is currently producing 100,000—160,000 cars p.a., running 2 shifts and 223 production line days. This could easily be increased to 3 shifts and enough production line days to produce 300,000 cars per annum[30]. To achieve the required production of electric vehicles, the remaining plants would need to increase production to 3 shifts, creating more employment and a combined capacity at the three plants of 900,000 cars p.a.

Although the technology of the plug-in electric vehicles is considerably different from that of an internal combustion engine, the overall production of the car is the same[31]. For this reason, the required tooling changes in the plant would be comparable to those required for the Toyota Hybrid Camry. The manufacture of this hybrid vehicle in Australia was initiated by a $35 million Government grant in July 2008. Just 18 months later in December 2009, the car began production, from a plant designed with the capacity for every vehicle built to be a hybrid vehicle.

At the beginning of World War II, Holden was transformed from a struggling automotive manufacturer to a produceer of high volumes of cars, aircraft, field guns and marine engines[32]. Increased production to 900,000 vehicles per annum across the three existent auto plants is certainly achievable in the twenty-first century, and would allow the production of six million plug-in electric vehicles by 2020.

FIGURE 2.13
Range-extended Electric Vehicle Drive System[39]



Charging

Most cars are stationary for up to 22 hours a day. Car batteries are charged passively during this time, as cars can be left plugged in. When a correlation of high wind speed and solar incidence across the geographically diverse grid occurs, charging electric cars would be used as a means of absorbing "excess" power. In this case the dumped power is useful, both to society and to electricity consumers, rather than being an inconvenience to be managed, as would otherwise be the case for an electricity supply system without adequate energy storage.

The plug-in electric vehicles would be charged at standard domestic single phase sockets (240V/10amps). Full recharging of the national electric vehicle fleet's batteries would require 14.5 GWhr/day, and so could theoretically occur in just over one hour if 14.5 GW grid power was available. The ZCA2020 grid is capable of delivering this charging rate, because it is specified to transmit up to 60 GW with near full wind output. However, this "rapid recharge", would only occur rarely, when low electricity demand coincided with high wind and/or solar output. In the normal charging scenario, vehicles are plugged in (at work or at home) and slow charging can take place over the whole 22 hours, with a required average of only 650 MW battery charging power supply.

"It is all about the batteries...for our hybrids and plug-in hybrids, ten years and 150,000 miles is not an issue at all"
NANCY GIOIA, FORD MOTOR COMPANY[31]

Net Cost

The transformation of transport away from its present mode to the proposed ZCA2020 mode will be cost negative, as capital investment in infrastructure and vehicle stocks give way to lower operational costs. The electrification of the vehicle fleet would present a number of advantages, both in economic costs and in environmental impact[34]. Electrification of the vehicle fleet is beneficial, primarily due to the efficiency of electric motors transforming stored electrical energy to motion. A battery electric vehicle fleet can get up to 5 times more work (motion) per unit of energy input than a fleet of vehicles powered by internal combustion engines (in kms of travel)[35]. That is, an internal combustion engine car such as the Honda Civic or the Toyota Camry might achieve 0.28 to 0.52 km/MJ of input energy, while an electric vehicle can achieve 2.18 km/MJ[36] electrical-outlet-to-wheel. There will, however, be some additional infrastructure investment and operational costs required to support this change. There will be variations depending on the specific model implemented, but solutions outlined by Better Place and other significant movers in the sector are in three principal categories:

- Charge points—these will need to be located in all areas that electric cars are likely to be parked for extended periods (i.e. work and home);
- Battery swap stations—conceptually similar to petrol stations, these will be used to replace depleted batteries;
- Increased electrical generation and distribution requirements.

The requirement for swap stations will likely be lower than petrol stations as they will only be needed when cars exceed the range of a single battery charge in one day.

The overall increase in peak demand and system capacity requirements, caused by additional load on the network, is subject to debate, which centres on the issue of when charging of the batteries will take place. Detractors claim that charging an electric vehicle fleet would require massive increases in power generation capabilities[37]. Instead, the timing of car charging can be controlled to take advantage of lower cost, off-peak power, peak solar generation times or when the wind output is very high and demand relatively low. This will cause zero or minimal increase in peak demand, and may even result in reductions in electricity prices due to increased utilisation of existing infrastructure.

Another argument against the use of electric vehicles regards concerns about the cost and relatively short lifespan of the battery. These concerns are being addressed by developments being made in lithium ion technologies[38] and in the use of next generation lead acid battery technologies such as those from Firefly, a spin-off from Caterpillar[39]. The high cost of the battery is also partially offset by the reduced complexity of the vehicle, and cost reductions are expected to continue. Overall there is a strong argument that even with substantial capital requirements, these costs will eventually be entirely compensated by the substantially lower fuel costs and operational costs for electric cars.

2.3.4 Industrial Energy Reductions

Report 4 on Industry will include proposals for significant efficiencies across Australian industry. For example, a 19% reduction in energy use in the aluminium smelting process, from an average of 14.8 MWh/tonne[40], can be achieved by using a new Chinese process (or equivalent) requiring less than 12 MWh per tonne[41].

Industrial Case Study—Alumina refining energy replaced by solar thermal co-generation. In Part 3 of this report, a single case study has been carried out using solar thermal with molten salt storage as a direct co-generation supplier of process steam and electricity to a large industrial user—the Gladstone Alumina Refinery.

Industrial gas use—Switching gas-fired furnaces to electric furnaces. Approximately 36% of all natural gas consumed in Australia is used by industry, making it the largest consumer in the country. Within industry, gas is the second most used energy source behind electricity. Natural gas is used in many processes, including heating and incineration[42].

The ZCA2020 Plan incorporates the switching of industrial heating loads from natural gas and other fossil fuels to electricity. This can be achieved with existing, proven technology such as electric resistance heating, electric arc furnaces, induction and di-electric heating. Super-critical water oxidation is a proven process for destruction of chemicals, and able to replace incineration. These processes are highly efficient and cleaner than the alternative fossil fuel combustion techniques, and are detailed further in Part 3.4.1 of this report.

Switching of coal for iron smelting. The steel works at Port Kembla and Whyalla respectively use 3Mt and 1Mt of coal p.a.[43], equating to 110PJ of coal energy. This is primarily used for smelting of iron ore, and cannot simply be replaced with electric heating. The Direct Reduced Iron (DRI) process, coupled with Electric Arc Furnace steel smelting, provides an alternative to this. DRI is already used to produce a significant quantity of the world's smelted iron, and is inherently more efficient. Syngas (carbon monoxide and hydrogen), sourced from waste-to-energy or biomass, can be used as a reducing agent in place of coal[44]. Electric Arc Furnace steelmaking is growing rapidly, and is already used to smelt over a million tonnes of scrap iron in Australia. The process is well suited to receiving DRI as a feedstock, which can then be smelted with electricity. An allowance of extra electricity and syngas from biomass has been accounted for in the Stationary Energy ZCA2020 demand scenario to continue smelting the 7.7Mt of steel per annum produced in Australia[45], with the 110PJ of coal removed from the ZCA2020 energy demand scenario. The Industrial Processes working report will present details of this process, including the required investment.

2.4 Proposed Pattern of Demand under the ZCA2020 Plan

This section describes the finer details of energy demand in Australia, as it varies both daily and through the seasons. In particular, the ZCA2020 Plan will see a shift of peak demand from summer to winter, and a decline in overall seasonal demand variability. The section contrasts today's highly variable demand profile, characterised by large spikes in demand that require the construction of expensive reserve plants, with the demand profile flattening brought about by the building upgrades and transport technologies of the ZCA2020 Plan. The Plan promises to significantly reduce the need to construct the underutilised peaking plants of today.

2.4.1 Seasonal Variation and Shift of Demand from a Summer Peak

Under the ZCA2020 Stationary Energy Plan, peak electricity demand will move from summer to winter in most Australian states because of phased replacement of gas fired space heating with electric heat pumps. Seasonal variation in energy demand will also be "flattened", by reducinging Victoria's "winter-peak" gas demand, the dominant factor in seasonal energy use variability. Heating-related efficiency measures will initially be tackled in Victoria, before rolling out efficiency programs Australia-wide. These energy efficiency measures will lower energy demand generally and in particular will mitigate energy demand spikes during hot weather. The energy demand profile will be further smoothed using smart-grids in combination with an electric vehicle fleet and demand-negating, small scale PV.

Implementation of the ZCA2020 Plan has an effect on both the overall energy demand and its variability. The present overall energy demand (supplied by electricity, gas, and liquid automotive fuels) is shown in Figure 2.14. Under the ZCA2020 Plan, there is a reduction both in total energy demand, and its variability. This reduced variability is both long term and short term.

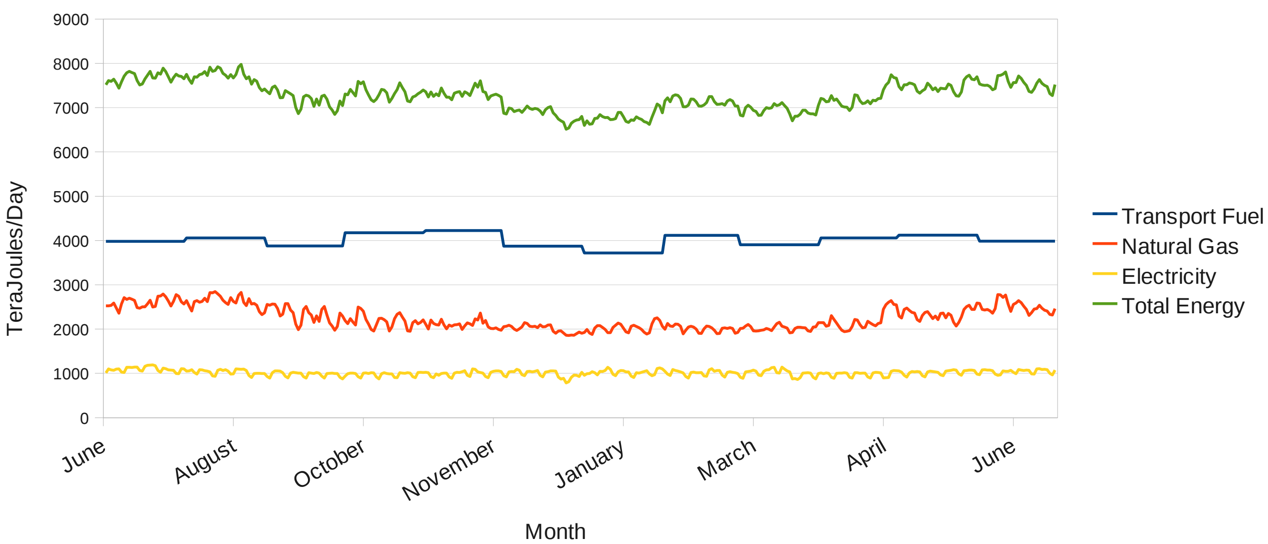
Peak Electricity Demand Will Occur in Winter in Most Australian states

At present, peak electricity demand periods in most Australian states occur during hot summer days. However, as the profile of Australia's total delivered energy shows (Figure 2.14), winter is the period of greatest total energy demand, primarily due to natural gas use. As natural gas is phased out, energy efficiency measures are implemented, and as the remaining temperature-dependent demand (i.e. space heating) is then supplied by methods derived from renewable electricity, peak Australian electricity demand will shift from summer to mid-winter. Efficiency measures such as improved insulation will also lower the demand for electricity for cooling in summer.

Reducing Seasonal Variation in Demand

Analysis has shown that the seasonal variation of the current Australian energy demand profile is heavily influenced by demand in Victoria, due to temperature-dependent gas demand (mainly for gas fired space heating) or the "winter peak" gas demand[46]. Gas consumption in other states can be assumed to be constant year round by comparison. Furthermore, while industry is the largest user of natural gas by total volume (as shown in Section 2.2.2), the seasonal variation in industrial gas usage is quite

FIGURE 2.14
Current (2007-08) Australian seasonal energy demand profile



SOURCE: AEMO [46]

small compared to the seasonal variation due to space heating in workplaces and businesses[46]. When an industrial facility is using gas to heat processes to high temperatures, for example 300˚C, it makes little difference whether the starting temperature is 30˚C in the summer or 15˚C in the winter. However, when tens of thousands of homes and businesses begin to switch on their natural gas heaters at the onset of the winter months, this results in considerably greater gas consumption. This is demonstrated in Figure 2.16 which presents Victoria's seasonal gas consumption, where winter gas demand is more than twice the summer gas demand.

A concentrated effort to flatten the Victorian winter gas usage peak would yield major gains in flattening the Australian energy demand profile over the year. The flattening would be achieved primarily by thermal insulation of Victorian commercial buildings and households. This can reduce heating loads by a factor of 2-4. A program of replacing gas furnace heating with heat pumps would further reduce space heating energy demand by a factor of 4, given an 80% efficiency for gas furnaces and 320% seasonal average efficiency for heat pumps[47]. It is therefore reasonable to assume that given widespread implementation of heat pump and building efficiency improvement in Victoria, "winter peak", space heating requirements could be reduced by around a factor of 10. Note: further flattening of the energy demand peaks, due to reduced air conditioner load during hot weather (as a result of improved insulation) is not modelled but would give further benefits.

2.4.2 Baseload and Peaking under Current Electricity Supply

The current electricity supply system typically groups generator types into "Baseload", "Intermediate", and "Peaking" generating plants.

- "Baseload generators" are designed to operate continuously at high output. Coal plants are almost always operated as baseload plants.
- "Intermediate generators" (or "load following" generators) are designed for faster startup and shutdown, but have higher operating cost. Intermediate generators provide "spinning reserve", which can react quickly to the variability of load and sudden unscheduled generation outages. Natural gas and hydroelectric power plants are typically operated as intermediate plants.
- "Peaking Generators" are held in reserve for periods of unusually high demand, but are the most expensive to operate. Some of these may operate for only a few hours per year[48].

Fossil fuel power stations are often claimed to be superior to renewables because of their capacity for 'baseload' power and energy supply security. However, the fact is that they represent an expensive and inflexible response to energy demands. Currently, Australia has an average power demand of 24,000 MW, which doubles to over 48,000 MW during peak periods. Currently, meeting peak demand is a more pressing issue for the Australian grid than meeting baseload generation[49].

The impact of short term peaking demands for NSW is shown in Figure 2.15. Almost one third of the annual wholesale cost of electricity comes from a few price spikes. These spikes have an extremely high cost (over $1000 per MWh, as opposed to a typical Australian wholesale electricity price of $30-40 per MWh[50]). These price spikes are passed on to

FIGURE 2.15
Current wholesale electricity market volatility[51].Price spike events offer opportunities for Demand Side Response (DSR) instead of building low-utilisation peak generating capacity.

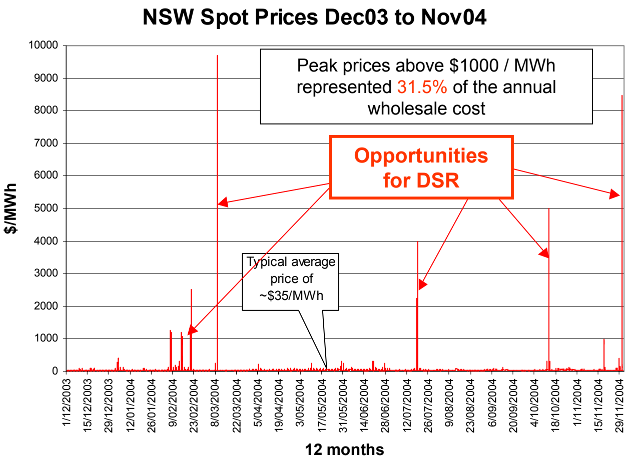
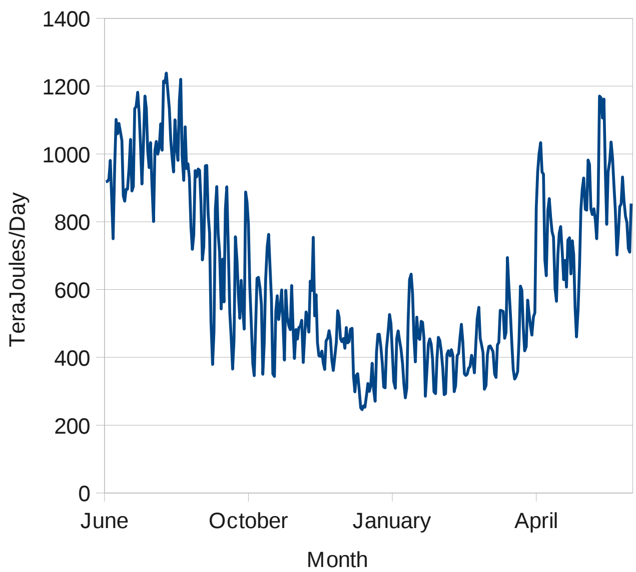
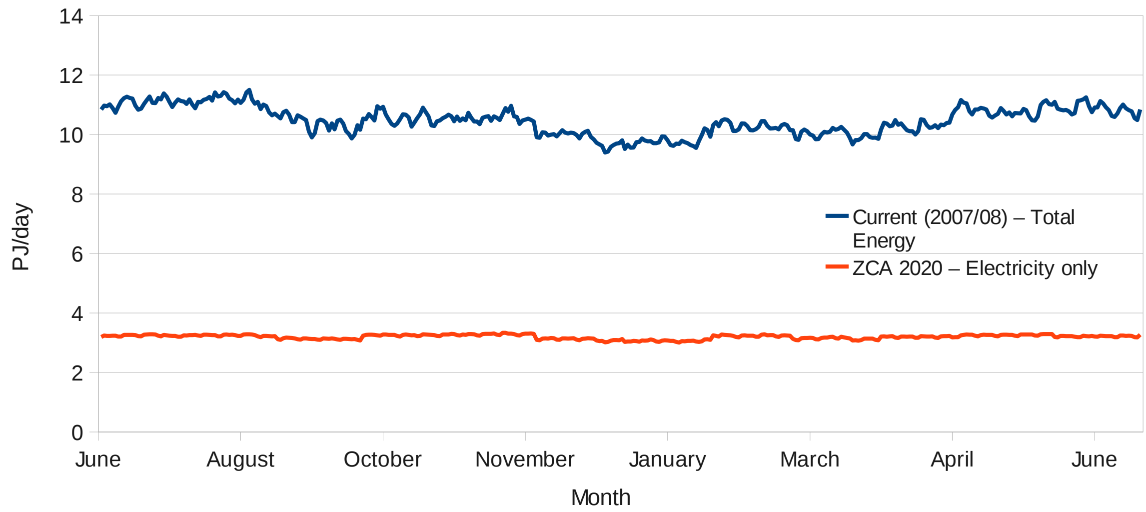


FIGURE 2.16
Victorian gas consumption—Winter 07 to Winter 08



SOURCE: AEMO[46]

FIGURE 2.17
Australian seasonal energy profile—Current (2007/8) (total 3915 PJ/yr) vs Projected ZCA2020 electricity (1170PJ/yr)



consumers, who currently have limited options for adjusting their energy use to avoid using energy during these 'peak price' events.

A recent example of this problem is outlined in the "2009 State of The Energy Market" report by the Australian Energy Regulator (AER). The report indicates that certain companies, who own peaking units, can exploit high demand events such as peak demand caused by extreme heat, to charge up to $10000 per MWh (over 150 times the normal wholesale electricity price[50]).

2.4.3 Flattening Electricity Demand Peaks

As outlined above, short-term electricity demand spikes (which are mainly due to air-conditioner load during hot weather) account for one third of the current retail price of electricity. Reducing short-term demand spikes yields high returns in minimising the overall capital and operating costs of the electricity supply system. Under the ZCA2020 Plan, improved insulation and the use of 'smart meters' assists in levelling short term spikes in electricity demand.

For example, well insulated houses with smart metering combined with advanced forecasting for smart grid operation can be preheated to 24 °C with electricity during lower demand periods, then allowed to slowly cool to 19°C over six hours or so. Virtual elimination of the energy demand spikes could be achieved by a large scale rollout of Building Integrated PV (BiPV). Buildings that are retrofitted with high performance insulation, passive ventilation and energy efficient devices can reduce their heating and cooling energy needs by 50-75%, with BiPV meeting much of the remaining demand[47].

The electric-transport fleet can also be useful in managing short term peaks, as off-peak charging of electric vehicles (nonessential deferred load) can be used to smooth peaks. Battery recharging of the transport fleet can occur during windy periods (or during coincidence of sunny and windy periods) when excess electricity is available, and during night-time hours when electricity demand is low, and the distribution network has spare capacity. Further detail on this measure will be available in Report 3 on Transport.

Under the ZCA2020 Plan the 'peakiness' of the pattern of demand is much reduced. This is due in part to the reduced volatility of domestic electricity use resulting from the measures described above, and further detailed in the later Report 2 on Buildings. However, it is important to note that there is also a substantial reduction in the proportion of electricity use that is subject to significant peaks.

2.5 Choosing Feasible, Cost Effective Zero-Emissions Solutions

This section details the specific zero-emission solutions that have been selected for use in the Plan. It describes why these technologies have been chosen, highlighting their advantages within the context of Australia's geography, resource availability, and demand curves. The electricity generation technologies that form the centrepiece of the Plan include a combination of wind turbines and concentrating solar thermal power towers with molten storage to meet the bulk of demand, with a small quantity of biomass and hydroelectric backup. Lastly, the life-cycle emissions of this system are analysed to demonstrate the rapidity of the expected CO_2 payback.

These technologies are all commercialised and ready for deployment today.

2.5.1 Australia's Solar Resource

Australia's solar resource is equal to the world's best. Figure 2.18 shows the annual average solar exposure, which is greater than 6 kWh/m^2/day (2,200 kWh/m^2/year) over much of the continent.

Australia has many sites with superior solar incidence, and less pronounced seasonal variations than overseas sites where extensive use of large scale solar power is planned and operating. Table 2.1 shows monthly solar incidence figures for three international sites which already have operational large-scale solar power plants (the Mojave Desert, California, and Granada and Seville in Spain) and three possible Australian sites — Mildura, Carnarvon and Longreach.

This demonstrates the excellent solar characteristics of Australia's proposed sites. Mildura, one of the sunnier places in Victoria, has a similar annual average insolation (5.9kWh/m^2/day) to the Spanish/U.S. sites (5.8-6.9kWh/m^2/day), with a less significant ratio from summer to winter (1.8:1 vs 2.4:1) than the Spanish sites. Further north, Australia's other sites become much better than overseas. This will make the economics of solar power in Australia even more favourable, as more energy can be obtained and sold from any given solar power installation.

2.5.2 Concentrating Solar Thermal Power—The Most Suitable Large-Scale Solar Technology

Two large scale centralised solar technologies are available:

- Concentrating Photovoltaic Solar (CPV); and
- Concentrating Solar-thermal Power (CST).

Both of these technologies can play a valuable role in a future zero emissions economy.

Choosing between large-scale CPV and large scale CST. Central dish and power tower CPV systems (for

FIGURE 2.18
Daily Direct Normal Irradiation solar exposure—annual average. From DLR[52]

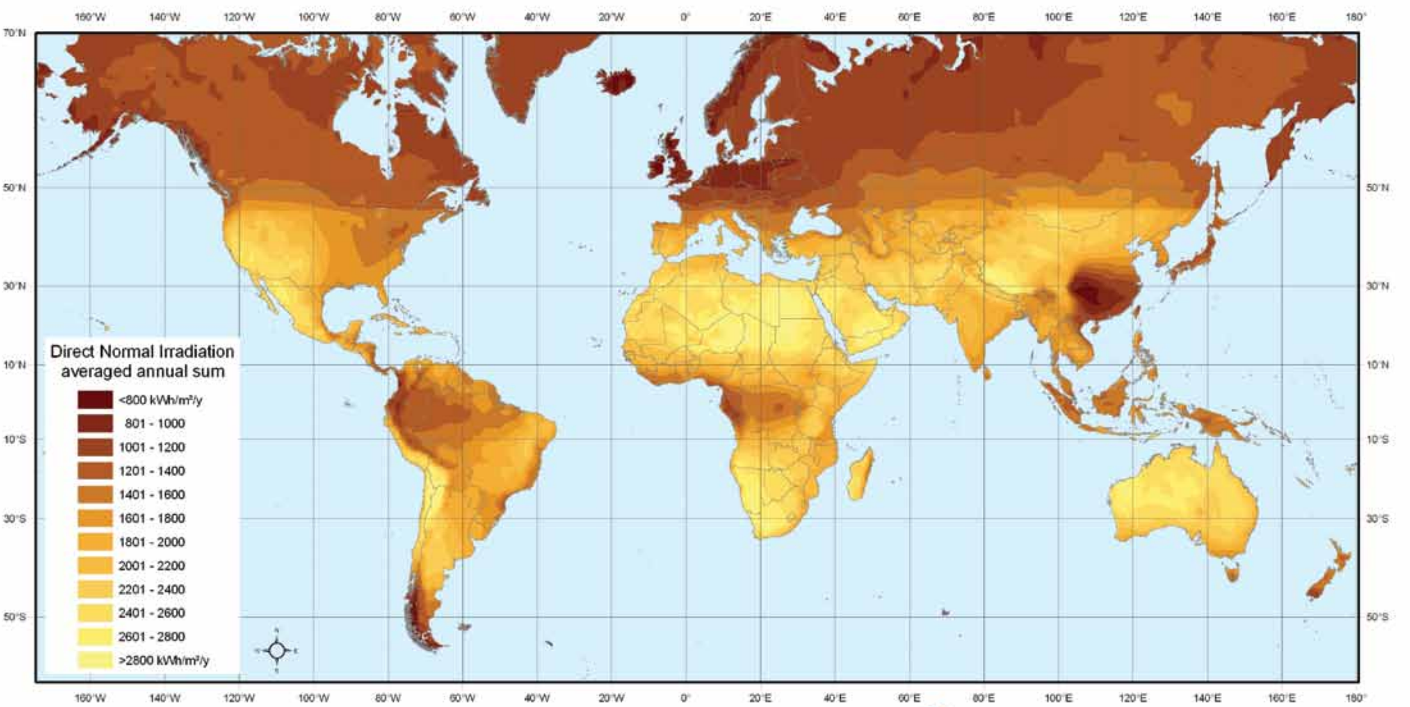


TABLE 2.1
Comparison of solar resource (Direct Normal Irradiation, kWh/m²/day) in Spain, southern U.S. and Australia. Data from NASA[53]

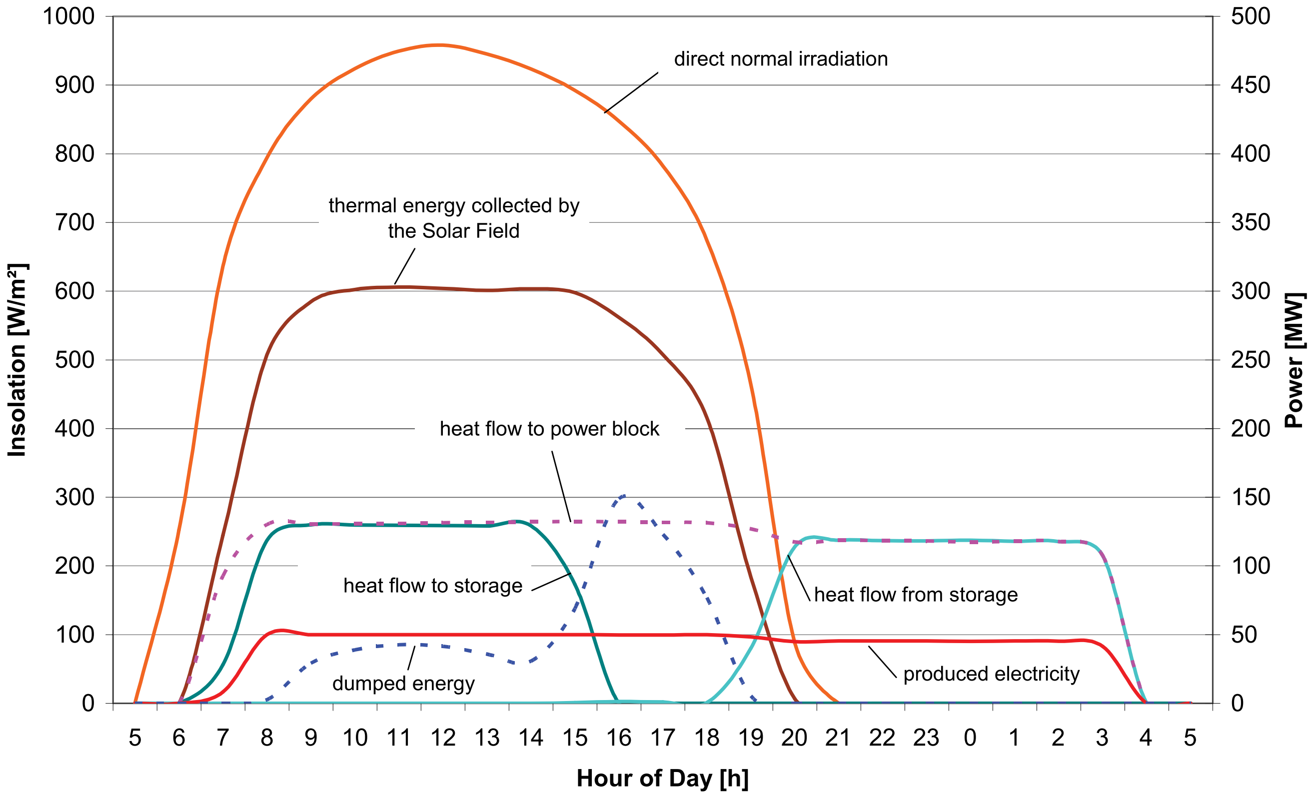
Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average	Max-Min Ratio
Mojave Desert USA	5.29	5.62	7.03	7.95	8.32	8.55	7.87	7.50	7.03	6.37	5.90	5.25	**6.90**	**1.6:1**
Granada Spain	4.36	4.96	5.68	5.71	6.33	7.93	8.80	7.57	6.08	4.60	3.96	3.64	**5.81**	**2.4:1**
Seville Spain	4.62	5.30	6.14	6.24	6.79	8.32	9.26	8.42	6.74	4.92	4.26	3.94	**6.25**	**2.4:1**
Mildura Australia	7.52	7.10	6.71	5.76	4.56	4.13	4.25	4.92	5.62	6.49	6.89	7.17	**5.92**	**1.8:1**
Carnarvon Australia	9.63	8.80	8.27	7.13	6.42	6.33	6.66	7.72	8.78	9.57	9.98	8.25	**8.26**	**1.6:1**
Longreach Australia	6.63	6.36	6.63	6.54	6.38	6.61	7.05	7.30	7.54	7.05	7.18	7.13	**6.87**	**1.3:1**

example, those developed by the Australian company, Solar Systems) are fast increasing in efficiency and reducing in price. These technologies will benefit from the development of multi-junction silicon cells by the space industry and National Renewable Energy Laboratories (NREL). Solar Systems' CPV systems currently utilise 34% efficient central receivers, however 40% efficiency has already been proven in the laboratory and up to 60% is achievable[54].

However, the ZCA2020 Plan grid design requires a fully dynamic, dispatchable generation source to complement wind power, which remains the cheapest way of generating renewable energy[55,56] (See Section 2.5.4 for more on wind power). Hence, large scale CST is more suitable than large scale CPV, as CST can be readily built with integrated commercially available storage. Central receiver CPV plants can only produce energy for reasonable costs during on-sun hours. The cost of producing energy from Molten Salt Storage based CST Power Towers is the same during sun hours and non-sun hours. And when the plants are positioned in sunny locations, they have the ability to generate electricity at full capacity 24 hours a day in summer, spring and autumn[57].

Solar Millenium's Andasol 1 & 2 solar thermal with storage plants in operation in Granada, Spain[63].

FIGURE 2.19
Energy flows in the Andasol 1 power plant on a typical summer day[65]



CST is a utility scale, proven and reliable technology, currently experiencing an exponential growth in global installed capacity. CST operates by concentrating sunlight to a focus, and using the resultant heat to create steam, which drives a turbine to generate electricity. For the last 20 years there has been over 350 MWe of CST operating globally[58]. A further 2,275 MWe of CST is to be commissioned and dispatching electricity into the Spanish grid by 2013[59]. In the U.S., the Californian Energy Commission has received applications for 4,800 MWe of CST projects in that state alone[60]. In addition, suitable land for 100,000 MW of CST is under assessment by the Bureau of Land Management across six states. As of June 2009, the BLM has received 158 active solar applications, with a projected capacity to generate 97,000 MWe of electricity[61]. There are solar thermal projects in various stages of development in Italy, United Arab Emirates, Algeria, Israel, Morocco and Egypt[62].

In Spain, 150 MWe of CST plants with molten salt storage are already in operation[60]. These plants—Andasol 1, Andasol 2 and Extrasol 1, each have an output capacity of 50 MWe. Built by Solar Millennium AG, they use parabolic trough technology coupled with molten salt thermal storage. A portion of the heat collected during the day is stored in a high-temperature molten salt tank, and used to continue despatching electricity for the equivalent of 7.5 hours, if operating at full 50 MWe output capacity. If ramped back to lower output overnight, the plants can operate for longer than 7.5 hours if necessary. Their flexibility means they can take advantage of the best power peak prices throughout the day[64]. This is shown in Figure 2.19. During sunlight hours, enough energy is collected by the mirror field to run the 50 MWe turbine and also fill the hot molten salt storage tank. As the sun goes down, energy is drawn out of the hot salt tank, continues to generate steam for the turbine, and the salt is cycled back into the cold tank[65].

Which CST Technology?

There are four major CST technologies available. These are described and compared on the following page. To aid understanding, one important feature of solar collection is explained first.

The Projection Effect – more wintertime energy from elevation tracking solar collectors

One of the key differences between the different solar collection technologies is whether they track the elevation of the sun (two-axes tracking) which varies with seasons, as well as the east-west daily path of the sun. When the sun is low in the sky in the winter time, beams of light hitting a horizontal surface are spread out over a larger area, compared to a surface at right angles to the sun's rays. This is known as the 'projection effect'. Systems which track the sun's elevation can collect more than twice as much energy per square metre of mirror surface in the winter than systems which remain horizontal, the exact ratio depends upon the latitude of the site. Radiation received on a horizontal surface is known as Global Horizontal Insolation (GHI), where as radiation measured on a surface facing directly towards the sun is called Direct Normal Insolation (DNI). DNI has a higher wintertime value than GHI.

A horizontal surface receives less radiation per m^2 than a surface perpendicular to the sun's rays. To put it another way, a horizontal collection system requires more mirror surface (i.e. paying for more glass, steel etc) to collect the same amount of energy as an elevation-tracking system.

Parabolic trough and linear fresnel systems do not track the sun elevation, so suffer significantly lower energy collection in the winter months. Heliostat and paraboloidal dish systems do track sun elevation, with heliostats or dishes spaced further apart to allow for shading. A dish is a near-perfect solar receiver, as it is always pointed directly at the sun. Heliostats bounce light at an angle onto a central receiver tower, and only approximate the performance of a dish. They therefore do lose some energy compared to a dish, but still have a much greater wintertime collection than a trough or fresnel system.

Chosen Technology: Power Towers with Molten Salt Storage

The ZCA2020 Plan recommends the use of the first of these technologies— CST power towers, with heliostat mirror fields, using molten salt as a working fluid and storage. It is recognised that other CST technologies may end up forming part of a final mix, especially in initial years of deployment, however power towers are recommended for their technical advantages, and for the ease of specifying the proposed Australian system with a single technology.

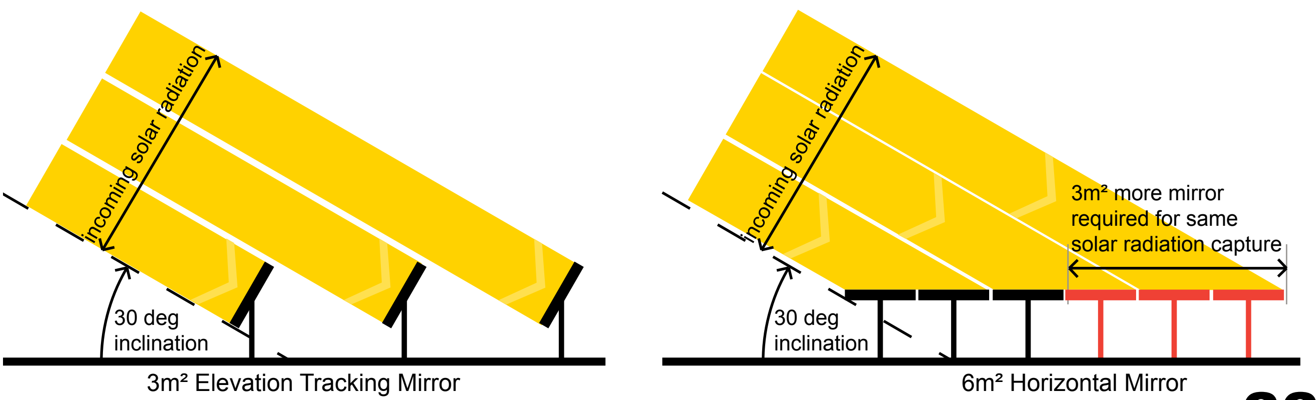
Heliostat mirror fields have the advantages of:

- They track the sun on two axes, so have a significantly higher collection efficiency than single-axis systems (trough & fresnel).
- They are simpler and more cost effective to manufacture and install on a large scale than curved collectors like dishes and troughs.

Central receivers have the advantages of:

- Lower re-radiative losses. Power Towers involve one central receiver tower, one turbine and one set of tanks, all contained physically in a very small area, there is no need to transport a working fluid throughout the field. Dish-based systems, by contrast, though having higher optical efficiency than towers, typically require relatively complex and expensive fluid transport between dishes and a centrally located electrical generator. Trough and Linear Fresnel plants both require kilometres of piping back and forth due to their line focussing arrangement.
- Achieving temperatures in the range of 550—650°C means that standard double reheat supercritical steam turbine technology (already deployed globally in coal, gas and nuclear facilities) can be used for generating electricity at the ZCA2020 proposed solar facilities. Higher temperatures also mean higher thermal efficiency of energy conversion to electricity.

FIGURE 2.20
Projection effect (Cosine losses). Diagram showing two solar extremes of DNI collection versus GHI collection.



Power tower (central receiver) and heliostat fields


IMAGE: ABENGOA

A heliostat field, comprising flat mirrors which track the sun, concentrates the solar radiation on a receiver located on the upper part of a tall tower. Heat is transferred to a fluid (water or molten salts) generating steam that drives a turbine.

- Heliostats track the sun in two axes, so suffer less projection effect and have improved winter-time solar collection.
- Receiver fluid can operate at 565, and potentially 650°C, the same temperature as conventional superheated steam turbines.
- Central receiver minimises area through which heat is lost from re-radiation.
- Molten salt thermal storage has been demonstrated with power towers.

Parabolic troughs


IMAGE: SCHOTT SOLAR CSP

Sunlight reflected from parabolic mirrors is concentrated onto a receiver tube, which runs parallel to the mirrors and contains a working fluid. A mature technology with over 20 years commercial history and more than 600 MWe in operation, more than 6 GWe in development. Parabolic troughs:

- Tracks the sun on one axis, aligned north-south in the horizontal plane, resulting in lower wintertime collection.
- Operate at around 400°C currently, aiming for 500°C.
- Line-focusing system means extensive piping in the field loses energy through re-radiation.
- Pipe plumbing requires specialised moving joints.
- Molten salt thermal storage already operational.
- Curved mirrors and specialised vacuum absorber tubes are relatively complex to manufacture.

Linear Fresnel reflectors


IMAGE: AREVA

Compact Linear Fresnel systems (CLFR) consist of multiple rows of flat mirrors track the sun, approximating the shape of a parabolic trough. Sunlight is concentrated a long receiver which runs parallel to the mirrors and contains a working fluid.

- Tracks the sun on one axis, aligned north-south in the horizontal plane.
- Operates at 290-500°C, and can require specialised low temperature turbines.
- Line-focusing system means re-radiative heat loss.
- Pipe plumbing is fixed, not moving with the mirrors.
- Uses relatively flat mirrors which are cheaper to manufacture than curved troughs.
- Requires less land area than parabolic troughs as mirrors are more closely spaced.
- Molten salt thermal storage not demonstrated commercially with CLFR.

Paraboloidal dishes


IMAGE: ANU STG

A parabolic mirror in the shape of a dish collects and concentrates the solar radiation onto a small area where a receiver is located. Heat is collected from the receivers on multiple dishes and then runs a steam turbine (with or without storage).

- Tracks the sun on two axes, with a higher optical efficiency than central receivers.
- Can operate at very high temperatures, greater than 650°C.
- Yet to be proven and commercialised in terms of installation cost and scale—challenges include wind loadings in large mirror systems and complexity of construction.
- Are available in a light-weight resource-efficient design, (from the Australian National University—ANU) which has the lowest resource requirements of the solar technologies.
- Energy storage is not yet demonstrated commercially, though it is compatible with molten salt storage, and others such as the ammonia thermochemical storage system at ANU.

Molten salts have the advantages of:

- Molten salt systems achieve higher temperatures than those using water or oil as a working fluid. High temperature steam is difficult to contain in its vapour state, and conventional synthetic oils used in trough fields deteriorate at temperatures above 400°C. Molten salts, on the other hand, have a known high degree of thermal stability to 600°C;
- Molten salt can be stored at temperatures in excess of 600°C in insulated tanks. Storage remains viable for weeks, with losses averaging less than 1% of stored heat per day;
- Using molten salt as a working fluid as well as a storage medium also reduces heat exchange losses that are present in systems with multiple working fluids, as there is no heat exchanger and therefore no heat exchange loss;
- The technology is commercially available—the Solar Two molten salt power tower was developed and proven in the 1990s, and the Andasol solar power plants have been in full-scale commercial operation with 7.5 hours of molten salt storage in Spain since 2008[66]. As mentioned previously, many larger plants incorporating molten salt storage are now in construction in the USA and Spain;
- The molten salt system is recommended primarily for its low losses, low cost, material stability, raw material availability and material safety - currently in common use as agricultural fertiliser.

Cost Projections

The wholesale price of electricity from CST is projected to be as cheap as electricity from new conventional coal-fired power sources (around 5c per kilowatt hour) under the proposed ZCA2020 installation timelines by around 2015[67]. The electricity cost of CST with storage is undergoing a declining cost curve, and has been projected to drop to 3.5—5.5 cents (US$ in 2003) per kilowatt hour when the installed base of Solar Thermal Towers with Storage reaches 2,600—8,700 MWe[65]. This is 5-8c/kWh in today's Australian dollars. In 2008, the weighted average wholesale price of fossil electricity in Australia ranged from 4.4 – 10 c/kWh[68].

CST has the additional benefit of being virtually independent of the carbon price, thereby removing significant investment risk, a critical factor in capital-intensive projects such as those required to address climate change.

Solar thermal technologies have the ability to store energy, which is really rare for energy technologies. Really only hydro power has a similar capability. But because we are creating heat we can actually stick that heat in a big tank, much like a large thermos, and then we can pull that heat back later on and use it to create steam and make electricity.

CRAIG TURCHI, US DOE, NREL SCIENTIST[69]

2.5.3 Smaller-Scale Solar Technologies

Smaller scale solar technologies, i.e. solar panels on roofs, play a valuable role in reducing grid electricity demand, and are well-suited to applications such as negating air conditioner demand during hot weather. Electricity demand spikes during hot weather are a major source of high price events and brown/blackouts on Australian electricity grids. Solar hot water systems are well-suited to being combined with heat pump boosting systems. Solar hot water is able to be stored for later use, meaning that daily variations in radiation are not as much of an issue as for solar photovoltaics. The Plan recommends the use of small-scale solar for point-of-demand use to displace grid electricity requirements. The full costings of these will be included in the Buildings sector report.

Although solar PV currently only provides a small amount of the world's energy, it is the world's fastest growing energy source, increasing at around 48% pa since 2002, to a cumulative total of 15,200 MW in 2008[70].

FIGURE 2.21
Price of Photovoltaic (PV) modules and systems[72]

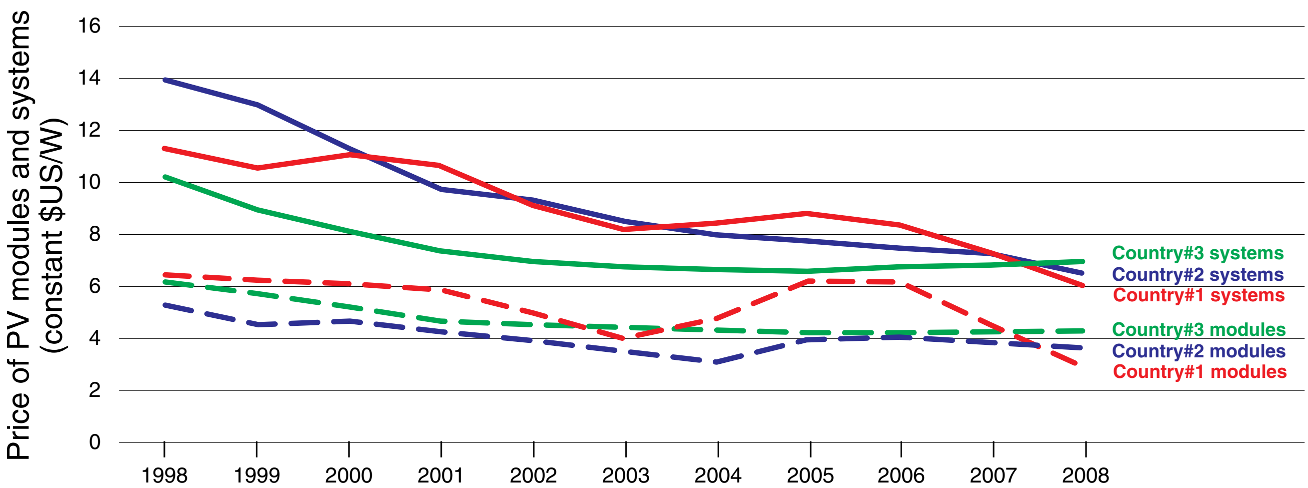
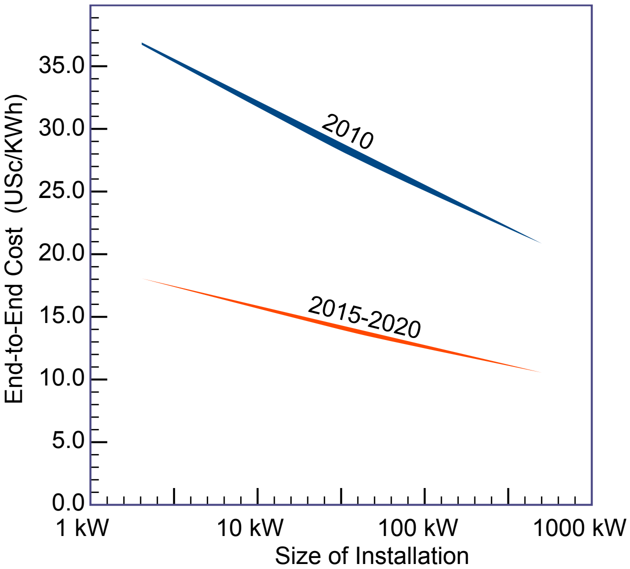


FIGURE 2.22
Cost of solar PV, kWh



Currently the cost of electricity from distributed solar PV is very high relative to the cost of centralised utility scale sources like CST with storage and wind, however it is worth noting that household PV competes with retail electricity prices currently (2010) around 20c/kWh in Victoria[71], which is much higher than wholesale electricity prices (3-4 c/kWh[68]). Also, in contrast to CST with storage, there are no large-scale commercial storage options for photovoltaics. Nonetheless the cost per installed peak watt of solar power has fallen rapidly, dropping 57% between 1998-2008 to US$6/(installed) Watt (peak). This has corresponded to a drop in cost of solar PV per kWh, and is projected to decrease further. It is also worth noting that the larger the installed PV system the lower the cost per kWh, as demonstrated in Figure 2.22 [73].

The IEA Photovoltaic Power Systems Program projects that solar PV could reach grid parity with current sources of generation (in certain parts of Australia) before 2017[74], thus Solar PV may reach parity with CST delivered to the consumer before 2017.

As it can compete with the consumer electricity price at point of demand, it is recommended that solar PV be developed on the demand side (at customer premises for instance) as a first dispatch with very low transmission costs, creating a negative demand for grid electricity. It is not recommended for use in central plants where the cost of transmission and storage need to be taken into consideration.

Because electricity produced from PV needs to be used as it is produced (during direct sunlight hours), this electricity could usefully displace the electricity being produced directly from solar thermal plants during daylight hours, allowing a higher percentage of thermal energy to be stored and dispatched when needed.

ZCA2020 System Flexibility

There may be a point where, for example, distributed PV is so prolific that there is close to zero demand for power from centralised power plants during direct sunlight hours. In these circumstances, the value of power from centralised PV without storage would be very low. Solar thermal power with storage, on the other hand, would offer a relatively high-value alternative, since it allows energy to be dispatched at any time during a 24 hour period, in line with demand.

The ZCA2020 system design is highly flexible and can be modified to accommodate different scenarios such as the situation just described.

In this example scenario, the ZCA2020 Plan system design would be adjusted by:

- using smart grid technology to schedule more nonessential demands during the day;
- reducing the number of wind turbines and/or solar thermal storage plants required;
- altering the design of planned solar thermal plants (with storage) by changing the ratio of mirror field to storage and turbine size appropriately; and
- adding 30% more heat storage to existing solar thermal plants by adding more storage infrastructure.

2.5.4 Wind Power

Australia has one of the highest commercially exploitable wind resources per capita in the world (see Figure 2.23)[75].

The wind resource in Australia is concentrated along the eastern and southern coasts, although there are also significant patches of inland resource. Wind speeds in Australia are conducive to the exploitation of the wind resource for power. The fact that many good wind sites are in areas that already have grid coverage is an added benefit.

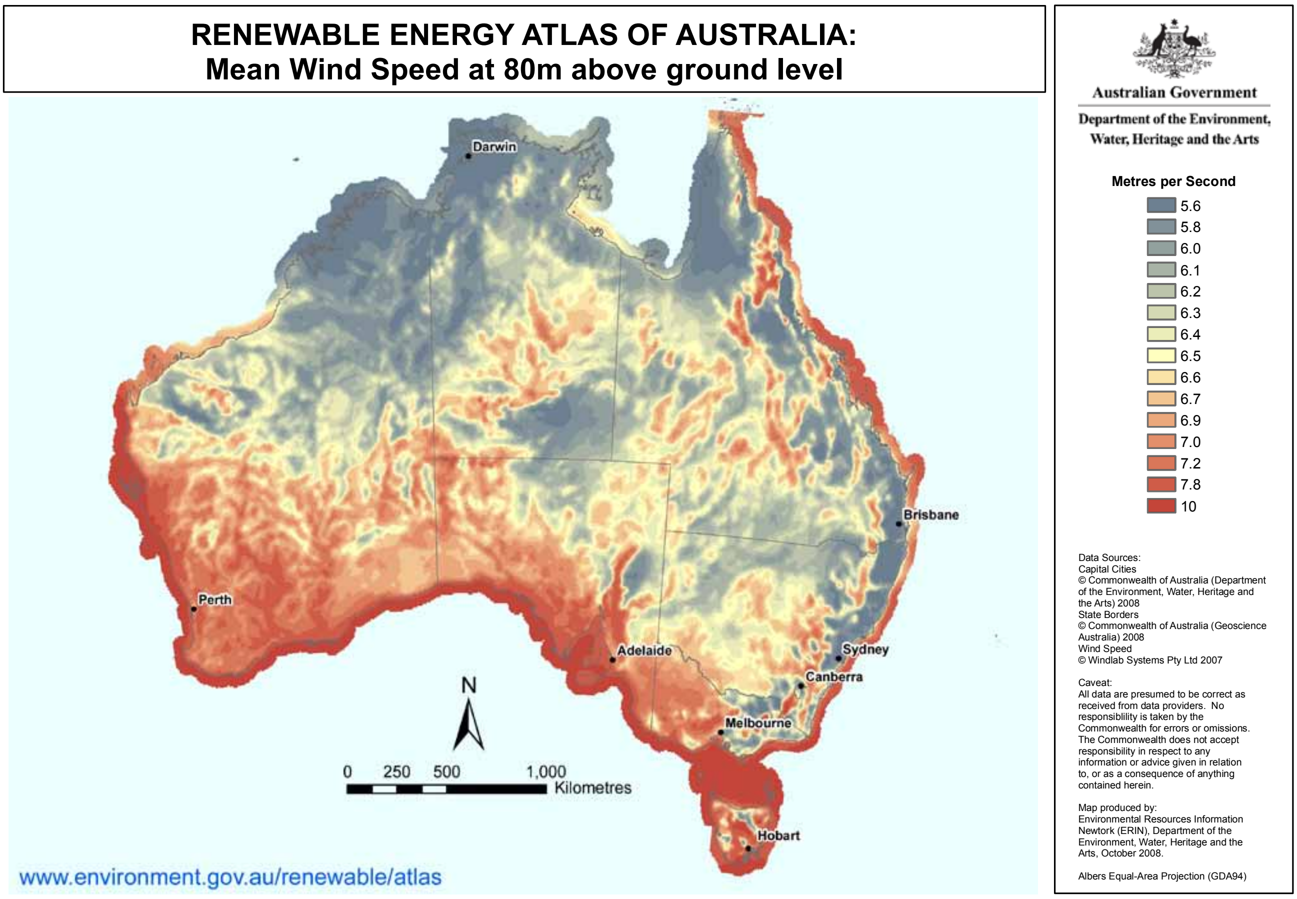
Wind power is the lowest cost renewable energy technology in Australia. The global boom in wind energy has already seen prices drop by 80% in the last two decades, from 30 cents per kilowatt hour in the 1980s to 5 cents per kilowatt hour today[77].

Projects such as the Chinese government's 20,000 MW 'Three Gorges of Wind' (already under construction) are expected to drop turbine costs to less than 75% of current prices in the short-term, judging by the cost of the project itself[78].

Ultimately wind's going to be the cheapest thing to do, so you'll dispatch that first

JON WELLINGHOFF, CHAIRMAN OF THE FEDERAL ENERGY REGULATION COMMISSION IN THE UNITED STATES[79]

FIGURE 2.23
Mean wind speed at 80m above ground Source: [76]

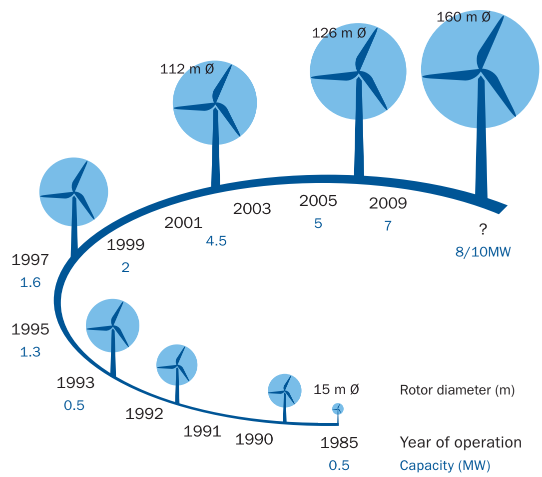


Major technical advances in the last decade have greatly increased the power capacity of individual turbines, and the viability of large scale power generation from wind. These include:

- taller turbines—from 80-138m hub height (distance to blade centre), giving improved access to faster, more consistent wind speeds;
- increased turbine power capacity has generally led to lower costs;
- improved blade design has allowed the harvesting of very low and very high wind speeds and increasing the amount of power per swept area;
- power control electronics, together with electronic and hydraulic pump system gearboxes allow modern wind turbines to offer grid support and low voltage ride through; and
- storage options (such as integration with Molten Salt Storage CST) can be used to provide dispatchable power to integrate with wind's variability.

Wind power is not only cheap and efficient, it is also widely utilised all over the world. In 2001, a total of 20 GW of capacity was installed globally, and in 2009 this has now exceeded 120 GW. Growth projections are very positive at around 20%—25% per annum" [81]. With less available wind resource than Australia, and 1/20th of the land area, Germany has in excess of 19,460 wind turbines and 23,000

FIGURE 2.24
Growth in turbine size and capacity (1980—2009)[80]



MW of installed capacity[82]. Many of the turbines installed in Germany were installed at more than twice the price of modern turbines.

The ZCA2020 Plan proposes the highest percentage of wind power that can be reliably and economically integrated into the grid. Based on published studies, 40% is chosen.

This percentage may turn out to be conservatively low considering international research and precedents.

The Danish experience: The Danish Government has mandated that 30% of total Danish energy demand (including gross heat, transport and electricity) should be supplied from renewable energy. To reach this target the Danish government has mandated 50% annual electricity production from wind on the national grid by 2025. The Danish national grid operator, Energinet has created the EcoGrid project to model scenarios in which the 50% target would take place. Energinet published a paper called "Steps towards a Danish power system with 50% wind energy" which indicates that high penetrations of wind (up to 50%) can be achieved by using some form of 'balancing power' to manage wind variability [83]. This concept of 'balancing power' is an elegant idea that has aspects that depend on the various timescales of system events, and on various parts of the system (such as supply side, distribution, or demand side).

The Danish national grid operator, EnerginetDK, has explored several scenarios (Ecogrid) for increasing the penetration of wind and balancing increased penetration against existing grid infrastructure. The Ecogrid project reports that 50% wind penetration is feasible with the use of a small amount of wind output curtailment (shutting down wind generators at high wind speeds to avoid an oversupply of electrical energy into the grid) and a source of balancing power[83]. Importantly, sources of balancing power can be either interconnection with neighbouring grids and/or new domestic dispatchable power and storage systems[83]. Under the Danish system some of this balancing power is expected to come from neighbouring grids or from domestically sourced Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)[83]. It should be noted however that Denmark has one fifth of the land area of the State of Victoria and therefore lacks the geographical diversity of the current Eastern seaboard electricity grid and the proposed ZCA2020 'national grid'.

While the Danish Modelling includes either grid interconnection or Advanced Adiabatic Compressed Air Energy Storage, in the Australian context, Australia benefits not only from geographical diversity, but also from the opportunity to use the balancing power of CST with storage.

In the ZCA2020 Plan, CST with storage provides the same service as the AA-CAES or neighbouring grid interconnection that is modelled in the Danish 50% annual wind contribution scenario.

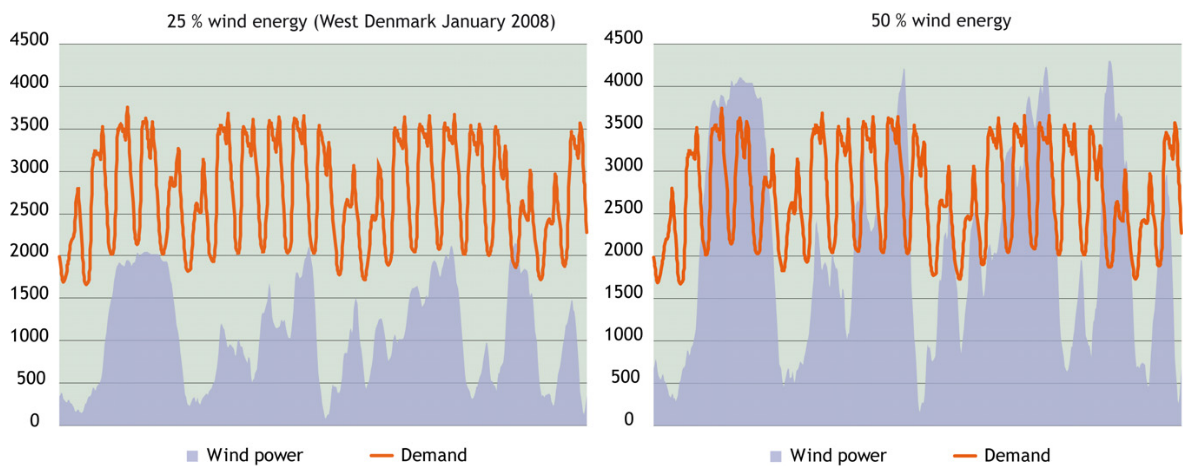
In the Australian context this balancing power can be achieved by adding grid interconnections to create greater geographical diversity, by active demand side management via a 'smart grid', and by the installation of CST with storage, which can effectively act as a giant distributed battery. Variability can be further managed by adjusting the demand curve through the supply side scheduling of space and water heat-pump loads in industry and homes and electric vehicle battery charging.

Research undertaken for the National Grid U.K. suggests that wind variability is not a significant barrier to wind penetration of up to and above 40% [84].

There are no significant barriers to the introduction of wind energy due to its variability, and contributions up to 40% or more of electricity consumption can be managed with quantifiable—and modest—variability costs'

DAVID MILBORROW,
GRID VARIABILITY EXPERT, UK

FIGURE 2.25
Danish wind energy contribution at 25% and 50% penetration[83]



These charts show Demand (orange) and Wind Contribution (Blue shaded) overlaid. In the 25% penetration example, wind power peaks provide 100% of demand in West Denmark and no wind power is discarded. When reaching higher penetration levels, such as 50% (right side of chart), on infrequent occasions wind output must be curtailed in order not to exceed the demand.

Variability of renewable sources is often deemed as a reason why renewables cannot provide 'baseload power'. However there are at least five ways in which variability can be mitigated, as follows:

1. To interconnect renewable energy sources. When numerous sources of power are combined over a large geographical region the effects of variability are reduced[85]. It has been found that by increasing the capacity of wind generation in a system, and increasing its geographical diversity, volatility could be reduced by up to 70% [86]. This was proven in a study completed by Archer and Jacobson in 2006. The study concluded that 19 wind farms guaranteed 312kW of power for 79% of the year, which was four times greater than the power generated from the same nominal capacity located on one farm. The more sites that were connected, the more the array resembled one single farm with steady winds[87];
2. Use appropriate forms of energy source that are able to respond reliably to demand. CST and wind are complementary technologies in that the thermal storage available with CST can be used to balance the variability of wind when required. Biomass and existing hydro technologies can also be used to accommodate the demand peaks.
3. Use smart meters, for example to provide electric power to vehicles when wind or solar sources are high;
4. Store electric power for later use; and
5. Forecast the weather to plan for energy supply. The weather forecast can be provided in minute-by-minute predictions up to 4 days in advance with good accuracy[88].

2.5.5 Biomass

Biomass, or plant matter, is renewable in the sense that plants grow and regrow in a matter of years, using energy from the sun and storing it as chemical energy. Biomass can be dried, stored, and later combusted. However, photosynthesis in most plants is only around 3% efficient at harvesting sunlight into usable energy. There is potential for algae to produce biomass at higher efficiencies, but this is not yet commercial technology. Sourcing biomass also raises issues such as biomass cropping competing with food production, and unsustainable forestry practices leading to ecosystem damage. Under the Plan, energy from biomass would only be sourced from wastes that would not otherwise be used (such as crop residue), and truly sustainably managed plantations.

Due to the relatively limited availability of biomass, sustainability issues and the fact that biomass combustion still causes localised particulate pollution effects, biomass is not a key primary supply of energy under the Plan. It will, however, play a valuable backup role by providing long-term energy storage, as dried biomass can be stored for many months. Pelletisation of agricultural waste can vastly improve transport and storage efficiency.

Biomass co-firing of the solar thermal plants is recommended as a contingency strategy for any extended periods of low wind output that coincide with full cloud cover at several CST plants. This co-firing would make use of existing steam turbine power block infrastructure within the CST plants, overcoming the need for additional turbines and power blocks, and requiring minimal additional costs. The ZCA2020 biomass backup system is based on the standard backup heater/boiler for CST plants, combined with a local distribution infrastructure (standard freight train hauling hopper freight cars and a biomass pelletising plant).

Solar Thermal plants will be built by bringing construction materials and labour force to the sites using rail infrastructure. This rail infrastructure will then be leveraged to distribute and amass pellets from pelletisation plants. Pelletisation plants would be distributed in locations near growers, before processed pellets are transferred to the rail network for distribution to the bunkers outside each of the solar plants. Local trains would then deliver the pellets from the bunker to the co-firing boilers at each of the solar thermal modules, allowing continuing electricity generation in the event that multiple sites are without solar radiation for extended periods (2-3 days).

Land use changes proposed in the ZCA2020 Land Use plan would free up some extra land for the production of biomass. However, electricity supply from biomass is limited by:

- land availability for growing feedstock without competing with food production;
- the risk of stripping vital nutrients from the land if too much crop residue is used; and
- the need for some biomass to also be used as liquid fuel to extend the range of electric vehicles—though initial ZCA2020 projections are that only ~50PJ/annum, or less than 5% of today's liquid transport fuel energy demand, would be met through liquid biofuels under the transport plan. It is used mainly for range-extension of plug-in hybrids in rural areas, and potentially for emergency services.

Biomass production could also be used to produce liquid fuels. For example, integrated wood processing of oil mallee produces bio-oil, agrichar and electricity[89], as well as reducing salinity in soils. Crops such as jatropha produce high yields of oil and can grow on marginal arid lands. While the energy density and ease of handling of liquid fuels (e.g. by using pipelines) would make them an attractive option for biomass backup, it must be remembered that there will also be some requirement for biofuels under the ZCA2020 transport plan. Therefore if liquid biofuels were chosen for CST backup, they would need to be priced at market prices for transport biofuel, and they would require more land dedicated to liquid fuel production, which currently yields lower calorific value per land area than other biomass harvesting options.

Processing our biomass into pellets is a cheap and easy storage option, so that processing can occur year round (or at the end of harvesting seasons). The biomass can be stockpiled in relatively cheap storage bunkers as used by wheat growers, and could be replenished or drawn down as required. A strategic reserve could allow for an additional buffer quantity over and above the predicted annual requirements under ZCA2020. This additional buffer could be amassed prior to achieving the 2020 target, to help create a more steady biomass industry.

Under ZCA2020, biomass is limited to less than 2% of the annual electricity production and is used to supply mid-winter electricity demand. This is a conservative figure and it is likely in practice that the grid will operate with less requirement for biomass backup than specified. In practice, biomass backup may not be required at all, and further modelling and optimisation could prove this scenario prior to implementation of the plan.

2.5.6 Hydroelectric Power—Meeting Peak Electricity Demand and Energy Storage

The Plan does not consider expanding Australia's current hydro capacity, but it is useful for its role in backup electricity supply and long term storage. Pumped hydro for long term storage has not been considered or costed in this version of the Stationary Energy Plan, but could play a part in a future energy mix.

Hydroelectric power is dispatchable electricity that can be used to help fill the winter shortfall from the CST component. However, changes in rainfall patterns are reducing the amount of hydroelectricity that can be relied upon in Australia. It is also likely that opposition to building more hydro power would be strong given the ecological effects of creating reservoirs in existing river systems. Hence, ZCA2020 does not propose adding to existing hydroelectricity infrastructure.

In those areas of Australia where rain continues to fall reliably, hydroelectricity can play a role in peak supply, dispatching power during peak demand times, when the solar and/or wind resource is less than adequate.

In areas where rainfall is declining or becoming erratic, hydroelectric facilities that are under-utilised, and possibly uneconomic, could also be used to provide pumped-hydro electricity storage rather than being decommissioned.

Pumped hydro is a method of energy storage as well as electricity generation. When there is a surplus of energy, it can be used to pump water from a lower dam to a higher one. When energy is needed, water is released to drive turbines and produce electricity. For existing hydroelectric plants, where turbine water races and turbines already exist, this option could offer some relatively cheap additional dispatchable firming power. This is not costed as part of the plan but is a viable additional measure that can be considered.

Given that there will certainly be times of excess energy production when high wind periods coincide with high solar incidence, and more energy is produced than can be held in thermal storage, **pumped hydro would be a useful secondary storage option.**

Pumped hydro storage using seawater in Okinawa

SOURCE: GOOGLE EARTH

One advantage of pumped hydro is that the same water supply is re-used with the only losses in water being evaporation from the dams. Australian topography and water scarcity limits the opportunities for this type of energy storage. However overseas examples of coastal pumped hydro plants using sea water may also be relevant in the Australian context.

Current proposals looking at the large scale addition of pumped hydro storage at existing hydro facilities require storage be built below (usually 200 metres or more below) the existing storage. Unfortunately, most areas where these facilities exist are of high ecological value and building these massive storages is considered inappropriate by the authors.

Round trip efficiency of pumped hydro is ~80%, this compares less favourably to storing sensible heat in molten salts and holding the heat back until dispatch is required, where losses are <1% per day.

2.5.7 Non-commercial Technologies

Only existing commercial solutions are specified, as deployment of the ZCA2020 Stationary Energy Plan needs to start right away. However, if other technologies become commercial during the roll-out at a competitive cost, they could also form part of the future energy mix.

There are other potentially promising renewable energy technologies on the horizon. However, as outlined in Part 1, a core parameter for the ZCA2020 Project is that we have specified existing technologies that are already a commercial reality, meaning that there are no technical barriers to their deployment. We already have the solutions that we need to address the urgent climate situation, so there is no need to wait for others to come along. This does not mean we should cease ongoing research and development of future technologies, but it needs to be recognised that further R&D is not a barrier to beginning deployment of existing solutions.

However, if other renewable technologies become available over the ten year transition period that are cost effective and could further improve the reliability and diversity of the overall energy mix, they could be included in later years. Technologies that it is anticipated may become commercially available during the 10 year transition period include:

- Arrays of Australian National Universities's 500 m^2 SG4 Concentrating Solar Thermal Big Dishes[90].
- Carnegie Corporation's CETO III Wave power technology, being demonstrated in Western Australia[91 92].
- Hot Dry Rocks geothermal (or Enhanced Geothermal), which currently is only going through first-phase demonstration and drilling. HDR geothermal, currently being tested in central Australia, is very different to the type of geothermal already commercially operating overseas in places like Iceland and New Zealand, and there are still technical issues to be overcome.
- Conventional geothermal, currently being commercialised in Victoria by GreenEarth[93], may be available before HDR, however at this stage only 140MW of potential has been identified.
- Beacon Power's large storage array flywheels [94 95].
- "Circulation control" aerodynamic technology which will increase wind turbine output at given wind speeds by up to 40%, allowing feasible commercial operation at sites with lower wind resources [96 97].
- Solar thermal Brayton combined cycle— such as that being trialled by CSIRO Newcastle[98].

2.5.8 Lifecycle Emissions of Energy Technologies

The first part of this section compares the emissions from building, running and supplying various "low-emission" sources relative to their energy output. The comparison shows that coal CCS still produces at least ten times the emissions of any other competitor. Nuclear, geothermal and solar PV fare better, but are still several times higher than the lower emission options. **The comparison clearly shows that solar CST and especially wind are best suited to achieving considerable emission reductions.**

The second part deals with the question of how long it takes from the time of the decision to build for a new plant to supply energy to the grid (as this is the time conventional sources need to be kept online and emitting) and how long it takes until the plant has produced more energy than it took to build and actually become a net producer. This comparison shows that nuclear power, due to its high technical and safety requirements, is by far the slowest to come online (on average 15 years), approximately ten years later than the low emission options. Coal CCS and hydroelectric fare better, but still take more than twice as long to come online than the other options. The remainder is similar in this regard, but **wind and solar CST dominate the field by their very fast energy input payback.**

Lifecycle Emissions (LCE)

It is important to know the timing and quantity of emissions produced by a given type of energy source. All sources require some form of construction and production. This involves concrete, steel and other materials as well as the transport and engineering to set up on site, followed by some form of ongoing maintenance. Fuel consuming sources require mining or drilling and pumping for the fuel, processing, transporting, energy extraction (e.g. by combustion) and possibly removal of waste. At the end of its lifetime the site will require some form of decommissioning. All of this results in at least some emissions. Summing all of this up and combining it with the site's lifetime and useful energy production allows us to calculate the emissions per kWh produced, usually quoted in g CO_2 equivalents/kWh. There is obviously some variability, for example due to location (wind speeds, hours of sunshine), fuel quality (ore concentration), particular design (reactor type), etc., but by combining the data from different locations, plant sizes, fuel sources, etc., it is possible to get figures that allow a comparison of the lifecycle emissions between the various types of energy source.

Conclusions that can be drawn from Figure 2.26

Wind power has the lowest LCE followed by CST. Both are within or close to the range of less than 10 gCO_2e/kWh. PV, geothermal, hydroelectric, wave and tidal power are in the range of 10—60 gCO_2e/kWh. As the lower end estimates for nuclear LCE underestimate or omit emissions resulting from uranium mining and processing, the actual LCE figure is likely to be at the higher end of the 9—70 gCO_2e/kWh bracket. Despite the capturing and sequestration of a high proportion of CO_2 emissions resulting from coal combustion, Coal CCS power produces at least 5 to 25 times the LCE emissions of any of the other sources discussed.

TABLE 2.2
Lifecycle emissions of various energy technologies

Technology	Notes	LCE (gCO_2e/kWh)
Solar PV	Requires mining of the materials, production of the cells, transport and on site setup, and minimal maintenance.	19—59 [99 100]
Concentrated solar thermal (CST)	Requires materials, transport and construction and maintenance.	8.5—11.3 [101 102 103]
Wind	Requires materials, construction, transport and setup and minimal maintenance.	2.8 -7.4 [104 105 106 107 108]
Geothermal	Requires construction, setup and maintenance. Might result in emissions from the decomposition of groundwater carbonic acid to water and CO_2, but this can be avoided by using binary plants.	15.1—55 [99 109 110]
Hydroelectric	Emissions come largely from construction, but also from rotting biomass, dependent on location (e.g. higher in tropics). This can be lowered by clearing before flooding. Usually these plants have long lifetimes which lowers the LCE.	17—22 [99 111 112 113]
Wave	Requires materials, transport and construction; low maintenance.	21.7 [99 114]
Tidal	Requires materials and construction; low maintenance.	~14 [99 115]
Nuclear	Requires construction, mining, enrichment, processing, transport, waste handling, maintenance and plant decommissioning. Figures for LCE vary considerably in the literature, mostly due to different assessments of the emissions resulting from mining and processing of the fuel and who commissioned the study.	9—70 [99 116 117 118 119]
Coal CCS	Requires construction and mining and transport of the fuel. The majority of its emissions stem from the combustion of the fuel (dependent on fuel quality). CCS reduces direct emissions by 85-90%, but also requires more coal per kWh produced to run the CCS equipment. Quantifying CO_2 leakage over longer periods is hard to predict as it depends on the local geology and is hard to accurately measure. Injection at high pressures makes at least some leakage likely and rock erosion from the formation of carbonic acid from water and CO_2 is hard to predict. It is also as yet unknown how leaks over large areas would be dealt with. It is estimated that leakage will result in additional LCE of 2- 42 gCO_2e/kWh. [120]	255-442 [99 121 122 123] without CCS circa 800—1000)

FIGURE 2.26
Life cycle emissions

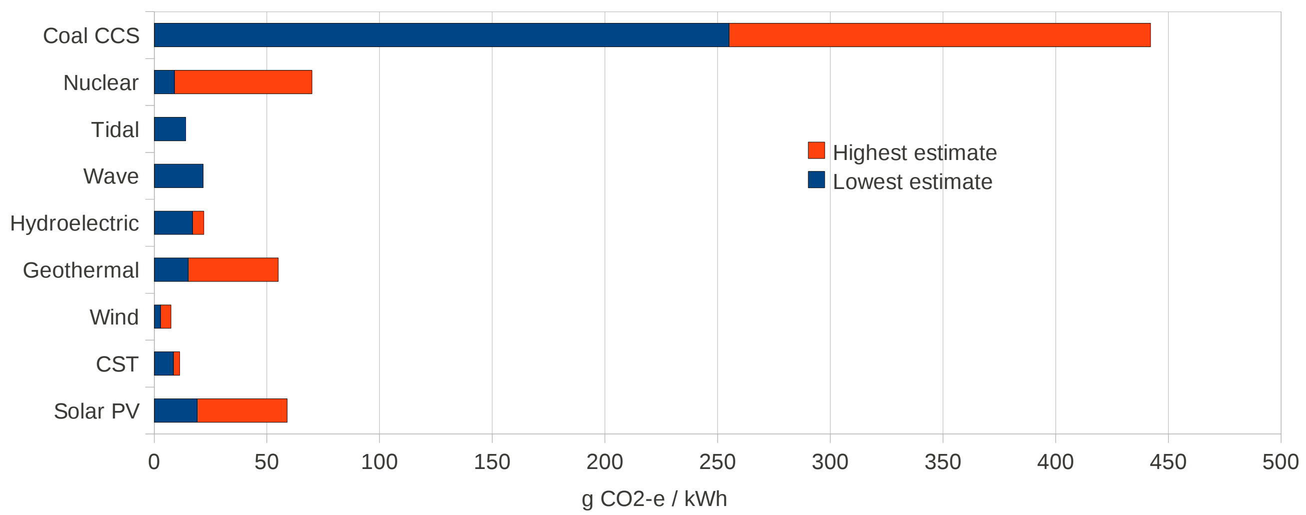
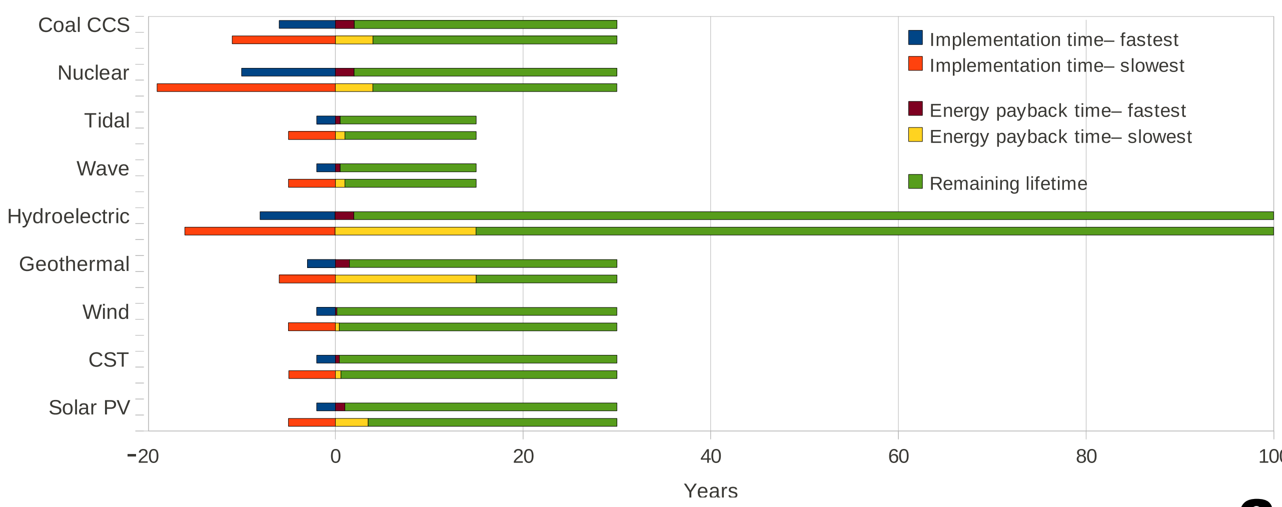


TABLE 2.3
Energy production timetable

Energy production timeline Technology	Notes	Implementation T ime
Nuclear	Due to the safety requirements and the complex design, this source has had very long ITs, varying slightly depending on the country. Easing bureaucratic hurdles and improving construction efficiency might improve this slightly. As it requires an ongoing energy input to mine and process the fuel, the EPBT depends strongly on the ore quality.	10—19 years. [124 125 126 127]
Wind	The typical planning period is 1—3 years and the construction period, depending on project size, 1—2 years. Similarly to CST the EPBT depends on the local wind speeds.	2—5 years [124 128]
Geothermal (conventional)	The construction time depends heavily on the location and its geology. The EPBT will depend on the local geology, which defines how much and how accessible the energy is. There is little data available on geothermal EPBT but is estimated that it will be between 5 and 50% of the plant lifetime.	3—6 years [124 129 130]
CST	This source is very similar to wind with regard to planning and construction aspects that affect ITs. The EPBT for concentrated solar power depends mostly on the location's hours and intensity of sunshine.	2—5 years [124 131]
PV	This source is very similar to wind with regard to planning and construction aspects that affect ITs. Solar PV has EPBTs depending mostly on which type of cells are used.	2—5 years. [124 132]
Wave and tidal power	These sources are very similar to wind with regard to planning and construction aspects that affect ITs. There is limited data on the EPBTs of these sources. Due to the harsher conditions these plants are exposed to, their overall lifetimes are slightly shorter than the other sources, so that despite the EPBT being nearly as short as (for example) wind and CST, it corresponds to a larger proportion of the overall lifetime.	2—5 years. [124]
Hydroelectric	Especially the construction time depends heavily on the size of the project. For the Aswan dam this was 13 years, the Hoover dam 4 years and the Three Gorges dam 15 years. The EPBT of these projects depends on the location and especially the scale.	8—16 years [124]
Coal CCS	Without CCS the typical IT of a coal plant is 5—8 years, with CCS it is estimated to be slightly longer. However, as no such plant has been built to date the actual figure is unknown. As these sources require an ongoing energy input to mine and process the fuel, the EPBTs depend strongly on the ore quality.	6—11 years [124 133]

FIGURE 2.27
Energy Payback Times for various technologies, where Year Zero is commencement of energy production



A long term consideration for LCE emissions is that recycling at the end of the plant's lifetime would lower the LCE even further, this is especially true for sources where construction materials such as steel and concrete are the main source of emissions. For example, this recycling could be for construction of the successor plant. Considering that plant lifetimes are in the order of several decades, a quantified prediction of the effect of recycling is not feasible, but qualitatively, the effect of lowering LCE is very likely. Energy inputs for successor plants (including those to power transport, materials acquisition etc) would be derived from the established zero emissions energy system. This would significantly reduce CO_2 emissions. If a low emissions replacement for Portland-cement was used, then emissions for a subsequent successor plant could conceivably be close to zero. For Portland cement, 50% of emissions are from a chemical reaction during the cement production (the other 50% is due to the high temperature kiln, which can be powered from a Renewable heat source such as solar thermal).

Energy Production Timeline

Lifecycle emissions are the total emissions from the planning and construction stage to the final decommissioning stage averaged out over this period. For emission reduction planning, it is important to know how long is required to implement and hence replace a higher emissions alternative. This is needed to calculate when the actual emissions savings will set in. Choosing a source with a long implementation time over a faster one results in conventional plants having to continue running for longer and therefore produces more emissions.

Implementation Times (ITs)

The implementation time is the sum of licensing, site acquisition, planning, construction and connection to the grid. This depends on guidelines and the application process of the responsible agencies, the specific design, the location and many more aspects of this process. As a future prediction of these is ambiguous at best, the umbers in Table 2.3 are estimates arising from previous and current construction.

Energy PayBack Time (EPBT)

The energy payback time is how long it takes for the facility to produce as much energy as its construction required, and therefore is the point in time when it has paid for itself energetically and begins to produce net energy.

Conclusions that can be drawn from Figure 2.27

Two different factors need to be considered in deciding the types of production sources to include in the stationary energy system. The first factor is the lifecycle emissions for that type of source. The second factor is the implementation time, because this affects the time for which existing higher emission sources need to continue to run. In principle, these continuing higher emissions during implementation should be added to the lifecycle emissions of the new sources for a valid comparison. For most of the sources discussed here, a source with longer implementation time also tends to have higher lifecycle emissions, and so it is mostly reasonable to focus on lifecycle emissions.

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Part 3

Australia's 100% renewable energy supply

Contents

PS10 Solar Tower

SOURCE: ABENGOA SOLAR[1]

Part 3 describes the Plan for each of the recommended technologies in detail:

- Part 3.1 describes the specifications of the proposed Concentrating Solar Thermal (CST) power plants with storage.
- Part 3.2 describes the installation of wind power and its complementary relationship with CST with storage.
- Part 3.3 describes modelling of the grid behaviour with renewable energy sources.
- Part 3.4 describes the use of other renewable energy technologies as backup, allowing for the event of several consecutive days of cloud cover.
- Part 3.5 provides extra detail on how the Industrial sector energy requirements can be compatible with 100% renewable electricity, together with case studies.

As outlined in 'Designing the system' of this report, Australia's projected on-grid electricity demand in 2020 is 325 TWh/yr.

40% of this electricity (130 TWh/yr) will be supplied from wind power, which the Plan proposes to provide through 48,000 MW of new wind turbine capacity, spread over 23 sites across the country. This requires 6,400 7.5 MW turbines. Due to the geographical diversity, it is projected that half of the electricity produced from wind will be 'firm' — always available with the same reliability as conventional 'baseload' generators.

The rest of the electricity will be supplied from Concentrating Solar Thermal (CST) with storage, providing reliable, 24-hour dispatchable power. 42,500 MW of CST capacity is proposed for twelve dispersed sites across Australia, and the plants have up to 17 hours of molten salt thermal storage capacity for provision of electricity overnight.

In the event of prolonged winter-time periods of low wind and high cloud cover, backup will be provided by existing hydropower capacity (5 GW on the mainland), and from biomass-fired heaters attached to some of the CST plants. These will only use waste biomass such as pelletised crop residue, and directly heat the molten salt tanks, to provide thermal energy to the existing CST generators. Modelling of the ZCA2020 Stationary Energy System shows that the wind and solar installations alone can meet 98% of the electricity demand, and biomass heater backup capacity is required to produce 15,000 MW (electrical equivalent) to ensure a 100% reliable supply of renewable electricity.

There is also an existing total of 4,810 MW of off-grid generation capacity in Australia, which includes remote mine and town sites. To replace this fossil fuel capacity with renewables, allowance has been made to supply the equivalent generating capacity from extra solar thermal plants, including their own biomass heater backup systems. After allowance is made for the parasitic energy losses in the existing plants, the renewable replacement capacity is sized at 4,475 MW.

The total investment capital requirements for the proposed system are summarised in Table 3.3. To build the 100% renewable grid will cost $AU353 Bn (2010 Australian dollars). The extra $AU17 Bn for off-grid installations takes the total investment requirements to $AU370 Bn.

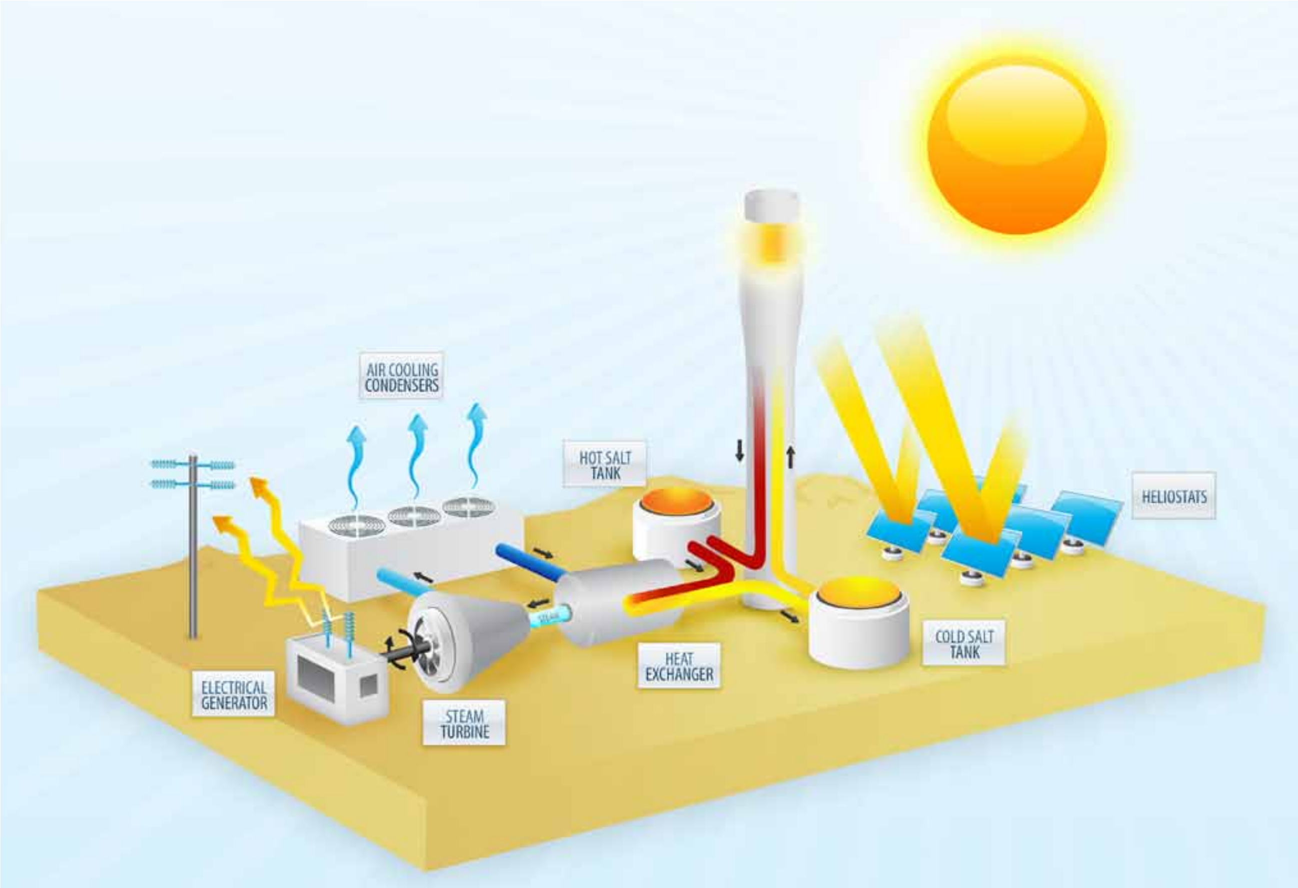
Detailed costings for the renewable energy generation infrastructure are explained in the rest of Part 3. The transmission upgrades and associated costings are detailed separately in 'Part 5 Grid and load management — creation of a national grid'.

TABLE 3.1
ZCA2020 Stationary Energy Plan total investment costs

Component	$AU,Bn
CST	$175
Backup Heaters	$8
Bioenergy supply	$6
Wind	$72
Transmission	$92
TOTAL	**$353**
Off-grid CST + Backup	$17
TOTAL + Offgrid	**$370**

FIGURE 3.1
Direct heating of molten salt in a power tower.

DRAWING: SHARON WONG



3.1 Concentrating Solar Power with Storage — 24 hour dispatchable power

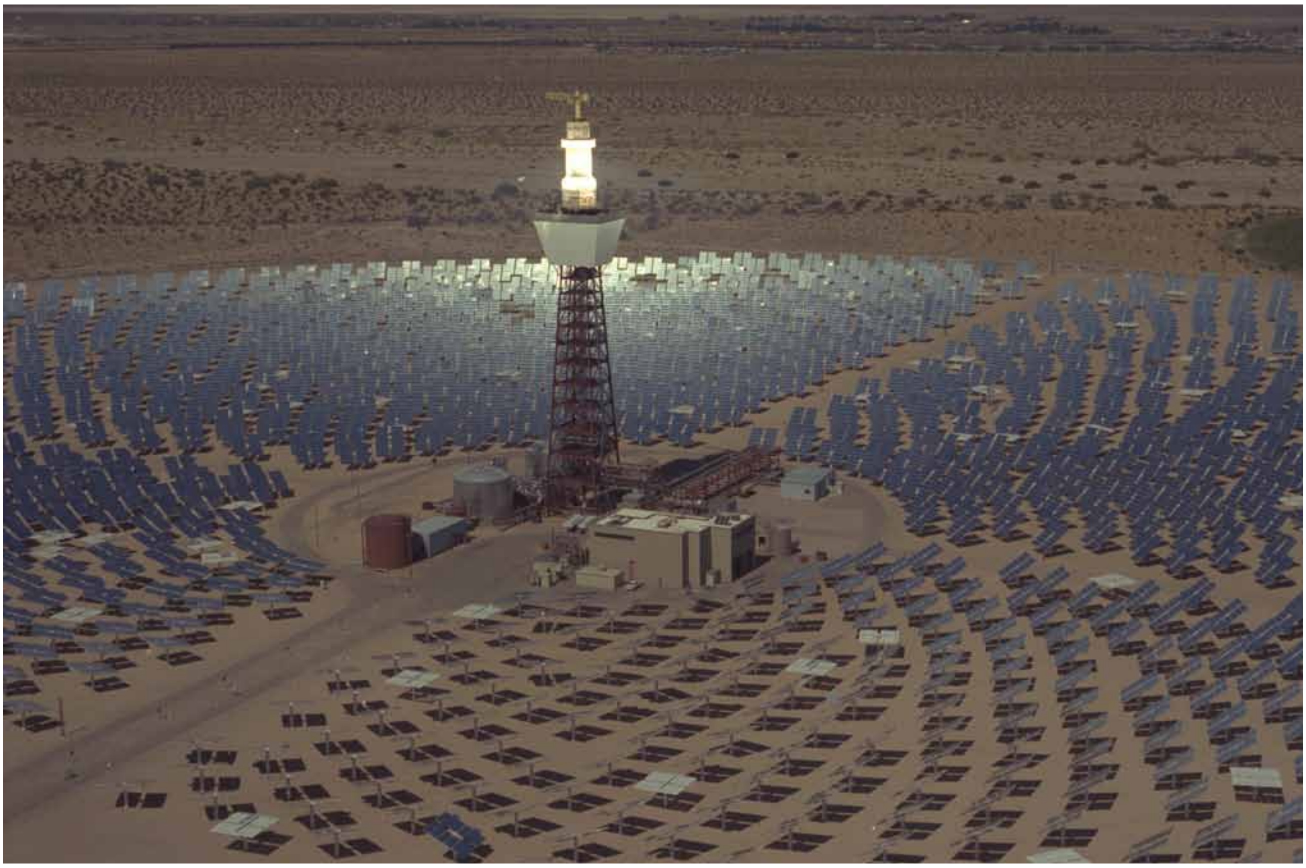
Under the ZCA 2020 plan, it is proposed that 60% of Australia's estimated 2020 electricity usage (195 TWh/yr) be generated by large-scale, dispatchable Concentrating Solar Thermal Power (CST) plants with storage. Solar Power Tower technology with molten salt storage is specified for all of the CST installations. As described in Part 2.5.2, power tower technology with molten salt as both working fluid and storage medium is the most suitable technology.

The general principle of operation of the chosen CST Power Tower technology to be used in the plan is shown in Figure 3.1. Note that for simplicity only six heliostats are depicted — in reality there are hundreds to thousands of heliostats for each tower.

The Sun's rays are reflected by several thousand heliostat tracking mirrors which follow the Sun's path and keep maximum energy focused onto the central receiver located on top of a central tower, which is up to 280 m high. The temperature generated in the receiver is 565-650°C, and the received heat is transferred directly to molten salt, which flows down the tower into the hot tank (shown in red). To meet electricity demand as required, hot molten salt is taken from the tank and passed through a heat exchanger to boil water and generate steam. This flows to the steam turbine where the energy is used to spin an electric generator and create the required amount of electricity. The heat energy extracted from the molten salt in the exchanger cools it down to 290°C, at which temperature it still remains molten, and returns to the cold tank (shown in yellow) where it awaits reheating again in the tower. The steam is re-condensed to water again by dry air-cooling fans so it can be reused.

The technical specifications and costings for the CST plants have been referenced from the U.S. Department of Energy's "SunLab" solar thermal program, a collaboration of Sandia National Laboratories and the National Renewable Energy Laboratories. These have been published in detail in the subcontract report "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts" carried out by Sargent & Lundy Consulting Group, LLC[7].

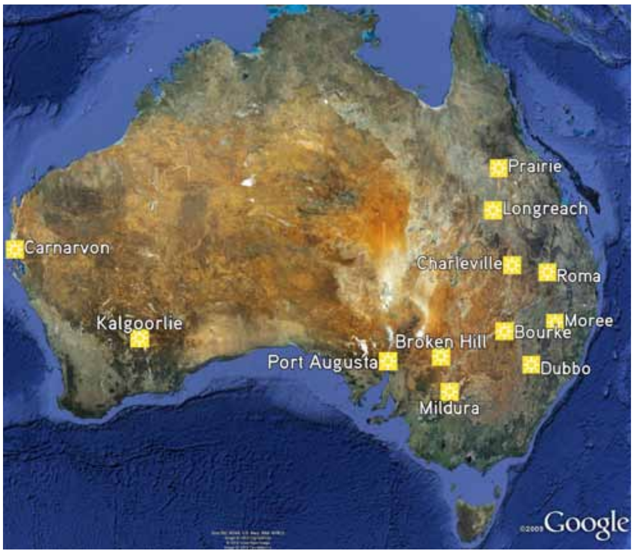
"... it is S&L's opinion that CSP [Concentrating Solar Power] technology is a proven technology for energy production, there is a potential market for CSP technology, and that significant cost reductions are achievable assuming reasonable deployment of CSP technologies occurs."



Solar Two in operation at Daggett, California, 1999[2]. Molten salt tanks are the silver pair at base of tower.

The 2003 Sargent & Lundy Report is one of the most detailed and thorough sources of data on solar thermal power publicly available, and is yet to be superseded.

FIGURE 3.2
Map of twelve proposed solar thermal sites



The Plan proposes 3,500 MW of CST capacity to be installed near each of the 12 towns shown in Figure 3.2. Each site is primarily made up of "Solar 220" generating units, which have a net output of 217 MW. Each unit consists of:

- A single central receiver power tower, a concrete tower 280 metres high, using molten salt as the working fluid (40% potassium nitrate, 60% sodium nitrate);
- 2.65 km^2 of mirror surface, consisting of 17,900 heliostats with an area of 148 m^2 each (just over 12x12 m);
- 13.9 km^2 of total land surface, in a circle with a 2.1 km radius. This is due to the spacing required between heliostats;
- A 245 MW (gross) supercritical reheat steam turbine, delivering 217 MW to the grid at full output, including an allowance for the air-cooling system;
- A two-tank molten salt storage system, able to store enough heat for 17 hours of full turbine output without sunlight; and
- Air-cooling system, using 15 fans of 9 m diameter each.

An allowance has been made for the first few power tower units at each site to be of smaller capacity, for example a progression of one 75 MW unit, two 100 MW units and three 150 MW units. This is explained in more detail in the following section. As a result, the exact specification for each site is for thirteen Solar 220 (217 MW) modules, and up to half a dozen smaller modules, for a total net output of just over 3,500 MW.

Torresol Gemasolar solar thermal power tower, Spain (Artist's impression) SOURCE: TORRESOL

3.1.1 Which CST power tower technologies?

Power towers with molten salt storage were proven during 3 years of commercial-scale operation of the Solar Two tower in the USA from 1996-1999[2]. Table 3.2 gives an overview of CST commercialisation history to date, including the latest project to be constructed — Torresol's 17 MW Gemasolar tower in Spain.

There are currently two companies offering commercial-scale concentrating solar power towers using directly heated molten salt for storage, namely:

- **Torresol Energy** — A joint venture between Spanish engineering firm SENER and the Abu Dhabi MASDAR corporation, Torresol is currently constructing the 17 MW Gemasolar Tower project with 15 hrs storage in Seville, Spain[5].
- **SolarReserve** — A US company, licensing Rocketdyne's molten salt tower technology, with active projects for 50 MW, 100 MW and 150 MW power towers.

TABLE 3.2
Molten Salt Power Tower History

Years	Project
1978-1985	Themis 2 MW prototype tower with molten salt storage operated in the Pyrenees, France (now being recommissioned)[3].
1996-1999	10 MW Solar Two tower operated with 3 hours of molten salt storage in California, backed by the US Department of Energy, Boeing, Bechtel and others.
2008-2010	Construction of Torresol's Gemasolar tower near Ecija, Spain — 17 MW with 15 hours of molten salt storage (~75% capacity factor)[5]
2010	Scheduled ground-breaking for SolarReserve's 50 MW power tower in Spain (~70% capacity factor)[4], and 100 MW plant in Nevada with 10 hours storage

In addition, there are several companies actively researching and developing capability in this storage technology, including:

- **Abengoa** — Spain's engineering and construction multinational (builder of the power towers PS10 and 20 in Seville, Spain).
- **Brightsource Energy** — an Israeli-American company with over 2,200 MW of tower projects announced in California. This includes six 200-220 MW towers. However they do not have storage and only operate during daylight hours[6].
- **eSolar** — backed by Google, eSolar has created innovative 1.14m^2 mirrors in close racking system, which are cheaper and quicker to construct and use less materials than conventional large heliostats.
- **Solar Millennium** — German technology provider for the Andasol 50 MW trough plants already in operation with 7.5 hours molten salt storage.

None of the latter four companies offers storage power tower products commercially as yet, however Torresol Energy and Solar Reserve do. These two companies are using the molten salt power tower technology developed by SunLab, a U.S. Department of Energy partnership between Sandia Laboratories (run by Lockheed Martin) and the National Renewable Energy Laboratories. The engineering designs and costings for 13.5, 50, 100, 200 and 220 MW power towers with molten salt storage developed by SunLab were reviewed and published by Sargent & Lundy, LLC, a power engineering consulting firm with over 100 years experience, in 2003[7]. This published data, along with information from **Torresol Energy** and **SolarReserve** projects in the construction and planning phases, has been used as the basis for designing ZCA2020's solar thermal energy system. The optimal plant capacity identified by SunLab of 220 MW with 17 hours storage forms the bulk of the installed CST capacity specified in the ZCA2020 Plan, once full industry scale-up has been achieved.

3.1.2 Technical specifications and description of CST plant design

TABLE 3.3
Basic CST plant components

	Component Technology
Mirrors	148 m2 Heliostats
Towers	Torresol / SolarReserve — concrete tower (similar to existing power station smokestacks)
Receivers	Torresol / SolarReserve — direct molten salt receiver, 550-650°C
Turbines	Supercritical Rankine steam cycle
Storage	Two-tank molten salt storage, 40% Potassium/60% Sodium Nitrate Salt
Working Fluid	40% Potassium/60% Sodium Nitrate Salt

Mirrors

A single Solar 220 unit will require just over 17,900 heliostat mirrors of 148 m^2 each.

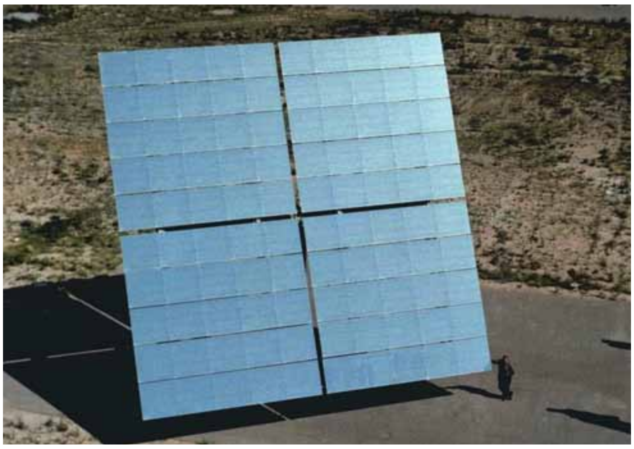
As mentioned in Section 2.5.2, the heliostat mirrors are slightly curved and track the sun through the course of the day, focusing solar radiation on the receiver. The conventional heliostat design includes large glass mirrors (50 - 150 m^2) with a supporting steel structure mounted on pedestals with concrete foundations in the ground. Larger heliostats of this design tend to be cheaper per unit area than smaller ones[9]. This is because there is a greater mirror surface area for each concrete foundation and pole — which require earth drilling and cranes for installation — along with the associated motors and tracking systems[10].

The 148m^2 Advanced Thermal Systems (ATS) heliostat, as shown in the photograph, is currently the largest heliostat specified by Sandia Laboratories[11]. Heliostats of similar size and design have been operated commercially in the Abengoa Solar PS-10 and PS-20 towers with a combined mirror field area of 200,000m^2 since 2006 and 2007 respectively. These heliostats were 121m^2 each. In addition, the ATS heliostat has been successfully operated at the US Department of Energy National Solar Thermal Test Facility in Albuquerque for over 20 years.

Over half the cost and most of the raw materials (concrete, steel, and glass) of a solar thermal power plant is in the heliostat field, therefore optimisation of this technology is important for improving efficiency and price. The heliostat field takes up the vast majority of land area in a solar thermal plant, and the size and spacing of heliostats are important factors in the land-use efficiency of the field.

eSolar option — While it has not been specified for the ZCA2020 plan, another innovative approach to heliostat fields is that invented by eSolar, a U.S. company backed by Google. The eSolar field uses very small mirrors — 1.14 m^2 in area. These are installed on a modular racking system which involves an interconnected steel frame mounted on concrete pedestals or ballasts which do not penetrate the ground. The modules are prevented from moving by the combined weight of the whole rack.

121 m^2 heliostat at Abengoa PS10 power tower, Spain[11]

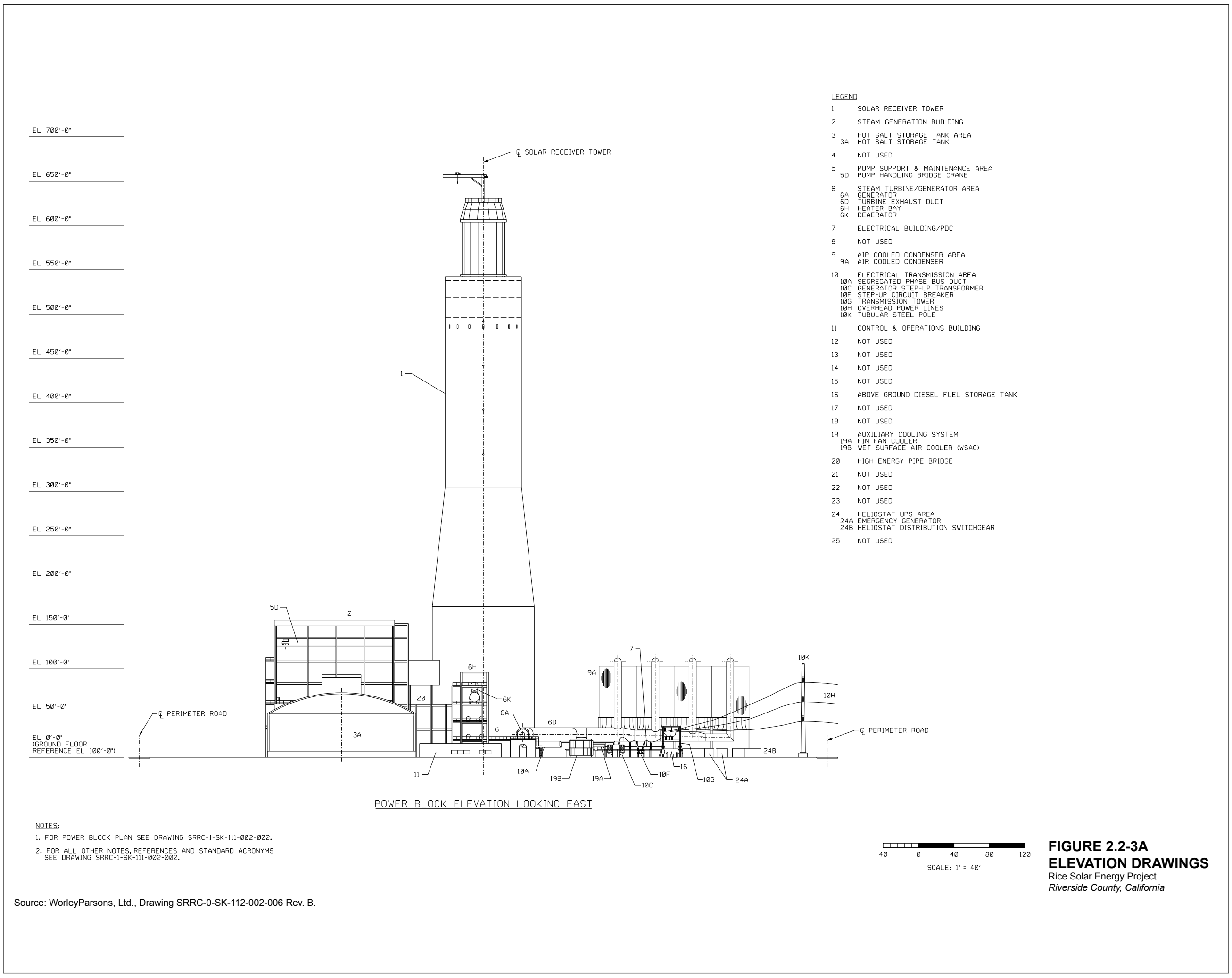


ATS148 Heliostat at Sandia Laboratories[12]

eSolar field in California[13]

Torresol Gemasolar construction site, June 2010, showing the hot and cold molten salt tanks, the tower, and the initial heliostats. Gemasolar is the third step in the scale-up to the Sandia/SunLab specified Solar 220 MW.

SOURCE: TORRESOL



Drawings of a SolarReserve Solar 150 MW tower to be installed in Rice County CA[8]

Workers at eSolar mirror field[13]

The result is advantageous for several reasons:

- less overshadowing by the smaller mirrors results in less land-use per unit area of mirror than larger heliostats
- small mirrors can be installed by hand by semi-skilled labourers, or electricians and other tradespeople on site, without the need for cranes and earth drills
- lower resource use (concrete, and steel) per m^2 of mirror
- lower overall cost
- very low wind loadings which leads to lower operational and ongoing costs due to less mirror damage and replacement, but also allows a lighter supporting structure for the mirror in the first instance[15].

Currently the eSolar technology is used without thermal storage for direct on-sun steam generation in small modules — 16 towers of 2.9 MW size each forming modules of 46 MW.

The benefits of eSolar technology were noted, and the authors considered the option of a hybrid incorporating eSolar (small form factor) mirror fields with Torresol/SolarReserve towers and receivers (with molten salt as a working fluid). However, no work has yet been done looking at integrating these small form mirrors with the very large 2.1km radius fields required by a Solar 220 Power Tower. Therefore, consistent with a conservative approach, the Plan recommends the ATS heliostat technology.

"...when we were developing this design we looked at all the resources that go into making a solar plant and the cost of virtually all those commodities — steel, copper, aluminum — was going up. The only thing going down was the cost of processing power. So we consciously decided to trade a design that needed much more computational power in return for using less materials."

BILL GROSS CEO ESOLAR [15]

Storage tanks

The proven commercial storage currently available is the two-tank molten salt system used by the 50 MW Andasol 1 and 2 plants, and being constructed at the Torresol Gemasolar and SolarReserve projects. However, it is likely that single-tank systems, or Thermocline, will be proven commercially in the near future, as it has already been proven at demonstration scale by Sandia Laboratories. Torresol will have a commercial scale thermocline system setup at Valle I and II Solar plants in Spain that are currently under construction[18]. In a thermocline tank, the layering effect due to density differences keeps the hot salt floating on top of the cold salt — similar to how a home hot water system works. Cheap quartzite is used as a filler for thermal mass, displacing a significant amount of salt requirements with even more readily available materials. This system uses 32% of the salt of a regular two-tank molten salt system[19]. These fillers are very low cost, and reduce the requirements for more expensive processed nitrate solar salts.

Molten salt storage tanks, Andasol 1, Spain

SOURCE: ACS COBRA

For a standard salt requirement of 25 tonnes per MWh electrical[19], the tank for a Solar 220 module will need an operating capacity of 52 Megalitres (ML). This is comparable in size to tanks used for oil storage and petroleum refining. For example, the largest crude oil tank at Altona Refinery in Victoria, Australia, has an operational capacity of 80ML, with dimensions 24m high x 72m diameter[20].

Receivers

The receiver is positioned at the top of the concrete central receiver tower. It is a high-temperature heat exchanger, designed to absorb the reflected solar radiation and transfer it to the heat transfer fluid (in this case molten salt). In its simplest form, a receiver consists of many parallel tubes through which the molten salt flows while being heated by the focused solar radiation. This receiver technology was proven in the 1990s by the US Department of Energy's Solar Two program. It is recommended that the receivers be equivalent to those available and designed by Rocketdyne Laboratories, suppliers to SolarReserve or Spanish engineering firm SENER, supplier to Torresol Energy. They have the ability to operate at high temperatures whilst having low losses from re-radiation of heat. Use of direct heating of molten salt for both the working fluid and storage medium minimises losses compared to the extra piping and heat exchange mechanisms needed for using intermediate working fluids such as steam or oil for the receiver working fluid.

Other heat exchangers used in the power station (e.g. salt-to-steam) are simple shell and tube type designs that are standard for processing industries world-wide.

Working fluid and storage medium

As noted earlier in Section 2.5.2, systems using molten salt as a working fluid can achieve higher temperatures than those using water, or oil as a working fluid. For example, thermal oil as currently used in trough plants is limited to an operating temperature of approximately 400ºC[19]. The salt used is a mixture of 40% potassium nitrate and 60% sodium nitrate. When in its molten form, it is a clear liquid with a viscosity similar to water. Molten salt as a working fluid and storage medium has the benefits of low cost, material stability (it is not flammable), abundant raw material availability, material safety (it is already used as an agricultural fertiliser) and a product development roadmap[7]. This roadmap would include molten salt use in:

- the current two-tank system with a 565ºC hot tank.
- single tank thermocline systems with two-thirds quartzite filler and a temperature of 565ºC.
- two-tank systems with a 650ºC hot tank and oxygen blanket to prevent salt decomposition.
- single tank thermocline systems with two-thirds quartzite filler and a 650ºC temperature and oxygen blanket.

In addition, as the molten salt only has to travel up and down the tower, it experiences lower heat losses compared to the long pipes required to return the oil to the power block in a trough plant. As the molten salt serves as both the heat transfer fluid and storage medium, there is no need for a heat exchanger and thus, further losses before entering the storage tank are prevented.

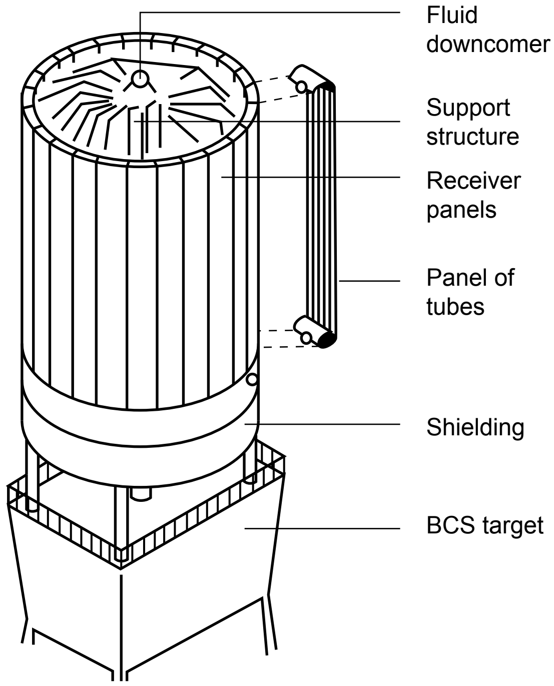
To generate steam, water is passed through a series of standard shell-and-tube heat exchangers to transfer heat from the salt to the steam. This heat exchange system is very flexible — changes in flowrate and energy transfer can be achieved in seconds to minutes, meaning that the power output can be ramped up and down quickly.

Turbines — High efficiency, Fast start

A standard supercritical double reheat Steam Turbine and Generator set is recommended, because these are currently being specified for the most efficient coal plants, are commercially available, and can achieve over 45% thermal to electrical efficiency[22] with temperatures above 565ºC. Both Siemens and General Electric have 10-15 years experience with supercritical steam turbines.

Solar thermal power plants have a fast response start-up time, and are well-suited to matching the variable output from wind power generation. Coal power plants have large boiler systems with high thermal inertia, complex coal-pulverising equipment on the front end and pollution control systems on the back, so they are unsuited to being ramped up and down. Siemens offers the SST-700 as part of their range of standard steam turbines, which is specifically adapted to use in solar thermal power plants. They are designed for rapid start-up and power cycling, making them more flexible than a standard coal turbine. There are already over 40 of these

Solar Two receiver[12]



A receiver showing the tubes through which the molten salt passes[16].

on order for solar thermal power stations around the world[23]. The SST-700 operates up to 585ºC[24] which is the same temperatures as specified by the high-temperature molten salt power tower applications, and has separate reheat cycles for flexibility. It is optimised to maintain high efficiency across a range of power loadings[25]. If the turbine is shut down overnight, energy from the 290ºC 'cold' salt is used to continue generating small amounts of steam, which is used to keep the turbine and seals warm, meaning that it is ready to start-up as soon as full steam generation recommences[26].

Cooling

Conventional air-cooling using fan banks is specified rather than water cooling, due to the limited supply of available water at many of the best solar sites, which are mostly located inland in low rainfall areas. Total plant water requirements are reduced to less than 12% of the requirements of a water-cooled plant[27]. This is inclusive of the small amount of water required for washing the heliostat mirrors and in the steam cycle makeup. The net annual performance loss due to slightly lowered efficiency and higher power use for the fans amounts to only 1.3% for power tower systems. Therefore the Solar 220 system, net rated at 220 MW, is de-rated to 217 MW. Air-cooling of thermal power cycles is a mature technology. The Kogan Creek black coal-fired 750 MW power station near Chinchilla, QLD uses air-cooling[28], with a bank of 48 fans each of 9 metres diameter. It is also specified in existing solar power tower projects, for example Brightsource's standard Luz Power Tower technology incorporates air-cooling[29], as do SolarReserve's projects at Tonopah, NV (Crescent Dune) and Rice, CA.

An even more attractive option may be the Heller system, pioneered in the 1950s, and the subject of recent studies from DLR and the Electric Power Research Institute. This is an 'indirect' dry cooling system, which could potentially be cheaper and have less parasitic energy losses than direct fan air-cooling[30].

Plant annual capacity factor

The solar thermal power towers specified in the Plan will be able to operate at 70-75% annual capacity factor, similar to conventional fossil fuel plants.

Storage of 17 hours provides enough energy to allow full power output 24 hours a day when fully charged. The annual capacity factor of a power plant is a measure of its power output over the course of a year. No power plant, whether renewable, fossil or nuclear, runs at full output 100% of the time, throughout an entire year. There is always downtime for maintenance and repair, and depending on the type of power plant, they may be throttled up and down at various times in response to changes in demand. Coal and nuclear plants are usually operated at constant or slowly varying load, though in low-demand periods may have to resort to the wasteful practice of blowing excess steam. Typically these plants can maintain a capacity factor of up to 80%, and 90% for plants of modern design. This means that, while a 1,000 MW power plant could produce 8,760,000 MWh/annum if operating at 100% output 24 hours a day 365 days a year, this is impossible, and in practice it actually produces, for example 80% of that figure — 7,008,000 MWh/annum. However it should be noted that in the Australian context, even so-called 'baseload' coal plants do not operate at such high capacity. In the state of New South Wales, there are 11,730 MW of coal-fired generation, which in 2008 generated 67,500 GWh net electricity[31]. This corresponds to a fleet capacity factor of around 66%, though some individual power stations are operating even lower, such as the 2,000 MW Liddell at 10,000GWh/yr, which is 57% capacity factor[32]. It can be seen therefore that individual power stations do not need to operate at full capacity 100% of the time to ensure reliable electricity supply. The NSW coal fleet is capable of operating at higher capacity if required, but the economics of importing cheap brown coal power from Victoria mean that they do not need to.

Gas plants are more flexible and many are designed as peaking plants that can adjust their output rapidly to meet grid demand at any given point in time or to respond to weather changes or emergencies. As such their capacity factor, which may be high technically, will often be much lower as their output is not called for long periods.

In the Australian context summer is currently the season of peak demand events and for this reason coal and gas generators do not schedule maintenance during this season. Conversely, a grid based on 100% renewable energy, with suitably managed end-use efficiency measures, will have its seasonal peak demand in winter. Therefore maintenance on solar thermal plants will be scheduled for the non-winter months.

The ability of solar thermal with storage to provide dispatchable power at high capacity factors is discussed and demonstrated below. For example, a "Solar 100" heliostat field and receiver as specified by the U.S. Department of Energy's Sandia Laboratories/Sargent & Lundy can collect enough energy to provide 2,066 MWh of electricity per day. If the plant did not have storage, then a 258 MW turbine could

TABLE 3.4
Mirror fields annual capacity

Mirror Field Size (m^2)	Total Electricity Per Day (MWh)	Storage Hours	Turbine Size (MW)	Hours of Operation Per Day	Annual Capacity Factor
1,366,100	2066	16	86	24	75-80%
1,366,100	2066	8	130	16	50-60%
1,366,100	2066	0	258	8	30%

be run for the average 8 hours a day that the sun is shining at full strength. However this electricity would not be available overnight, and the plant would have an average annual capacity factor of only around 30%. Alternatively, if the plant has storage, it can deliver the electricity over a longer time period throughout the day and into the night. The trade-off is a smaller turbine size, but the plant will still deliver the same total amount of electricity. This is summarised in Table 3.4.

The Solar 220 plants specified in the Plan have a "Solar Multiple" of 2.6 — this means that the mirror field and receiver at peak output produce 2.6 times more energy than is required by the turbine at full output. Therefore, during the day, for every unit of energy going to produce electricity directly at the turbine, 1.6 units of energy are sent into the storage tanks for use later at night.

3.1.3 Scaling up of CST

Solar 220 Power Tower plants will be able to produce electricity at a cost competitive with fossil fuels, after an initial period of industry scale-up from 2011-2015. This is dependent upon achieving a cumulative installed capacity of 8,700 MW by 2015.

As with most industrial technologies, larger installations of solar thermal plant become cheaper per MW due to the economies of scale of construction. For this reason, larger power plants generally deliver cheaper electricity than smaller ones. The Solar 220 described by SunLab/Sargent & Lundy is currently the maximum size specified for a single generating module. A 72% capacity factor Solar 220 with enough mirror area and salt storage for 17 hours has mirror field diameter of 4.2km. Beyond this distance, much of the light hitting the mirrors would not reach the central receiver, due to diffusion and reflection angles. Therefore, for larger installations than 220 MW, a number of modules are built side by side. This is common practice in existing power stations. For example, the Hazelwood brown coal fired power station in Victoria's Latrobe Valley has a total gross generating capacity of 1,680 MW, which is made up of eight 210 MW gross (193 MW net) turbines in parallel[33].

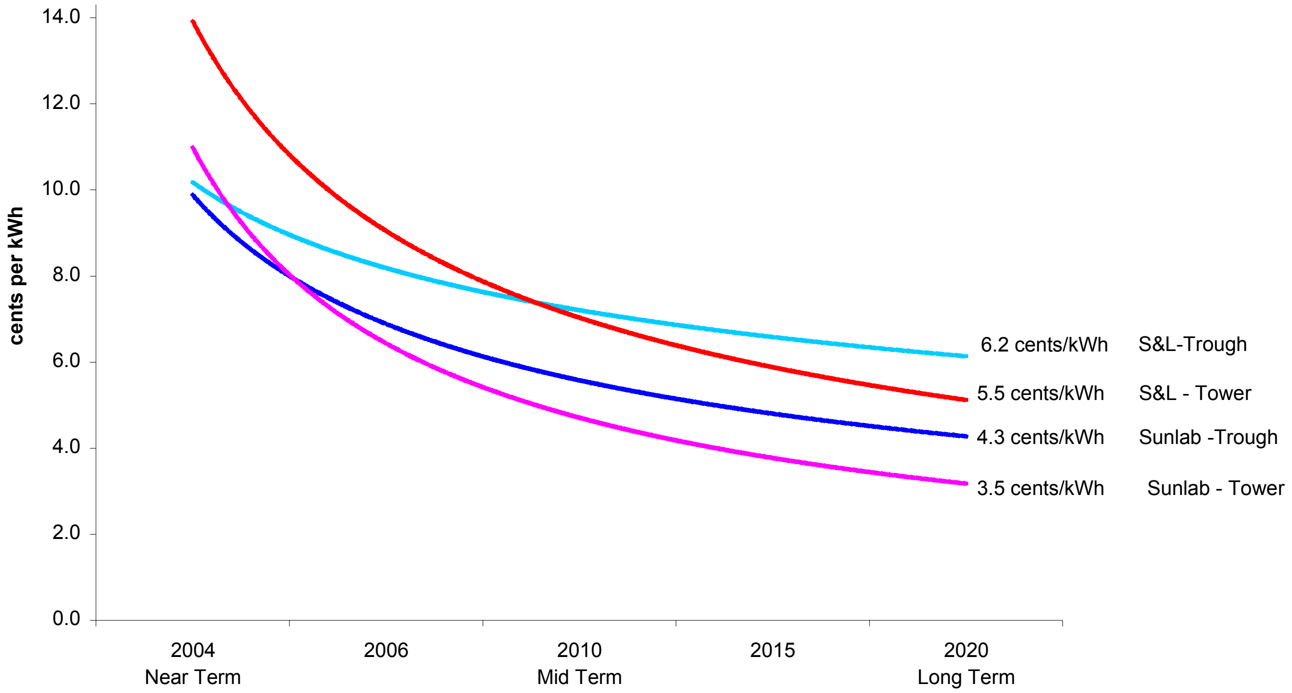
The 17 MW Gemasolar power tower being constructed in Spain is based on the Solar Tres design from Sandia Laboratories and will likely not be repeated at such a small scale. Existing projects in the pipeline from SolarReserve are of comparable size to a 75 MW plant if they ran at 75% capacity factor. Note that due to the different combinations of turbine sizes and storage with a given mirror field, the nameplate power rating (MW) is less useful for comparison than the annual power output (GWh/yr) or mirror field area. Indeed, in their initial applications to the Public Utilities Commission of Nevada, SolarReserve had not yet settled on a turbine size for their Crescent Dunes power tower in Tonopah, Nevada. Based on the size of mirror field and tower receiver they applied to build, SolarReserve could have used a turbine size ranging from 100-180 MW, depending on the final configuration and number of storage hours chosen. Since their original application they have settled on a 100 MW plant, meaning that it will have enough storage to run at a 50-55% annual capacity factor. It will have 10 hours storage[34], meaning it can run well into the evening peak with enough heat left over for fast start-up the next day, but will not dispatch electricity at times of lowest demand such as 3am in the morning. This ability to provide peak dispatchable power on-demand is of very high value to the electricity utility customer.

From the pipeline of actual projects seen in Table 3.5, it can be seen that the commercialisation is following the scale-up projected originally by Sargent & Lundy/SunLab, with Torresol's Gemasolar the equivalent of the Solar Tres, and SolarReserve's Alcazar equivalent to the scaled up Solar 50. If the Tonopah and Rice SolarReserve projects had 15 hours storage and 75% capacity factor, they could have a net output of 75 MW with their mirror field and thermal size – midway between Solar 50 and Solar 100. The approach of a solar thermal industry in Australia will be to progressively scale up the size of tower projects over time, until reaching the optimum size of 220 MW (with 2.1 km mirror field radius).

TABLE 3.5
Solar power plants annual power output. SOLARRESERVE ALCAZAR[35], SOLARRESERVE TONOPAH[36 37], SOLARRESERVE RICE[38]

Developer	Name	Net Power MWe	Storage hours	Capacity Factor	Mirror area m2	Annual power GWh /yr
SunLab	Solar Two	10	3	21%	80,000	18
SunLab	Solar Tres	13.65	16	78%	230,000	93
SunLab	Solar 50	50	16	75%	720,000	329
SunLab	Solar 100	100	13	73%	1,320,000	639
SunLab	Solar 200	200	13	74%	2,610,000	1,296
SunLab	Solar 220	220	17	72%	2,650,000	1,388
Actual Projects (— indicates details unknown at this time)						
Torresol	Gemasolar, Spain	17	15	67%	282,500	100
SolarReserve	Alcazar, Spain	50	—	70%	-	300
SolarReserve	Tonopah, NV	100	10	55%	1,100,000	480
SolarReserve	Rice, CA	150	—	34%	1,100,000	450

FIGURE 3.3
Cost Reduction Trajectory for Concentrating Solar Thermal[7]



	S&L High-Cost Bound	Cumulative Deployment 2002-2020	SunLab Low-Cost Bound	Cumulative Deployment 2002–2020
Troughs	6.2 cents/kWh	2.8 GWe	4.3 cents/kWh	4.9 GWe
Towers	5.5 cents/kWh	2.6 GWe	3.5 cents/kWh	8.7 GWe

As detailed by the Sargent & Lundy cost curve it is projected that at an installed power tower capacity of 8,700 MW, the price of electricity will drop to 3.5c/kWh (US, 2003 dollars). This translates to about 5-6c/kWh in today's Australian dollars, which is competitive with the price of conventional coal power, in particular of recently built coal fired power stations which are still paying off their cost of capital. The weighted average wholesale electricity price in Australia ranged from 5.37-6.38 c/kWh from 2006-2008[39].

The red curve in Figure 3.3 represents the Sargent & Lundy cost projection for towers while the pink curve represents the SunLab projection. The 3.5-5.5 c/kWh is the Levelised Electricity Cost (LEC) — the wholesale price at which a power plant needs to sell its electricity to break even over the life of the plant. The main difference between the two projections is the cumulative installed capacity assumed by each. The key difference between these two figures was an estimated deployment of 2.6 GW in the case of Sargent and Lundy as compared to 8.7 GW in the case of Sunlab. In the original report, these were referenced to an installation timeline from 2004—2020, but the key factor in achieving the cost reductions was not the timeline but the total installed capacity. This projection of 8,700 MW is likely to be substantially exceeded. There is currently 14GW of planned CST projects in Spain[40] and 2,440 MW under advanced development and construction[41], 97 GW[42] of solar applications received by the U.S. Bureau of Land Management, and the ZCA2020 plan requires **47 GW** of CST deployment in Australia. Thus, the use of the lower levelised energy cost figure from Sunlab as the basis for costing the ZCA2020 Plan is conservative.

Sargent and Lundy noted the significant reductions in cost from the initial pilot projects of the 1990's to 2003 and foresaw continuing reductions based on:

- Industry learning from scaling up of plants to larger commercial size (49% of reductions)
- Economies of scale from large volume production of components (e.g. heliostats) due to high deployment rates (28%)
- Technological developments from R&D such as cheaper heliostat (mirror) modules and more efficient super-critical steam turbines (23%)

Since the Sargent and Lundy report in 2003 the development of the CST industry has been progressing, as has research and development. Companies, such as Torresol and SolarReserve, are commercialising industrial-scale power tower technology. Companies such as eSolar have commercialised cheap, high production volume, heliostat mirror designs — eSolar power tower stations are already in operation and producing electricity. An updated publication from Sargent and Lundy in 2005 confirmed that high-temperature super-critical steam turbines were now in operation.[43]

The first plants to be built will naturally be more expensive than those produced when more industry experience and manufacturing capability are able to drive costs of solar thermal down to AU5c/kWh, as projected by Sargent & Lundy. This has been taken into account when designing and costing the ZCA2020 CST system, with initial project costs referenced to the actual costs of SolarReserve's Tonopah Solar 100.

Therefore the first 8,700 MW of solar thermal capacity in the ZCA2020 plan will be made up of plants in the range of 50—150 MW and up to 200-220 MW. If distributed evenly across the 12 sites, this will result in 725 MW of initial capacity at each site. This could be made up, for example, of a single 75MW module, two 100 MW modules, and three 150 MW modules. After this point in time, it is proposed that all further CST installations be Solar 220. These later installations have been costed at the prices from SunLab/Sargent & Lundy.

Appendix 3 has more details of scaling up existing power towers to Solar 220 MW modules in Australia, including the overall costs of the first 8,700 MW of power towers based on existing project costs and SunLab mid-range cost estimates.

3.1.4 Choosing geographically diverse sites for CST

Geographical diversity is important in harnessing renewable energy resources, to take advantage of different weather conditions at different locations. CST is suited to large installations in areas of high solar incidence, and, as it can store energy, it is not affected as much by daily weather patterns to the same extent as other renewable energy sources.

As the locations with high solar incidence are typically inland, and a long distance from Australia's coastal centres with high electricity demand, the CST plants require high-voltage transmission to connect them to the locations of demand. Building a smaller number of high-power-rating transmission cables is more economical than a large number of lower power transmission cables, which has been taken into account in determining the number of solar sites and their locations. Large high-voltage direct-current transmission lines can deliver up to 4,000 MW, so the solar sites have been sized just below this. While the most ideal sites for solar would be around the centre of Australia, the transmission costs involved in connecting these to the main grid would be prohibitive. Therefore sites have been selected that are inland to take advantage of high insolation, but still in relative proximity to the main grids, in order to lower transmission costs.

Out of a number of potential high insolation sites, 12 have been chosen: Mildura (VIC), Moree (NSW), Bourke (NSW), Dubbo (NSW), Broken Hill (NSW) Port Augusta (SA), Carnarvon (WA), Kalgoorlie (WA), Longreach (QLD), Charleville (QLD), Roma (QLD) and Prairie (QLD). It is believed that these selections represent a good solution taking into consideration the factors discussed already. It is possible that with more in-depth multi-variable analysis of the trade-offs between solar resource, transmission costs, geographical diversity and other environmental factors, various different and potentially more optimised scenarios could be conceptualised, but the ZCA2020 team has made the best decision possible with available data and resources.

The proposed sites for the ZCA2020 CST plants were chosen based on three criteria:

- Relatively high solar incidence and daily sunlight hours to provide maximum 'charge up' time and solar intensity for the plants.
- Low winter to summer ratios i.e. avoiding areas which may enjoy excellent solar resource for one part of the year but which are dramatically less productive in another part of the year.
- Proximity to load centres. (See Part 5) The quality of a site in terms of the first two criteria needs to be reconciled with the need to connect the plants to existing population centres, which entails the construction of high voltage transmission infrastructure.

The economies of the townships adjacent to the sites chosen in accordance with the above criteria would benefit substantially from the project; first from the construction of the plants and then from ongoing operation and maintenance work.

3.1.5 Sizing Capacity for winter minimum

The impact of seasonal solar variations — such as lower solar incidence during winter in the southern part of the country, and lower solar incidence in northern Australia during summer monsoonal activity — can be mitigated by the choice of geographically diverse sites for CST plant locations. This reduces the need to oversize mirror fields and molten salt storage systems to accommodate these local regional variations. The annual average daily insolation collected across all of the 12 sites is 7.95 kWh/m^2/day, in terms of direct normal irradiation that is collected by the mirror fields. In the winter, the available aggregate energy drops by 24% below average across the twelve sites, while in the summer there is in fact more energy available than required.

Supplying a total of 325 TWh/yr of electricity to the Australian grid would require an average of 37 GW of installed turbine capacity, if demand were flat at all times. However, this does not take into account the extra turbine capacity required for peak output, during times of high demand such as winter evenings and summer afternoons. Extra CST capacity has been sized to meet peak demand.

As solar thermal draws its power from salt storage tanks independently of whether the sun is shining or not, it can produce power at full output at any time of the day. i.e., a Solar 220 can produce 217MW regardless of whether it has 15 hours of salt storage remaining, or only 2 hours. However, lower insolation in the winter lowers the total amount of energy that can be collected and stored per day.

Due to lower solar insolation and wind availability combined with space heating electricity requirements, winter will be the time when matching supply and demand is most crucial. Therefore, the solar thermal capacity has

FIGURE 3.4
Solar radiation collection at 12 proposed CST sites, kWh/m²/day (mirror field efficiency factored in). From JAC modelling (details in Part 4)

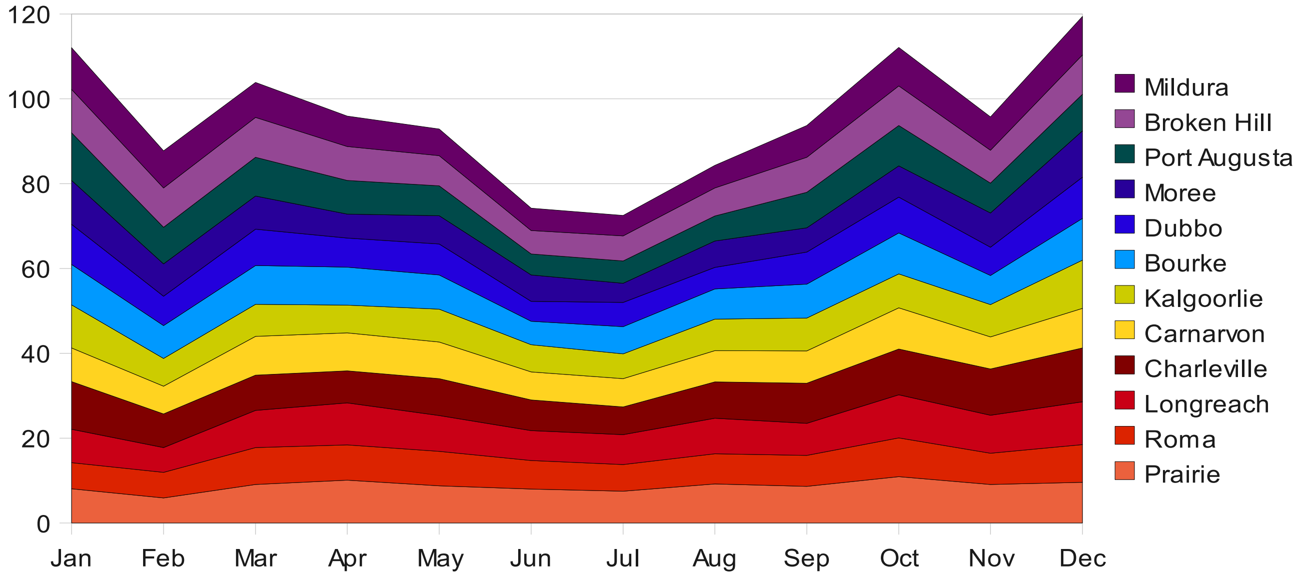


TABLE 3.6
Solar radiation collected by a solar thermal power tower, kWh/m²/day (mirror field efficiency factored in). From JAC modelling (details in Part 4)

Insolation collected by solar thermal power tower, kWh/m²/day															
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Max	Min	Min/ Avg
Carnarvon	7.9	6.5	9.1	9.0	8.7	6.6	6.6	7.4	7.6	9.7	7.6	9.4	9.7	6.5	82%
Charleville	11.2	7.9	8.4	7.5	8.7	7.2	6.5	8.5	9.4	10.8	10.9	12.7	12.7	6.5	82%
Roma	6.2	6.1	8.7	8.3	8.1	6.7	6.3	7.1	7.4	9.1	7.4	8.9	9.1	6.1	76%
Prairie	8.1	5.9	9.1	10.1	8.8	8.0	7.5	9.2	8.6	10.9	9.1	9.6	10.9	5.9	74%
Longreach	7.9	5.8	8.8	9.9	8.4	7.0	7.1	8.4	7.5	10.2	9.0	10.2	10.2	5.8	73%
Kalgoorlie	10.2	6.6	7.5	6.5	7.7	6.4	5.8	7.4	7.7	8.0	7.6	11.4	11.4	5.8	73%
Bourke	9.5	7.7	9.1	9.0	8.1	5.5	6.4	7.1	8.0	9.6	6.9	9.8	9.8	5.5	70%
Broken Hill	10.2	9.3	9.4	7.9	7.1	5.5	5.9	6.7	8.2	9.3	7.7	9.3	10.2	5.5	70%
Port Augusta	11.2	8.6	9.1	8.0	7.0	5.0	5.3	5.9	8.4	9.5	7.0	8.6	11.2	5.0	62%
Mildura	9.9	8.8	8.3	7.2	6.3	5.3	4.8	5.3	7.5	9.1	7.9	9.1	9.9	4.8	61%
Dubbo	9.5	6.9	8.6	6.9	7.4	4.7	5.7	5.1	7.6	8.5	6.7	9.7	9.7	4.7	59%
Moree	10.3	7.6	7.8	5.6	6.7	6.2	4.5	6.3	5.7	7.3	8.0	10.9	10.9	4.5	57%
Total	112	88	104	96	93	74	73	84	94	112	96	119	Overall annual average		
Average	9.3	7.3	8.7	8.0	7.7	6.2	6.0	7.0	7.8	9.3	8.0	9.9			
Overall winter minimum: 76% of average														7.95	

been sized to make sure that demand can be met in the middle of winter.

Through an iterative process of modeling output, 42.5 GW of solar thermal generating capacity has been sized for the ZCA2020 plan.

As outlined in Section 3.1.2 above, the first 8,700 MW of CST capacity will use plants with outputs in the range of 50-200 MW capacity. If divided equally between the 12 sites, this will result in 725 MW (gross) at each site, but this could be arranged differently depending on how the first stages of the roll-out proceeds. From then on, 13 Solar 220 modules will be rolled out per site, for a total generating capacity of 3,585 MW. When taking into account the average 1.3% parasitic energy for aircooling, this results in a net output of 3,535 MW per site.

The CST plants are designed for a 72% capacity factor with the equivalent additional mirror field to service this, but due to the extra installed capacity to meet peak demand periods, the plants combined will only have an effective annual average capacity factor of 52% to deliver the 195TWh/yr. They will still have a 90% availability factor. Thus, significant (73 TWh/yr) additional power generation would be available for at least eight months of the year. This cheaper energy would create opportunities for growth in innovative industries that can use seasonal energy surpluses.

This is similar to the situation in Australia today — there is a total 48.5 GW of (gross) power generation capacity on-grid, producing 227 TWh/yr (gross) which is an overall annual capacity factor of 55%[44]. Some baseload plants have higher capacity factors than this, but other peaking and intermediate plants operate at much lower capacity factors

Further optimisation to the system

All of the solar thermal power towers have been specified with 17 hours storage and solar multiple (oversized mirror field) of 2.6, for simplicity, and because these designs are already available from Sargent & Lundy. However, further optimisation could involve having some solar thermal plants with larger turbines and smaller storage, to act more like 'peaking' plants, which could reduce overall costs.

3.1.6 Installation timeline

Under the plan, the CST power stations are installed in two stages, to allow time to build up manufacturing capacity, establish sites and up-skill the workforce. It is proposed that the 2020 timeframe be achieved with a ramp-up of installation rates to 2015, then a constant rate of construction through to 2020.

Stage 1 (2010-2015): It is proposed that a target of 8,700 MW is set for installation by 2015, to be distributed across a number of the 12 sites depending on least cost opportunities for prioritising transmission infrastructure. An equal distribution across the 12 sites would end up with 725 MW at each one. This will involve fast tracking of site acquisition, and other planning measures in order to meet these tight timeframes. The plants will include 17 hours of storage — to provide 55 TWh/yr. The Torresol/SolarReserve towers and receivers would be built in module sizes such as 50, 75, 100, 150 and 200 MW. The first-of-a-kind plants will take 2.5 years to construct, as seen with SolarReserve's Rice and Tonopah projects[8].

Stage 2 (2015-2020): During stage 2, a constant rate of around 6,000 - 7,000MW/yr of construction will see the completion of the bulk of the required CST capacity, around 30 Solar 220 units per year, tailing off towards the end of the decade. It is expected that the construction time of a Solar 220 module will drop to 1.5 years, as the industry experience streamlines the rollout. The Andasol projects already completed in Spain took 1.5 years to construct[45].

3.1.7 Land Use for Solar Thermal Sites

One Solar 220 (217 MW net) module has a 280 metre high concrete tower surrounded by a field of mirrors covering a total land area of 13.9km^2. This is roughly in the shape of a circle with a diameter of 2.1km^2, with the tower offset towards the equator. This land is not completely covered by heliostats, there is a large allowance for spacing. There is in fact only 2.65km^2 of mirror surface for the Solar 220.

Each 3,500 MW site will require 230km^2 of land for the solar thermal fields, taking into account the effect of spacing between individual fields, each site could take up an area of land approximately **16km x 16km**. This would ideally be situated on areas of marginal farmland,

TABLE 3.7
Timeline of CST construction and electricity production

Year	Under Construction, gross (MW)	CST Operational net with Air Cooling (MW)	Capacity Factor	Annual Generation (TWh/yr)
2010		0	0	0
2011	1,000	0	72%	0
2012	3,500	0	72%	0
2013	5,750	0	72%	0
2014	8,060	1,974	72%	12
2015	9,680	4,935	72%	31
2016	10,120	11,410	72%	72
2017	10,120	18,141	72%	114
2018	9,240	24,655	72%	156
2019	8,580	33,992	65%	194
2020	2,640	37,032	60%	194
2021	0	42,461	52%	194

which already has low commercial or ecological value. The solar sites would not be located on good-quality farmland, National Parks or other areas of high value.

The total minimum land footprint of all twelve 3,500 MW sites will be approximately 2,760 km^2, equivalent to a block 53 km x 53 km — less than 5% of the area of Tasmania, or less than 0.04% of the area of Australia as a whole. All twelve sites would fit onto an area the size of Kangaroo Island and their total area would be considerably smaller than many of Australia's large cattle stations.

An approximate comparison of a proposed 3,500 MW site with existing coal fired power stations at Hazelwood in Victoria and Collie in Western Australia shows that the efficiency with which CST power stations utilise land to produce energy is well within an order of magnitude of both coal-fired cases. This comparison does not of course account for the fact that open cut coal mines will need to expand over time in order for their power stations to maintain constant energy output, whereas CST plants do not.

Figure 3.6 gives a relative comparison of the land area for the 19 solar modules at a 3,500 MW site. An initial site design was performed at Longreach to show a possible arrangement of the modules (shown in orange). The circles do not represent exclusive land use, just the region in which mirrors would be contained, with spacing in between. Alternative arrangements are also possible including greater distances between individual 220 MW plant modules to allow for other uses of the land. In Figure 3.7, the single 3,500 solar site is super-imposed over the land area used by Australia's largest cattle station in South Australia, known as Anna Creek, owned by S Kidman and Co. The total land area, shown in purple, of the three adjoining stations (Anna Creek, Peak, and Macumba) is 34,740 km^2. Also on the diagram is the total footprint of all 12 CST sites (green square) and the total footprint (tower base and foundation) of the 6,400 wind turbines (tiny blue square).

FIGURE 3.5
Heliostat field layout for Rice Solar Power Tower[26], showing increased spacing in outer field

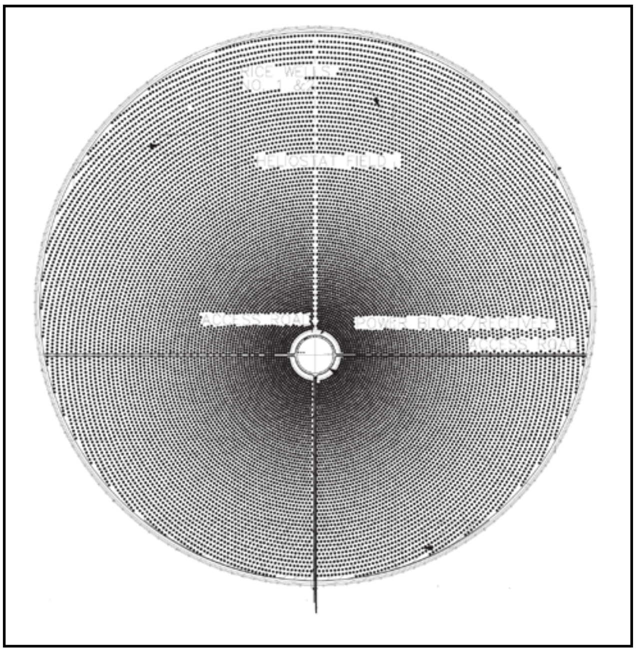


TABLE 3.8
Details of land requirements for ZCA2020 CST sites

Land Area Requirements	
Solar 220 land area	13.9 km^2
Diameter of circle	4.2 km
Net output	217 MWe
Land use efficiency	0.064 km^2/MWe
One 3,500 MW site	3,537 MWe
One x Solar 75	5.5km^2
Two x Solar 100	13.2km^2
Three x Solar 150	30.5km^2
Thirteen x Solar 220	180.7km^2
Total	230 km^2
Total Australia, 12 sites	2,760 km^2
Square analogy	53 km x 53 km
Circle analogy (if one large circle)	59 km diameter

TABLE 3.9
Land requirement comparison

Land Use Comparison	
Land use efficiency for a proposed CST site (22,700ha/3,500MW)	6.5 ha/MW
Land use efficiency for Hazelwood complex (3,554ha/1,540MWnet)[46]	2.3 ha/MW
Land use efficiency for Muja and Collie (~4,700ha/1,100MW)[47]	4.3 ha/MW
Area occupied by all twelve 3,500MW CST sites	2,760km^2
Total area of Kangaroo Island [48]	4,400km^2
Cattle station owned by Brunei, NT [49,50]	5,858km^2
Anna Creek and adjoining cattle stations, SA[51]	34,000km^2
Land at serious risk of being lost due to salinity in Australia (2000)[52]	57,000km^2
Area of Woomera Prohibited Area, SA[53]	127,000km^2
Total Australian Land Area[54]	7,688,503km^2

FIGURE 3.6
Possible layout of CST plant sitings near Longreach, Queensland.

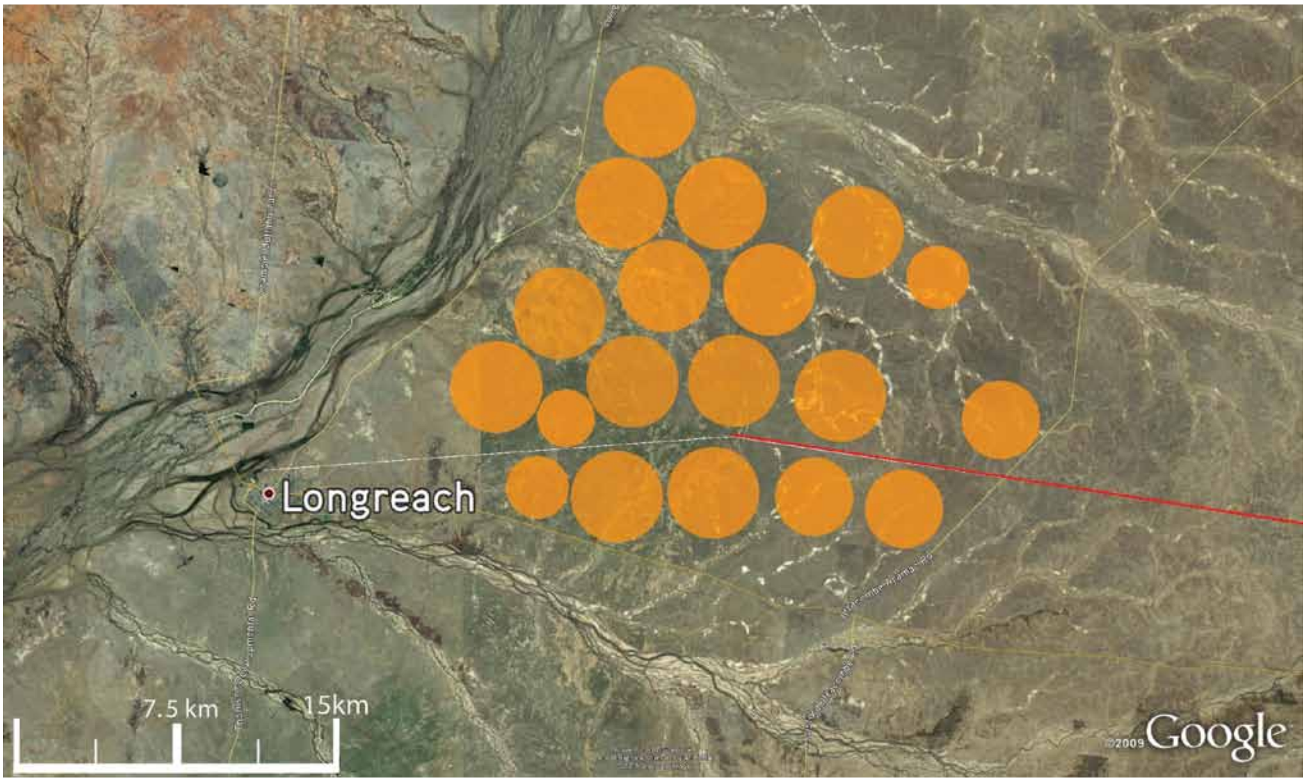
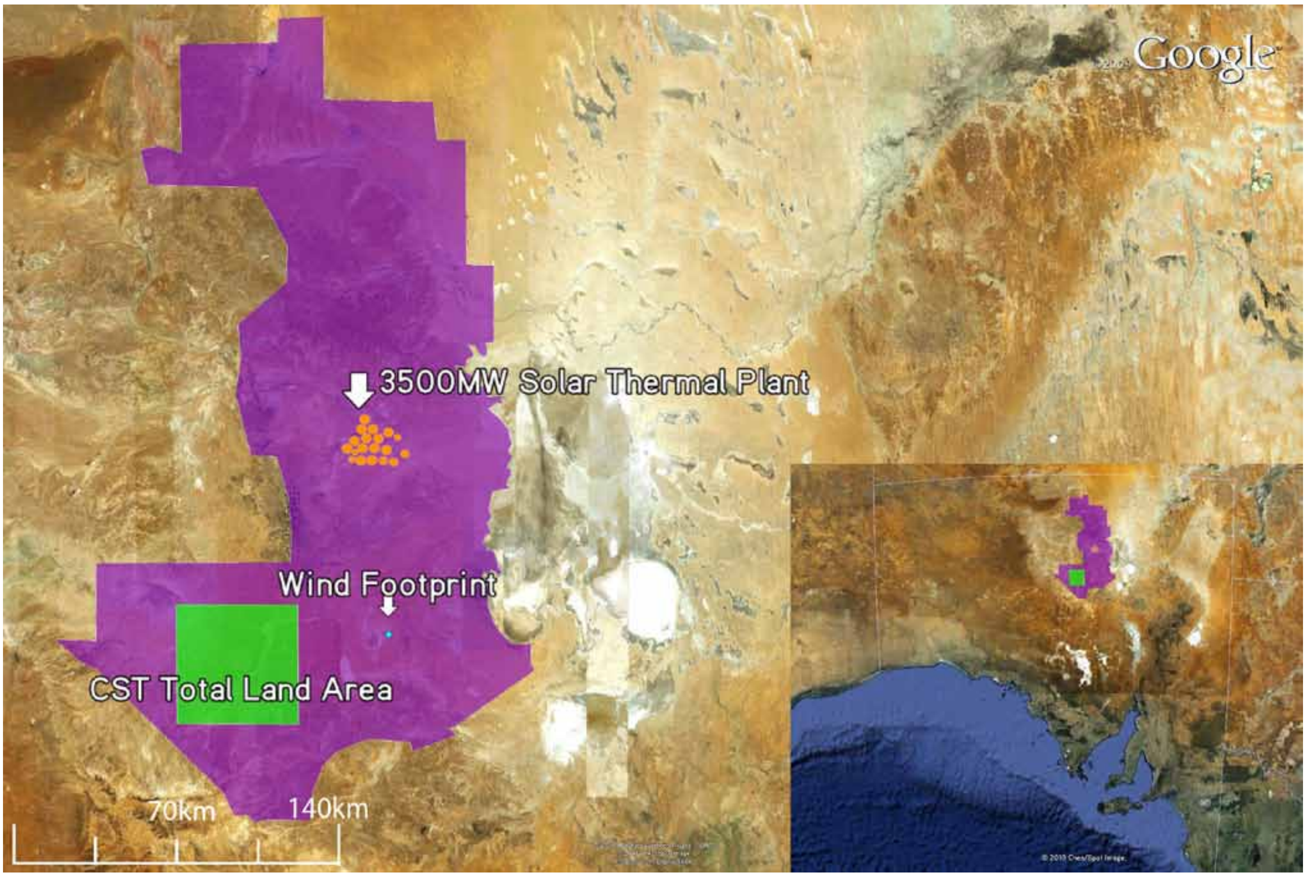


FIGURE 3.7
Comparison of ZCA2020 CST & Wind land area with Anna Creek Cattle Station, SA. Green box (CST Total Land Area) is the 2760 km^2 required for all 12 sites, which does not consider spacing in between the individual CST fields.



3.1.8 CST Water consumption

The solar thermal power plants proposed in the Plan will consume some water during their operation, although this will be kept to a minimal level through the use of air-cooling rather than water-cooling. Most of the water consumed will be for the occasional cleaning of the mirrors. The total water consumption of the 42,500MW grid of CST plants outlined in the Plan is 76 GL/yr. In contrast, the brown-coal generation of 7000 MW in the Latrobe Valley uses 106 GL/yr alone[55]. Clearly, Australia's total water consumption for power generation will reduce under the Plan.

Air-cooling to minimise water consumption

The steam Rankine cycle used by solar thermal power plants (as well as by coal and nuclear thermal power plants) requires cooling in order to function. Although many thermal power plants are water-cooled, technology is available to use air-cooling instead. For example, the 750 MW Kogan Creek coal-fired power station in Chinchilla, Queensland operates with air-cooling, using only 1,500 ML water/yr[56]. The solar thermal plants as outlined in the Plan will also use air-cooling, thereby reducing their potential water consumption significantly. Although a small amount of water is required for the occasional cleaning of the mirrors, this is carried out using efficient high-pressure jets and is still significantly less than the total water consumption of water-cooled coal-fired power plants.

As outlined in detailed studies from the U.S. Department of Energy on the consumption of water by solar thermal power plants, an air-cooled power tower uses 340 L/MWh, with only a 1.3% performance penalty on the power cycle[27]. In contrast the brown-coal power generation in Victoria's Latrobe Valley currently uses 2,100 L/MWh[57]. A single 217 MW solar thermal generating unit running at 60% capacity factor in 2020 will use 389 ML/yr, which, given the plant has an area of 13.9 km^2, corresponds to 0.28 ML/hectare/yr. In contrast, the national average irrigation rate is 4.2 ML/hectare/yr[58]. These figures are summarised in Table 3.10.

Water availability at each site

The water consumption of the CST plants outlined in the Plan only amounts to approximately 0.4% of Australia's total water consumption and only 5.7% of Australia's industrial water consumption (which includes the generation of electricity)[59]. Although this is not a significant amount, it is important to demonstrate the feasibility of each of the CST sites proposed in the Plan with regard to water availability (as they will each consume 6.3GL/yr) which is outlined in Table 3.11.

This investigation focuses on the availability and use of surface water. The average total surface water availability is the mean annual outflow of water. Not all surface water is available for use however, as some must be allocated to the environment. The sustainable yield of water is defined in the Australian Natural Resource Atlas as "the limit on potentially divertible water that will be allowed to be diverted from a resource after taking account of environmental values and making provision for environmental water needs"[60]. Although the "sustainable yield" of water is a more useful

TABLE 3.10
Water use for CST plants

Water Comparisons	
AIR-COOLED SOLAR THERMAL POWER TOWERS	
Water per power generated	341 Litres/MWh
Water requirements per land area	0.28 ML/hectare/yr
Water per ~3500MW CST site	6.3 GL/yr
Total Water All 12 Australian sites (~42,500MW)	**76 GL/yr**
LATROBE VALLEY BROWN COAL	
Water per power generated	2,100 Litres/MWh
Total water for Latrobe Valley Power (7,000MW)	**106 GL/yr**
FARMING IRRIGATION WATER USE	
National average irrigation application	4.2 ML/hectare
Total Irrigation usage (2004-05)	**10,085 GL/yr**

TABLE 3.11
Water use at Solar sites

Proposed Site	Surface Water Management Authority	Current Available Surface Water (GL/yr)	Current Water Usage (GL/yr)
Carnarvon	Gascoyne River	646[61]	<18[62]
Kalgoorlie	Salt Lake	No data	>11.4[63]
Port Augusta	Mambray Coast	38[64]	4[64]
Broken Hill	Darling River	2944[65]	299[66]
Mildura	Mid-Murray River	11,162[67]	4,045[67]
Bourke	Barwon-Darling Rivers	3,515[68]	230[68]
Dubbo	Macquarie-Castlereagh	1,567[69]	371[69]
Moree	Gwydir River	782[70]	321[70]
Roma	Condamine-Balonne	1,363[71]	722[71]
Charleville	Warrego River	423[72]	11[72]
Longreach	Cooper Creek	1,126[73]	6.9[73]
Prairie	Flinders River and Belyando/Suttor	6,718[74 75]	86.3[74 75]

figure, there is very little current data about sustainable yields in most of the proposed sites (see Appendix 4 for sustainable yields in some of the proposed sites). Hence, the average water use is also noted to indicate the potential availability of water. This figure must be considered cautiously however, as current water use is not necessarily at a sustainable level. These figures are summarised in Table 3.11.

3.1.9 CST cost

The total capital cost for the CST system described is $AU174 billion for on-grid CST (42,460 MW net) plus $AU15.1Bn for 4,475 MW of off-grid CST(see Appendices 2 and 3 for calculations).

This is divided into two phases. As described in Section 3.1.3 above, the first 8,700 MW to be built will be more expensive than end-of-cost-curve Solar 220 MW plants. As detailed in Appendix 3A:

- The first 1,000 MW is priced at similar price to SolarReserve's existing Crescent Dunes Tonopah project — $AU10.5 million per MW.
- The next 1,600 MW is priced slightly cheaper at $AU9.0 million per MW.
- The next 2,400 MW is priced at Sargent & Lundy' conservative mid-term estimate for the Solar 100 module which is $AU6.5 million per MW.
- The next 3,700 MW is priced at Sargent & Lundy Solar 200 module price of $AU5.3 million per MW

The total cost for the first 8,700 MW of CST with storage at 72% capacity factor is **$AU60 Billion**. Aircooling adjustment gives this a final net output of 8,587 MW. If installed across the 12 sites, this would be 725 MW (715 MW net aircooled)

Once 725 MW is installed at each site, the remaining capacity will be built as 220 (217 MW) modules — 13 modules per site. This will result in 3,585 MW of CST capacity per site, that is, **3,537 MW** minus aircooling.

Across all twelve sites, there will be a total of 43,020 MW CST, **42,460 MW** with aircooling.

The capital cost data for the Solar 220 plant (US$499.9Million) from the Sargent and Lundy report was used as the basis for costing the proposal. This figure was adjusted for inflation and converted to Australian dollars with an assumed foreign exchange rate of $AU1 = US$0.85. The extra capital cost of dry air-cooling has been calculated from data published by NREL separately. Dry air-cooling does cost slightly more in capital expenditure, and lowers the efficiency of the steam cycle, but delivers the benefit of requiring only 10-12% of the water of a conventionally wet-cooled plant.[78] The larger the air-cooling capacity, the better the efficiency of the steam cycle. Thus, there is a cost trade-off between the extra capital cost versus the returns made from higher efficiency. Kelly 2006[78] determined the optimum air-cooling size based on this trade-off, delivering the lowest Levelised Electricity Cost (LEC). The sizing of the air cooling was based on Kelly's model.

TABLE 3.12
CST installation cost table

Phase	Cost (2009 $AU)
Phase one — First 8700 MW	$60 Billion
Phase two — 156 x Solar 220	$115 Billion
Total Ongrid CST	**$175 Billion**
Off-grid CST — 4,475 MW	$15 Billion
All CST sites for ZCA2020 + off-grid	**$190 Billion**

Based on these adjustments, the cost for one Solar 220 CST plant, (217 MW aircooled), is $AU739 Million. 156 Solar 220 (217 MW) modules, will cost **$AU115 Billion**.

4,475 MW of CST for off-grid installations have been costed at the same price as end-of-cost-curve Solar 220, $AU3.41 Million/MW **— $AU15.2Billion**.

Therefore the total cost to supply 60% of Australia's projected 2020 demand under the ZCA2020 plan would be **$AU190 Billion.**

See Appendices 2 and 3A for more details.

BrightSource Luz Solar Thermal Power Tower[77]

3.2 Wind: Cheap, Clean and Technologically Advanced

The ZCA2020 Plan proposes that 40% of Australia's total estimated electricity demand of 325 TWh per year be supplied by wind power. Therefore each year approximately 130 TWh will be generated by wind turbines. Assuming a 30% capacity factor this requires the construction of an additional 48,000 MW of wind turbines.

To supply this 130 TWh/yr the Plan proposes that approximately 6,400 7.5MW wind turbines be deployed at 23 geographically diverse sites across Australia at a total cost of $AU72 Billion.

Based on international studies, the Plan considers that 40% penetration from wind is achievable, with at least 15% of the aggregated rated capacity being considered 'firm' (guaranteed output available to the system at any time) and only 4% of power lost annually in avoiding an oversupply of power (curtailment) in high wind output conditions.

3.2.1 Wind Power Requirements

As presented in 'Designing the system', the Plan proposes that 40% of Australia's total estimated electricity demand of 325 TWh/yr be supplied by wind, which equates to 130 TWh/yr.

Due to the intermittent nature of wind resource, wind turbines do not operate at full capacity all of the time. The percentage of actual wind energy that is generated at a particular wind farm is called the capacity factor. This is measured by taking the actual annual energy generation and dividing it by the total amount of energy that would be generated if the turbine was always operating at full rated output.

In Australia capacity factors for operating wind farms are in the range of 30-35%, however higher capacity factors require sites with consistently high wind speeds and good topography, which is unlikely to be the norm for most future wind farm locations. In Victoria, the average capacity factor of currently operating wind farms is 30%.[79]

Given the large number of sites required for the Plan, an average capacity factor of 30% is expected.This means that a 7.5 MW wind turbine will produce an annual average output equivalent to running continuously at 2.25 MW all year round.

To supply 130 TWh/yr at 30% capacity factor, 50,000 MW of combined rated capacity is required. There is already an installed capacity of 1700 MW of wind turbines in Australia, with a further 300 MW of wind farm projects expected to be completed by the start of 2011 [80], so the Plan proposes to build an additional 48,000 MW of wind.

Which Wind Turbines?

The Plan proposes that high quality, technologically advanced 7.5 MW onshore wind turbines be utilised, as these are the largest commercially available turbines at present and their size enables the extraction of more energy from a given site by tapping into stronger and more consistent wind resource at greater heights. It is better to use fewer large turbines than many smaller turbines as there are less moving parts to maintain (and periodically replace)[82]. Smaller 2-3 MW turbines are currently used in Australia and in early years, this may continue. However as shown in Part 2.5.4, the global trend in wind has been towards larger turbines.

The Enercon E126 land-based wind turbine is currently the only commercial 7.5MW turbine, upgraded from 6MW previously[86]. However, given global growth trends, it is expected that 7.5 MW (and larger) turbines will be rolled out by all the major manufacturers. The Enercon E126 has a hub height of 138 metres, and a blade diameter of 127 metres.[83]

These turbines could be sourced from European manufacturers such as Enercon, Vestas, Nordic Wind, Repower, or Areva Multibrid, or their Chinese competitors. Another option is for a publicly owned company to produce proprietary technology under license and direction from one or more of these manufacturers. Incentives could be made available to locate these factories in coal communities.

Enercon E-126 turbines in Belgium. Source: Steenki[88]

Wind turbine blades transported by train[87]

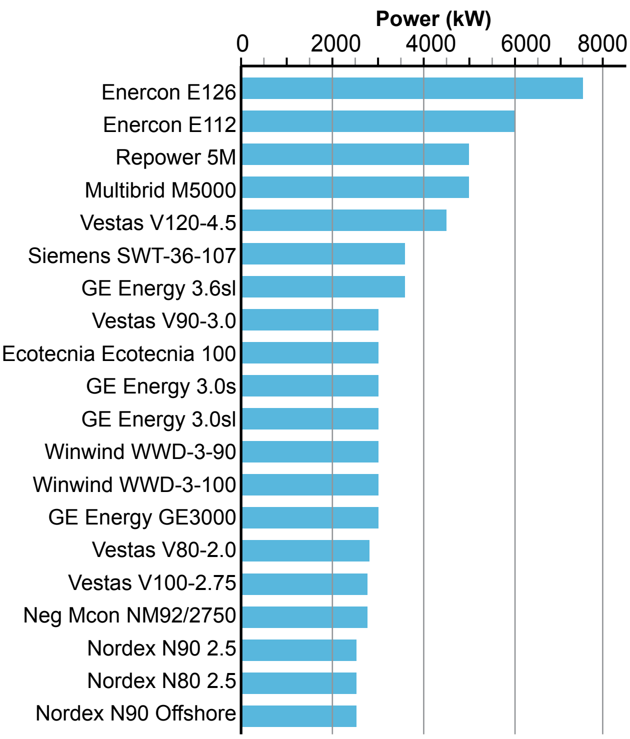
Larger turbines are currently being commercialised, for instance UK based Clipper Wind is developing a 10 MW offshore wind turbine[84].

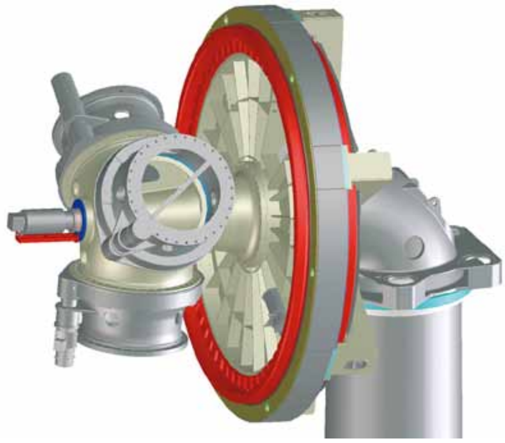
The Enercon E126 has other benefits including:

- Direct-drive turbines with gearless operation that require very little maintenance
- Improved blade design which enables more power generation per swept area, and the harvesting of a greater range of wind speeds

Transportation of the turbines represents a significant cost, which rises as the turbines become larger. In spite of its larger size, the Enercon E126 is easier to transport than its predecessor, the E112. This is due to the blades being manufactured in two sections, allowing for standard transportation, which could predominantly occur on existing rail networks.[87]

FIGURE 3.8
Wind turbine model capacity (kW)[85]





Direct Drive of Enercon Wind Turbine[90]

3.2.2 Siting for Geographical Diversity and Winter Peak Demand

The Plan proposes 23 sites for wind power — each consisting of either ~2,000 or ~3,000 MW of turbines. This is of comparable size to other large wind projects such as the Markbygden wind farm in Sweden, planned to have a capacity of 4,000MW and up to 1,100 turbines. Enercon is the supplier for this project.

Under The Plan the grid is strengthened (see 'Grid and load management — creation of a national grid') and the wind farms are located across the length and breadth of the country. The geographically dispersed wind sites exploit the diversity in weather systems that occur simultaneously across the Australian continent and counter localised wind variability.

Attempts have been made to select wind sites according to highest average winter wind speeds rather than highest average annual speeds, to accommodate the projected winter peak.

Figure 3.9 shows the proposed wind farm locations selected for the Plan. It should be noted that the locations are indicative only and further site design, environmental studies, and community consultation would be required to determine the precise location of wind turbines. Moreover the turbines at each site do not need to be grouped in one single location. For example the 3,000 MW of wind capacity at Ceduna could be made up of ten 300 MW wind farms located in the general region of Ceduna, all linking back to the same single high-voltage AC transmission line hub.

Estimating reliable wind capacity. The Plan is based on a minimum reliable instantaneous output of 7,500 MW from the wind generators. This is 15% of the combined rated capacity (50,000 MW) of all wind generators installed across the country. This 'firm' wind output is as reliable as conventional baseload power.

A grid planning study by South Australian utility company ETSA, modelled output from sites without geographical diversity. The report found that the worst case reliable wind contribution for South Australia in isolation was

8% of aggregate turbine rated capacity for grid planning purposes.[91] Therefore the 15% estimate is twice that of the ETSA South Australian minimum. This figure is seen as a conservative estimate of reliable wind contribution, given the geographical and meteorological diversity of proposed wind farm locations under the Plan.

This estimate is consistent with a recently published study for the US National Renewable Energy Laboratory. This study modelled the amount of firm power that can be relied upon at any given time for different scenarios of wind farms located in the Eastern States of America, generating 20% of America's power. This estimated a minimum reliable instantaneous wind capacity for onshore wind generators of between 14 and 27%, depending on the transmission model used. For an upgraded and interconnected grid using high voltage DC and AC lines similar to those in the Plan, capacity values of up to 27% were achieved. However there are significant differences between the Australian and American electricity grid which limits the possibility of a direct comparison [92]. In the absence of a similarly detailed study for Australia, the authors believe, based on the NREL study and the level of diversity and grid interconnection proposed for the Plan, that a higher percentage could be 'firm'. However the conservative value of 15% is assumed.

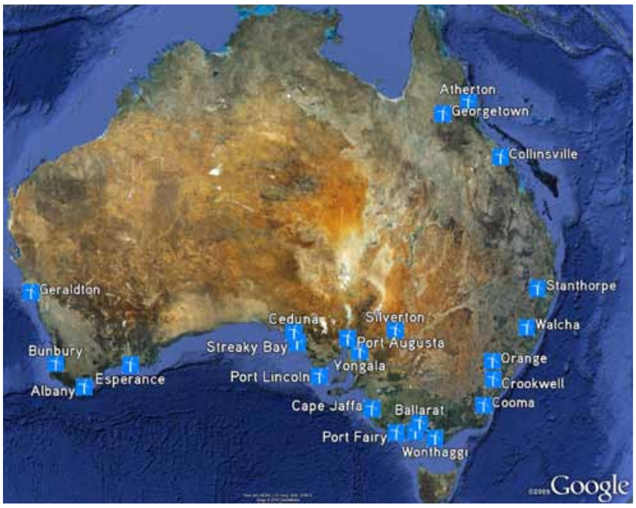
If this instantaneous grid-wide minimum is assumed across the whole year, it can be considered a baseload equivalent of 7,500 MW, equating to 67.5 TWh. Given that each individual wind farm is projected to operate at 30% capacity factor, this means our baseload equivalent is approximately half the expected average annual ouput of the whole system.

If a period of system-wide low wind supply coincides with high total demand (such as the winter peak), then the system can draw upon the standby solar thermal energy, and on the very rare occasions when solar thermal storage is also low, the biomass boilers will be used to supplement dispatchable solar energy from the molten salt tanks.

Accommodating the winter peak. Under the Plan, the seasonal peak demand is expected to occur in winter due to the conversion from gas to renewable electricity for space and water heating in winter, and reduced air conditioning use in summer. As outlined in Section 3.1 Solar incidence in Australia is at a minimum in winter, and specifically in June.

Along the southern and western regions of Australia, the Roaring Forties westerly wind patterns generate the

FIGURE 3.9
ZCA2020 Plan Wind Energy Sites



strongest wind speeds in Spring and the lowest wind speeds in Autumn [93, 94]. This differs from other wind patterns, which rely on land/ocean warming and cooling, where minimum wind speeds are in winter.

Figure 3.10 illustrates estimated power output from wind farms located in South Australia, New South Wales, and Victoria, using Bureau of Meteorology wind data and a Vestas V80 2MW Turbine power curve. This study was undertaken by the CSIRO in 2003. It shows the minimum wind output occurring in April/May.

To offset the reduced solar incidence in winter, some attempt was made to locate wind farms in southern regions and other areas with high average winter wind resource and low seasonal variation. Additionally sites were chosen to maximise geographical diversity, in order to minimise the effect of local wind patterns and weather events.

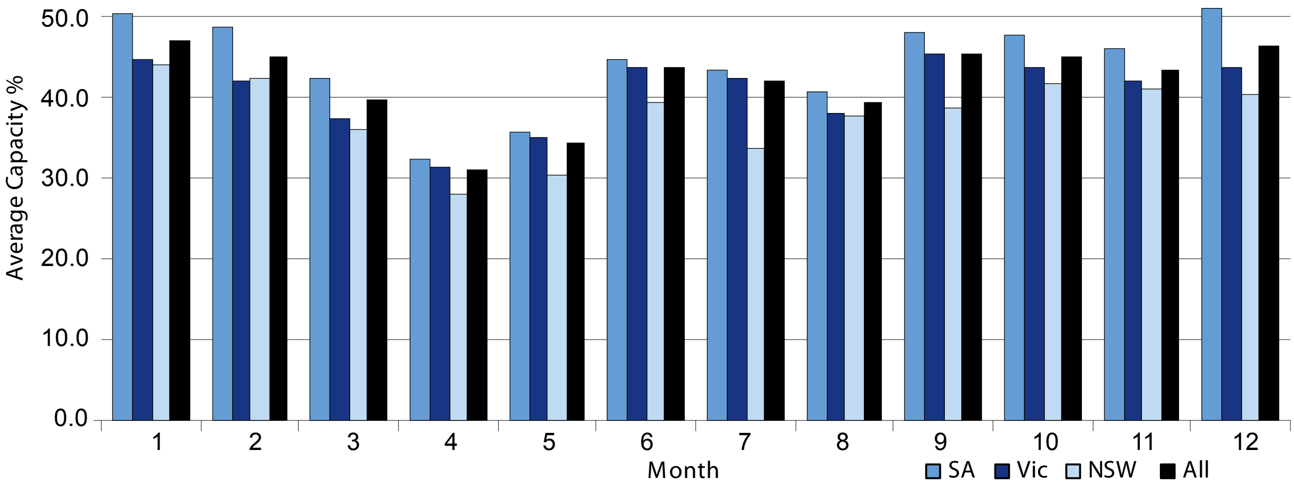
Sites with high wind resource have less variation at high wind speeds and reduce the intermittent nature of wind[97]. Therefore sites were chosen to have a minimum average annual wind speed of 7 m/s (at 80m hub height) from the Australian Renewable Energy Atlas.

The final location of sites will need to take into account site suitability, focusing on accessibility (for heavy machinery) in rural areas with non-critical farm land, away from forests

TABLE 3.13
Wind sites table

WA	Capacity (MW)	SA	Capacity (MW)	VIC	Capacity (MW)	NSW	Capacity (MW)	QLD	Capacity (MW)
Albany	2,000	Ceduna	3,000	Port Fairy	2,000	Crookwell	2,000	Stanthorpe	2,000
Esperance	2,000	Yongala	2,000	Ballarat	2,000	Orange	2,000	Atherton	2,000
Geraldton	2,000	Port Lincoln	2,000	Mt Gellibrand	2,000	Walcha	2,000	Collinsville	2,000
Bunbury	2,000	Cape Jaffa	2,000	Wonthaggi	2,000	Cooma	2,000	Georgetown	2,000
		Streaky Bay	3,000			Silverton	2,000		
		Port Augusta	2,000						

FIGURE 3.10
Estimated Annual Wind Power Variation Across South Eastern Australia[95]



and sensitive environments, and with reasonable proximity to urban areas. Once installed, wind turbines have a low impact on the land, allowing farmers to continue using the land for grazing and crops.

3.2.3 Installation timeline and resource requirements

The Plan proposes that 1,250 MW of wind turbine construction begins in 2011, and that the rate of turbine installation increases between 2011 and 2013 until the rate reaches 6,000 MW per year. From 2014 to 2020, 6,000 MW of wind capacity (800 x 7.5 MW turbines) should be installed per year for a total installed capacity of 48,000 MW by 2020.

This allows for an increase of domestic manufacturing capacity for turbines, and for establishing the sites. This approach is consistent with the experience internationally in Spain and Texas. In Spain, for instance, the rate of annual wind installation rose from 1,500 MW in one year (2006) to 3,000 MW (2007) [98]. In Texas, 1,618 MW was installed in 2007 and 2,671 MW in 2008 - an annual increase of 65 per cent [99, 100]. This was all achieved using smaller turbines and with less global experience in installing wind power than we have today.

The scheduled construction will occur in batches, with new installations beginning every 6 months. Each batch will be completed in approximately a year. For example in January 2011, 500 MW of wind power will begin installation, finishing by January 2012, and 750 MW of projects will begin in July 2011, finishing by July 2012.

It should be noted that there are currently just over 11 GW of wind farm projects in the pipeline for Australia [80]. We have not directly incorporated these projects into our timeline as most of the projects have not left the planning stage. If they do reach construction stage they will help to reduce the overall requirements of The Plan. However it is important that they are installed at a pace which meets the requirements of the projected timeline. This will require assistance and support to fast-track all the projects.

3.2.4 Managing wind variability by means of integration with CST with storage

Wind integrates more efficiently with a predominantly CST plus storage electricity system than it does with a coal-dominated system. This is because conventional coal plants have little or no large-scale energy storage. Instead they must cope with large, difficult-to-manage boilers. Therefore conventional coal power plants cannot efficiently dispatch energy at relatively short notice to fill in troughs in the wind energy delivery. Currently gas peaking plants would play this role in the absence of dispatchable stored CST electricity.

CST with storage, in combination with wind, creates an effective synergy. The dispatchable stored solar energy ensures energy security, by providing effective backup for the wind turbine fleet. At the same time, wind generated electricity that is supplied during the day displaces daytime electricity production, which would otherwise need to come from the solar thermal generators. Thus the wind energy allows a build-up of stored energy via the molten salt tanks.

On these occasions, instead of putting only 60% of the harvested solar resource into storage (as is specified in the average design provisions) a higher percentage (at times up to 100%) would go into storage. This would extend the reserves available for operation at night, and when there is no sun, beyond the plant's specified 60%.

During periods of no solar input (at night or during cloudy periods), wind-generated-electricity can be used in preference to accessing thermal energy stored in the molten salt tanks, thus maximising the available backup store of energy.

3.2.5 Wind surpluses at high penetration levels

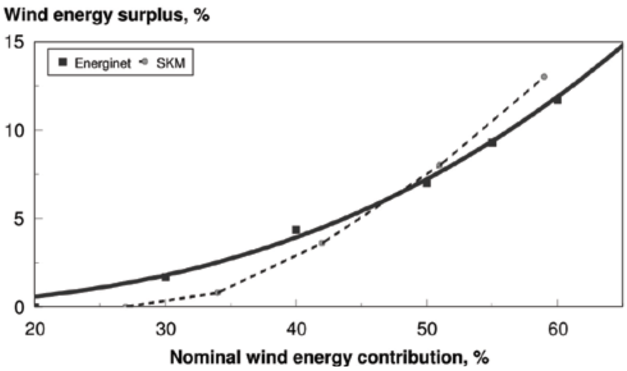
Based on international studies the Plan expects that 40% penetration of wind is possible, with a maximum of 4% of wind power lost to oversupply.

The issue of wind variability management is also discussed in 2.5.4 Wind Power, and the problem of curtailment is illustrated. For larger installed capacities of wind power, occasions are possible when high wind events push the combined output of the wind farms above what the electricity system can cope with. This is even more of a problem during low demand periods. At these times curtailment action is required to reduce the amount of power generated by each turbine. Curtailment is the technical term used to describe the process of remotely instructing the required number of wind turbines (at one or more windfarms) to reduce their output (by physically rotating them to face out of the wind). In these cases the wind turbines are stopped from producing as much power as technically possible, and power is un-utilised (or lost).

Work by British Energy Consultant David Milborrow[101] combines information from engineering consultancy Sinclair Knight Merz and the Danish grid operator Energinet DK in a report on managing wind variability. This study indicates that, at 40% annual production from wind, only 4% of wind power would be lost due to curtailment.

The percentage of wind power lost to curtailment increases with higher grid penetration. This is an important consideration when calculating the optimum level of grid penetration by wind for a given nation or region. The proposed Australian grid would have far greater geographical and meteorological diversity than, for instance, the Danish grid — which is one fifth the size of Victoria. Yet Denmark has a target of 50% annual electricity production from wind by 2025 [102]. This diversity in Australia ensures that the overall wind system will have a steadier output, meaning that Australia could potentially have a higher percentage of its power coming from wind than a country like Denmark, whilst at the same time requiring less curtailment. Some curtailment may occur where regional power lines are at capacity, but is expected to occur only rarely across the whole system.

FIGURE 3.11
Estimates of surplus wind energy for contributions up to 60% [101] of total demand)



If we plan for the conservative figure of 4% power loss due to curtailment, the absolute contribution from wind is factored to reduce by not more than ~5 TWh/annum. The CST system is over-specified to allow for this. This allowance is conservative, because curtailment is likely to occur mostly in the summer months, since this would be the period of highest supply (due to a relative abundance of spare capacity from the solar resource compared with the winter months) and of lowest demand (because cooling in summer uses less energy than electric 'heat pump' heating during the winter).

3.2.6 Cost of wind turbines

The total investment for the 48,000 MW of new wind capacity is estimated at $AU72 Billion. This takes into account cost reductions that would occur with a large ramp-up of the wind industry as proposed by the Plan.

Assessment of the forecast and real capital costs of seven large new and recently completed wind farms in Australia gives the current average Australian capital cost for wind farms as $AU2.5 Million/MW.

This cost is relatively high compared to other regions such as Europe and America. Australia has seen a much slower growth in wind power than other countries and as a consequence there are no turbine manufacturers in Australia, with most turbine components needing to be shipped from overseas. In addition, the current world price of wind turbines is higher than in previous years, despite the long term trend of price reductions with increases in turbine sizes and improvements in technology. This price increase was caused by a slower than expected expansion of the wind industry in 2001-2004, followed by a sharp increase in the global market for wind turbines (30-40% annually) until around mid 2008. This was combined with an increase in raw material prices and later the Global Financial Crisis[103].

The ZCA2020 Plan involves a large scale roll out of wind turbines, that will require a ramp up in production rate, which will help to reduce wind farm capital costs, and bring Australian costs into line with the world (European) markets.

A 2009 report by the European Wind Energy Association (EWEA) on the Economics of Wind Energy, included a long term projection of wind capital costs, taking into account the effect of current demand and supply on the costs of wind turbines[103]. Based on this study the 2010 forecast capital cost of onshore wind is approximately €1,200/kW (2006 prices) or $AU2,200/kW (current prices). By 2015 the European capital cost of onshore wind is estimated to be around €900/kW (2006 prices) (or $AU1,650 in current prices) and this is forecast to drop further to €826/kW (2006 prices) by 2020.

The European Wind Energy Association research however did not take into account the expected impact that China's wind turbines will have on the global market in the near future.

The Chinese government has recently announced plans to build seven wind power bases, each with a minimum capacity of 10,000 MW, by 2020. Laws in China require that new wind farms must have at least 70% of all wind power equipment manufactured in China. This is generating a massive boom in the Chinese wind turbine industry and some Chinese manufacturers are already selling their products internationally. Current industry estimates suggest that wind turbines manufactured in China cost 20-25% less than the Australian market price.

The first Chinese wind base, dubbed the "Three Gorges Wind" project, is the 20,000 MW wind farm to be constructed in Jiuquan city in the Gansu Province. Construction of this wind farm is now under way at an estimated capital cost of USD 17.6 Billion (120 Billion Yuan). This equates to roughly $AU 1 million/MW, less than half the current capital cost for wind farms in Australia [104].

Due to the planned nature of the ZCA2020 program, turbine suppliers would be given significant forward notice of orders for the Australian market. This significantly reduces the risk of capacity constraints, as the turbine suppliers are able to address their supply chain, and ensure that components and materials are available to meet the significant upswing in demand. Implementation of the plan would involve forward contracting for the supply of turbines in order to guarantee this.

Setting up a local wind turbine manufacturing industry would also assist in supplying some or all of the necessary components.

For the aforementioned reasons and the large scale of the Plan it is expected that Australian wind turbine costs in 2011 will reduce to the current European costs of $AU2.2 Million/MW.

For the first 5 years of the Plan, the capital costs of wind turbines are expected to transition from the current European costs to the forecast 2015 European amount — $AU1.65 Million/MW. This is because it will require some time before manufacturers can ramp up production and for orders to be fulfilled in Australia.

It is expected that the final 5 years of the plan will benefit from the influence of Chinese manufacturers on the market, either indirectly or directly (by purchasing from a Chinese wind manufacturer). Accounting for differing labour costs and adopting the 25% rule of thumb, capital costs are expected to drop to approximately $AU1.25 Million/MW in Australia.

The capital cost projections for the life of the project are summarised in Table 3.14. As explained in Section 3.2.3, installations begin on a six monthly time frame and take a year to complete. Note that the costs of transmission infrastructure is not included in these figures as it is presented in Part 5.

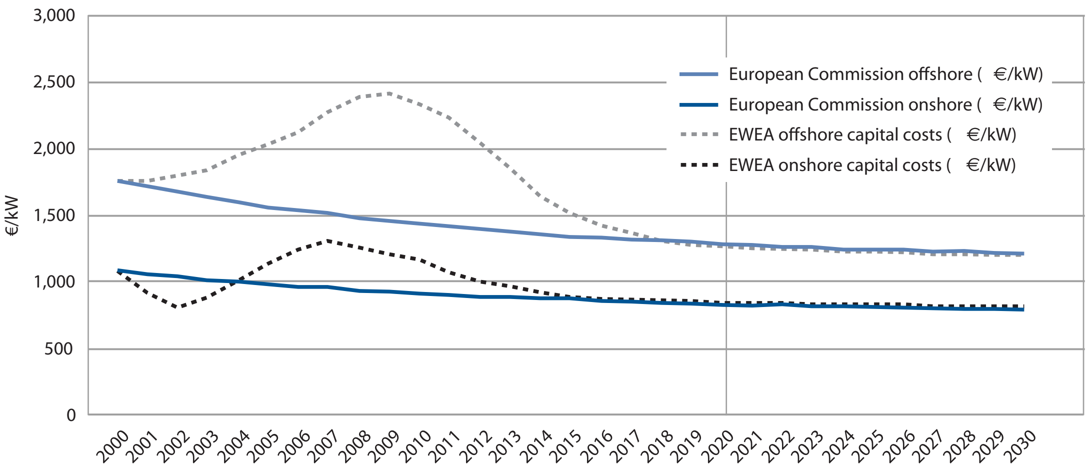
Thus, the **total cost** of 48,000 MW of wind power installed over 10 years to deliver 40% of Australia's electricity requirement in 2020 under the ZCA2020 plan is approximately **$AU72 Billion.**

See Appendix 3B for further details of wind power costs.

TABLE 3.14
ZCA2020 Projected Annual Capital Costs of Wind ($AU 2010 prices)

Year	$Million/ MW	Constructed Capacity (MW)	Operational Capacity (MW)	Costs ($Million)
2011	2.2	1,250	2,000	$2,750
2012	1.9	3,250	2,500	$6,175
2013	1.9	5,500	4,500	$10,450
2014	1.65	6,000	9,000	$9,900
2015	1.65	6,000	15,000	$9,900
2016	1.25	6,000	21,000	$7,500
2017	1.25	6,000	27,000	$7,500
2018	1.25	6,000	33,000	$7,500
2019	1.25	6,000	39,000	$7,500
2020	1.25	2,000	45,000	$2,500
2021			50,000	
			Total Capital Costs	**$71,675**

FIGURE 3.12
EWEA Onshore Costs Projection (€2006 prices)[103]



3.3 Modelling of the ZCA2020 Renewable Electricity Grid

Detailed modelling of electricity supply and demand on a half-hourly timescale shows that the specified 42.5 GW of CST and 50 GW of wind can meet 98% of electricity demand. This is outlined in further detail in Part 4. Initial sizing of the system was done based on monthly average energy availability data. At a later stage, more detailed modelling was used to test the system's performance. As expected, there are some short periods in which the wind and solar thermal with storage alone are unable to meet demand, so either backup is required, or extra solar or wind capacity would be needed. The tradeoff between backup sizing vs overdesign sizing has not been optimised, but the combination chosen has shown to be sufficient to meet 100% reliable demand.

Enercon Wind Turbine, Sweden[105]

3.4 Other renewable energy sources for energy security backup

Requirement for backup power. As described in previous sections, the geographic diversity and overcapacity of the proposed wind and CST installations will improve the system's ability to provide continuous baseload or dispatchable electricity. For example, there should be enough spare capacity in the grid to make up the 'slack', should one of the 3,500 MW CST sites receive several consecutive days of significant cloud cover, in which their molten salt reservoir becomes empty and unable to dispatch electricity.

There is the possibility of simultaneous cloud cover over several of the CST sites coinciding with a period of low wind and high demand. The kind of weather event which would cause this would be extended cloud cover over large areas of Australia, and this type of macro-scale weather front is easily forecast many days ahead of time. To completely ensure energy security under the plan, a system of biomass co-firing of the CST plants is incorporated, utilising only waste biomass. The proposed system is to incorporate a biomass thermal heater alongside the molten salt tanks at the actual CST sites. Biomass is burnt, and the energy used to heat the molten salt reservoirs, so that the existing steam power cycle, turbine and transmission can be utilised. This means the only extra expenditure is for the biomass heater, minimising the extra cost of the backup system.

Modelling of the proposed ZCA2020 Grid, detailed in Part 4 of this report, has shown that a combination of 5 GW of existing hydro capacity and 15 GW electrical equivalent of biomass-fired backup heaters will be sufficient to ensure reliable supply of electricity even at times of low wind and sun. Under the modelling, 5.5 TWh/yr is delivered from biomass via the CST plant turbines, and 1.1TWh is delivered from hydro.

3.4.1 Hydroelectric power to address supply peaks and store energy

It is proposed that existing hydroelectricity infrastructure be used to provide dispatchable electricity that can also be used to help fill the winter shortfall from the CST component. Changes in rainfall patterns are reducing the amount of hydroelectricity that can be relied upon, and opposition to the building of hydro power is increasing. Hence, ZCA2020 does not propose adding to existing hydroelectricity infrastructure.

In those areas of Australia where rain continues to fall reliably, hydroelectricity can play a peak supply role. On the Australian mainland, there is currently 5,195 MW of hydro power generation capacity [106] (including pumped storage hydro). The Basslink HVDC interconnector allows up to 630 MW of electricity to be exported from Tasmania to the mainland[107]. Allowing for seasonal availability and some run-of-river installations that do not have significant storage, it is expected that 5 GW of hydro generation will be available under ZCA2020 for helping to meet peak supply and winter shortfall from wind and solar.

In the modelling outlined in Part 4, only 1-1.5 TWh is required from hydro to meet demand during the key low-sun, low-wind periods. In 2008, 4.65TWh was generated from hydro on mainland Australia[108], meaning that there is extra stored hydro energy available if necessary. However, increased drought conditions may reduce this excess hydro availability.

3.4.2 Biomass — Co-firing with CST plants

It is recommended that biomass be used to fire CST plants when the solar resource is inadequate for consecutive days over several solar sites. This co-firing method has the benefit of eliminating the need to install more turbines, as combusting biomass can heat the molten salt — which would otherwise be heated by the sun — to make steam to drive the solar plant turbines. The only extra capital cost incurred would be a biomass-fired burner, a simple and mature technology. It is also a more economical option to heat the salt, which operates near atmospheric pressure, than directly boiling steam in the biomass heater, which operates at much higher pressure and therefore requires more expensive materials. The winter shortfall in power delivered by CST could also be addressed by increasing the CST capacity under the plan. However, using other forms of renewable energy generation adds resilience to the system and reduces the overall cost.

It is proposed that enough biomass heater capacity be installed to supply 15 GWe of the CST plants with backup. In conjunction with forecasting, this would be fired up in advance of large weather fronts that threaten to lower solar energy availability, providing extra heat to the salt tanks prior to the peak demand/supply event. These would be distributed across all twelve solar sites, but the optimum capacity at each individual site has not been determined. It is likely that far southern sites such as Mildura, and far northern sites such as Prairie (affected by monsoon clouds) would have a larger amount of biomass capacity than more inland, sunnier sites such as Kalgoorlie and Longreach.

Taking into account steam cycle efficiencies (45%) and parasitic energy requirements, 1 MWe of electrical output requires 2.5 MWth of thermal energy delivered from the molten salt system. Therefore 15 GWe of backup corresponds to 37.5 GWth of heater capacity. In consultation with current industry pricings and taking into account minor cost reductions associated with replicating the same biomass module across the sites without re-engineering, the cost of the biomass backup is estimated at $AU0.5 million per MWe electrical backup required[109]. The 15 GWe of biomass backup for the grid system will therefore cost an extra $AU7.5 Billion.

As shown in the modellling in Part 4, this backup capacity is better suited to being spread out across many solar modules, providing partial backup instead of full backup. That is, instead of providing a few Solar 220 modules with full backup to supply the 542.5MWth needed for the 217MWe turbine, it is proposed that a larger number of modules are supplied with partial backup. In this way, pre-emptive firing of the heaters can 'top-up' the salt tanks, and the backup heat is supplied to a greater number of turbines, as ultimately it is the turbine capacity that is required to meet electricity demand.

The majority of the plants to be built with backup will be built in the latter half of the CST rollout plan, reducing the upfront expenditure.

Biomass backup is also specified for the entire 4,475 MW of off-grid CST, at a cost of $AU2.2 Billion. As off-grid CST has to be more of a standalone system, it makes sense to provide full backup.

The 15 GWe of grid biomass would provide up to 7 TWh/yr of electrical energy, requiring 75 PJ of primary biomass energy (i.e. 75 PJ from biomass combustion), taking into account thermal losses of the heater.

The off-grid CST installations running at 72% capacity factor will produce 28.2 TWh/yr. 36 TWh/yr is the current gross generation from off-grid capacity, or 33.5 TWh/yr net generation. Therefore 5.3 TWh/yr of electricity will be met by off-grid biomass backup, requiring 19 PJ of biomass primary energy. The total CST biomass backup will require around 93 PJ of combusted energy from biomass (results rounded).

To demonstrate the feasibility of supplying this amount of biomass energy, the example of wheat crop waste is used to illustrate one option for meeting the biomass energy demand of 93 PJ/annum.

Biomass from wheat crop waste — one option

Australia's average annual wheat crop is 19.5 million tonnes[110]. Given that there is on average 1.8 kg of crop residue (stubble, husk) per kg of wheat grain[111], there is up to 35.1 million tonnes of wheat crop residue each year in Australia. With a calorific value of 17.1 MJ/kg[112] , this means there is a potential 'primary' energy resource of 600PJ/yr from Australia's wheat crop residue. The total backup energy required for ZCA2020 is only 93 PJ/yr or **15.5% of Australia's wheat crop residue**. This would leave plenty of crop residue to be left on the fields to improve the soil, using 'no-till' cropping methods. The 75 PJ for just the ongrid backup is 12.5% of Australia's wheat crop.

Taking into account the thermal efficiencies, this 93PJ/yr for on and offgrid would generate 12.3TWh/yr of electricity. A study by the Clean Energy Council[113] has assessed that there is 47 TWhe of end-use electricity available to Australia in the long term (by 2050 under the CEC scenario) from crop residue alone, with an additional 10TWhe available from urban waste, wood waste and non-crop residue agricultural waste. Based on this benchmark, ZCA end-use electricity from biomass requirements are 26% of that which is available to Australia.

Transport of bulk biomass — biomass pellets for greater energy density

Biomass is usually of a lower energy density than fossil fuels, so is traditionally seen as better suited to a distributed energy system, with small-scale, local energy generation reducing the need to transport bulky biomass long distances. In recent times, a technology known as 'pelletisation' has become widespread in North America and Europe. Woody biomass (e.g. woodchips and/or crop waste) is pressed and extruded into pellets or briquettes, which have a higher energy density and a lower moisture content, making transport and storage more economical[114]. The product is commonly referred to as 'wood pellets', but crop wastes are regularly used to manufacture them as well as wood waste. Wood pellets are used for domestic, commercial and industrial purposes in North America and Europe. The 2005 global wood pellet market demand was estimated to be 30 million tonnes[115]. In contrast, the 92 PJ/annum CST backup only requires 5.3 million tonnes of biomass pellets. These would be transported by rail to the solar sites.

The transport of 5.3 Mt/annum of pellets by rail is a small task by comparison with exports of coal at the port of Newcastle, the world's largest coal export terminal, which is currently running at 92.8 Mt/annum, and is expected to expand to 133 Mt/annum by 2011[116].

Small scale pelletisation plants, which are commonly used in Europe and North America, can be set up in areas where there is significant crop waste resource. The pellets will be transported through the existing and upgraded rail system to the CST plants, where it can be stored in bunkers until required. 2,500 tonne trains, each consisting of 100 x 25 tonne wagons, would be used in the late summer / early autumn to transport pellets from the pelletisation plants to the bunkers at the CST plant sites. The trains would then be placed on standby locally at the CST plants over the critical winter period, where there may be a need for biomass co-firing in order to continue seamless operation of the electricity supply system. The electricity requirements for this transport will be small compared to the rest of transport activity in the economy, but it should also be noted that this haulage task will be taking place over the summer/autumn period where there will be excess energy availability from wind and solar.

The pelletisation of the 5.3 million tonnes of waste in 5 months over summer/autumn, would require 150 small scale pelletisation plants with a capacity of 10 tonnes/hr, operating 24 hours a day during the period. These would be set up in large agricultural areas, and could be either allocated to a single farm, or share the tonnage from several farms.

Cost. From industry sources, a 10 tonne/hr pelletisation plant would cost $AU8.3million[117].

The total cost for 150 crop waste pelletisation plants would be $AU1.25 billion

3.4.3 Biogas for industrial methane supply

Currently, gas use in industry is primarily for heating purposes, which can be replaced with electric heating, reactive processes and direct solar co-generation (as shown by various examples in this report). There are certain industrial processes where gas is used for its chemical carbon content, i.e. making synthetic chemicals. While this is a very small amount of total gas use, it is demonstrated that biogas could meet this demand as one alternative to conventional fossil fuel gas. This is not the only way that chemical carbon requirements could be met, it is just one example.

In the ZCA2020 plan, an allowance of 50 PJ/annum has been made to supply a small amount of methane from biogas. Methane is used as a feedstock for some chemical production (of methanol, for example).

Preliminary costing for supplying this small amount of bio energy is based on European bio energy projects. In Germany, a single biogas plant is being installed at a cost of 10 million Euro €, with a capacity of 228 TJ/yr biomethane production[118]. Scaling up this kind of facility to supply 50 PJ/yr of bioenergy for ZCA would require $AU3.5 Billion of investment (using AUD/EUR ForEx rate of 0.6). This final number could be investigated in more detail, taking into account economies of scale and different configurations for biogas production, but, as bioenergy is a minor part of the ZCA2020 proposal, it is simply assumed that $3.5 billion is a conservative allowance for this part of the plan.

3.5 Industrial Processes

While the full changes required in the Industrial Sector to reach zero emissions will be covered in full depth in the separate Industrial Processes report, this section shows some examples of how major industrial facilities can be integrated with renewable energy. Heating loads currently delivered by natural gas and other fossil fuels can be delivered by renewable electricity, while solar thermal co-generation can provide both electricity and direct heat, saving on costs significantly. It is even feasible to use more efficient modern Direct Iron Reduction combined with biomass gasification to produce steel, replacing metallurgical coking coal.

3.5.1 Electrification of heating loads

36% of all natural gas consumed in Australia is used by industry; this makes it the largest consumer. Natural gas is used in a multitude of processes, a large portion being heating applications and incineration [119].

Industrial heating processes can be divided into 3 classes: low-temperature (to about 400°C), medium temperature (between 400°C and 1150°C), and high temperature (beyond 1150°C). Low temperature applications can include baking and drying, medium temperature applications include annealing or heat-treating, and high temperature applications include steel making, welding and preparation of chemicals[120].

For each gas application there is an available electrical substitute. Electrical heating methods have advantages over other forms of chemical combustion in regards to: precise control over the temperature, rapid provision of heat energy, and ability to achieve temperatures not achievable through combustion. Electrical heating applications are also cleaner and quieter, with limited heat by-product when compared to combustion, and therefore can be installed anywhere in a plant. They do not produce flue gases, which lose 20-30% of heat in combustion processes. Methods of electric heating include electric resistance heating, induction heating, electric arc heating and dielectric heating.

Electric resistance heating

Electrical resistance heaters work by forcing a large current through a small wire. The resistance in the wire generates heat. The technology is advantageous as it is low cost, has a low temperature coefficient of resistance and uses readily available materials. The process is extremely efficient, approaching 100%, making it an attractive alternative for high temperature applications[121]. Electric resistance heating can be used to heat space, or in industrial furnaces using forced convection to heat to temperatures greater than 650°C. Alternatively electric resistant heating can be used in an immersion heater to heat water or generate steam for processes[122].

Electric arc heating

Electric arc heating is generally used in the melting of scrap steel, the production of phosphorous, aluminium and other metals. The technology generally uses three electrodes. An arc forms between the charge material and the electrodes. Heating of the material occurs through two methods; by the charge passing through the material and also the radiant energy created by the arc. The electrodes are automatically raised and lowered, regulating the system to maintain constant current and power whilst the charge is melting. Electric arc heating greatly reduces the specific energy per unit weight required to produce steel in comparison to combustion technology. It also has the ability to vary production, and rapidly stop and start, allowing the plant to respond to varying demand. This degree of control is not available with blast furnaces, and therefore a reduction in energy use is also seen here.

Induction heating

Induction heating is a non contact heating process. It works by sending an alternating current through the coil, to generate a magnetic field. When a work piece is placed in the coil the magnetic field induces eddy currents. This generates precise amounts of localised heat.

The technology has been used in industry since the early 1920s, and advances in solid state technology have made induction heating a remarkably uncomplicated, cost-effective heating method for applications which involve joining, treating, heating and materials testing[123].

Dielectric heating

Dielectric heating is also referred to as radio frequency or microwave heating. It is used to heat materials that are poor electrical conductors. The heat is generated from within the material. This heat can be created in asymmetrical and polar molecules. When a changing electric field is transmitted through the material the molecules will try to align themselves with the field, causing them to move and rotate, and therefore collide with neighbouring molecules, generating heat. Currently the technology is used in industry for welding plastic pipes, vulcanising rubber, and many other applications[124].

Supercritical water oxidation (SCWO)

The treatment of organic waste in industry is usually completed using an incineration process. The purpose of incineration is to remove organic materials and substances from industrial waste through a high temperature combustion mechanism that converts the waste into ash, flue gases and particulates. The flue gases need to be cleaned of pollutants before release into the atmosphere. In most applications in industry natural gas is used as the fuel for combustion, however alternative technology such as SCWO can be used as a cleaner technology.

SCWO operates at pressures and temperatures above the critical point for water[125]. In this state, there is no sharp boundary between gas and liquid phases. Water, oxygen, CO_2 and organic compounds act as a single phase therefore facilitating a complete reaction. Operating under these conditions the destruction and removal efficiency rate for most wastes is 99.99%[126]. SCWO has proven to be more reliable and more robust than traditional combustion techniques[127]. Currently the technology can be used to treat numerous contaminants, from wastewater to aromatic hydrocarbons and it has the ability to treat sludges, paints, synthetics, explosive, agricultural products and many more[128].

3.5.2 Case-study: Conversion of Industrial facility to solar thermal

The following case study provides an in-depth analysis of the feasibility of powering an alumina refinery directly from a nearby solar thermal facility, modified to provide both the heat and electricity requirements for the refinery as with conventional industrial cogeneration systems. The analysis proved successful; showing that 4 modified Solar 220 plants and 1 unmodified plant could provide the refinery with the required steam and electricity. The project has a 9 year payback period and a Return on Investment of 25.2% making it an environmental and economically beneficial option.

The world's largest producer of primary aluminium, United Company Rusal, recently published a public submission for the Australian Government's energy white paper. Specifically, the submission highlighted the company's vulnerability to an Emissions Trading Scheme (ETS), and the economic impact an ETS would have on the viability of the alumina refinery. As part of the submission, the energy types and requirements used and needed at the plant were outlined. These requirements were used in this case study and to formulate an economic case to modify the plant, using Solar 220 technology to run the plant, eliminating the economic effects and liabilities associated with an ETS. Like any thermal power system, solar thermal power can be run as co-generation to supply both heat (via steam) and electricity with adjustments to the steam power cycle system, independent of the solar field/molten salt part of the plant.

The plant currently utilises energy from three separate sources: coal, electricity (albeit via coal) and gas. Coal is the largest energy input and is required to meet the large steam requirement; high quality steam (5000kPa, 270ºC[129]) is necessary to operate the bauxite digesters. The next greatest energy requirement is from the gas needed to fire the alumina calcination kilns, at temperatures in excess of 1100ºC. The electrical requirement supplying auxiliary plant demand, although constituting the smallest component of the plant's energy use, is still significant. As outlined in the submission, these sources of energy will be affected by an ETS, which will ultimately affect the viability of the project. In this case study, modifications are proposed which

Queensland Alumina Refinery at Gladstone[129].

economically divorce the refinery from the liabilities of the ETS, and will allow the refinery to maintain a competitive advantage in a carbon-constrained economy.

In the proposed plant modification, the steam requirements are to be met by co-generation power plants, and the gas requirements replaced by electricity. Co-generation of steam and electrical power is a proven technology, and it is well established that large efficiency gains can be achieved by implementing such a system; energy efficiencies of up to 85% have been recorded[130]. The gas requirement in the kiln is to be replaced by electricity. In most cases, the choice between electric and gas-fired power is economic, since most processes can be carried out equally well with either of these power sources[131].

The modified energy requirements were calculated based on the current energy needs. An energy grade function of 0.913 for natural gas[130] could be used to determine the electrical energy requirement, for an electrically fired kiln. However, a value of 1 was used in the calculation, as this is a more conservative estimate. Similarly, a conservative estimate of the steam energy requirement was determined, by assuming a 90% conversion from the coal energy to steam energy[132]. The use of these conservative figures will over-estimate both the electrical and the steam requirements for the modified plant.

A back pressure turbine was determined to be the most suitable co-generation option[132]. A back pressure turbine discharges a portion of steam into a pressurised piping system that can be used for process heating, whilst the remaining steam is converted into mechanical energy and used to run a generator also providing electricity to the plant. An electrical efficiency of 25% and thermal efficiency of 60% are regularly recorded[132]. The steam requirements for the plant (i.e. steam at 5000kPa and 270ºC) were used to determine the output conditions of the back pressure turbine. It was calculated that a back pressure turbine with a 15% electrical efficiency would be required to ensure that the output conditions were appropriate for the bauxite digesters. Based on this, the Solar 220 designs[133] were modified to include back pressure turbines (with the appropriate steam output conditions and electrical conversion efficiencies).

It was determined that four Solar 220 plants would be able to meet the total steam requirements, and 61% of the electrical requirements, of the entire processing facility. A single further unmodified Solar 220 (with no back pressure turbine) would be sufficient to meet the remaining electrical demand, and would even generate a small excess, which could be exported to the grid. This modification was therefore found to be technically feasible.

An evaluation of the modification was then performed to determine the economic viability and feasibility of the conversion. It was assumed that the modifications could be treated as a stand-alone project, whereby the revenue delivered by the project is realised by the offset of energy costs, delivered as a result of the modification. The revenue equivalent was determined by taking current treasury prices for the commodities used[134], and included the current wholesale (rather than retail) price of electricity. The capital expenditure for the project was taken from the Sargent and Lundy report[133], as were the operation and maintenance costs. It was assumed that the inclusion of back pressure turbines (as opposed to high efficiency turbines) would not affect the capital cost of the Solar 220 plants. In reality, the capital cost would be less, due to the use of smaller turbines with lower efficiency, however as a conservative measure, the unmodified Sargent and Lundy figures were used.

Utilising all the economic parameters, a cash flow analysis was performed and the internal rate of return, payback period, and net present value of the modifications were determined. A discount rate of 8% was deemed reasonable and the capital was assumed to depreciate in flat line manner over 10 years. The capital was assumed to be spent over the commissioning period of the plant, with the Solar 220 plant constructed over 2 years[133] and an economic life of 30 years[133] was also assumed. These figures indicate that the modifications have a Net Present Value of over $AU430 Million, and will provide a return on Investment of 25.2% and have a payback period of 9 years. The internal rate of return for such a project would be 10.5%. The project is therefore economically feasible in the current economic conditions. The introduction of a carbon price following this modification would have limited impact, and would in fact increase competitive advantage, over refineries which did not make such modifications.

With reference to Appendix 5 — Industrial Case Studies

3.5.3 Zero-emissions steel smelting

This section details the technical changes required to convert iron and steel production to a zero-emissions process, using the existing technologies of Direct Reduced Iron (DRI), and syngas produced from waste biomass. A detailed economic analysis has not been carried out as with the Alumina case study, however given that DRI processes are competitive overseas, it is expected that with appropriate policy measures, this zero-emissions process would be economically viable. The extra energy requirements for the process will be another 3.3TWh of electricity (1% of total ZCA2020 electricity demand), and 72PJ of gas, which could be provided through the gasification of 15% of Australia's wheat crop waste. This displaces 111 PJ of coal currently used for iron smelting.

Australia currently produces 7.86 million tonnes of steel per annum[135]. The method of steel making in Australia utilises the blast furnace[136], in which iron ore and coking coal are fed into a furnace to produce (liquid) pig iron (iron making). The pig iron is then fed to either a Basic Oxygen Furnace (BOF) or an Electric Arc Furnace (EAF), which reduces the carbon content, to produce steel (steel making). In Australia, the vast majority of steel making occurs in a Basic oxygen furnace. This is summarised in Table 3.15.

TABLE 3.15
Current Australian Steel Production by pathway and source (million tonnes per annum) [135,136]

	Recycled Steel	Virgin Iron	Total
Electric Arc Furnace pathway	1.4	0.35	1.75
Basic Oxygen Furnace pathway	1.22	4.89	6.11
Total	**5.24**	**2.62**	**7.86**

The blast furnace process relies on the iron oxides being reduced by the carbon, so unavoidably produces CO_2. Typically 500kg of coke is require to produce 1 ton of iron[137]. The Australian steel making industry's current total greenhouse gas emissions are almost 13 megatons of carbon dioxide equivalent[138] per annum, a significant emission to address.

The steel industry is an important part of the Australian economy, employing 78,000 people over Australia, with an annual turnover of $21 billion[139]. In order to transition to a zero carbon economy, the Australian Steel Industry must adapt to more appropriate low carbon process routes. Alternatives do exist, and have proven to be economic internationally.

The process with the greatest potential to completely eliminate the process's reliance on coal, and the emission of carbon dioxide equivalents, is Direct Reduced Iron (DRI), with 68 million tonnes of steel being produced via this process in 2008, the leading producer being India with 22 million tonnes[140]. This technique relies on the iron being directly reduced by process gas; coking coal is not required. The Midrex® and HYL® processes are commercially available technologies for DRI production, the predominant process routes for the total worldwide production of DRI. Typically, the process would involve natural gas or syngas (synthesis gas; a mixture of carbon monoxide and hydrogen)[141]. As such, DRI is usually produced in regions where the availability of gas ensures the iron production remains cost competitive with coal-based iron smelting[141]. The abundance of coal, (metallurgical grade coal required for steel making) in Australia has resulted in the industry being dominated by the blast furnace.

The DRI production route opens up the possibility of steel making via biomass; the direct reduction process can be carried out using syngas from biomass[142]. This allows a carbon neutral process route for steel making. A European program, Ultra Low CO_2 for Steel making (UCLOS), has performed a detailed analysis of this process route[142]. There is no technological or economical impediment to building a plant that incorporates both biogas to syngas, and syngas to DRI. The production of syngas from biomass is well documented, and the production of DRI from syngas is similarly proven technology; the plants could effectively be operated independently. UCLOS has indicated that DRI can be produced at a cost of $45-$90 per ton (30 - 50 €/t). Traditionally, DRI prices have been around the $150 per tonne mark, however recently input shortages have seen it at up to $435 per tonne[143].

The DRI can then be fed directly into either Electric Arc Furnace (EAF), or a Basic Oxygen Furnace (BOF) and refined to steel. The EAF is preferred over the BOF, as it can handle charges of almost 100% DRI[144]. The BOF is limited in that it may only be able to process as little as 20% DRI, (with the remainder being molten iron from a blast furnace)[136]. If the BOF is to be eliminated from the process route, then the EAF is essential.

In order to meet current production under a DRI process route, 8.19 million tonnes the the Direct Reduced Iron must be produced, (based on 94% iron content of the DRI[144]). That is, 8.19 million tonnes of new iron making capacity, via the DRI route must be installed to replace current blast furnace operation. Additionally, 6.11 million tonnes of new EAF furnace capacity must be installed, to supplement the current installed capacity, to allow the DRI to be processed to steel. Based on the modified installed capacity, 71.6 PJ of gas is required (at a rate of 8.74 GJ per tonne[142]), replacing the coke. This requires a total 5.33 million tonnes of biomass[142], which represents 15.2% of the Australian Wheat crop residue. The new EAF and new DRI installed required an additional 3.34 TWh (2.69 TWh for EAF[145], and 0.66 TWh for DRI[146]). A summary can be found in Table 3.2 outlining the current usage, the planned usage via a DRI path and also the usage via a DRI path but with the additional requirements needed to meet the steel demands under the ZCA2020 Plan.

A relatively small quantity of carbon is required in the EAF to control the reduction potential within the furnace. Coke can be used, however it is already common practice to utilise synthetic graphite[147]. Traditionally, synthetic graphite has been made through process routes involving coking coal, however, it has been shown to be possible through biomass routes[148]. This carbon requirement is essentially a control mechanism that is, in essence, wasted in the process. Its usage is in the 10s of thousands of tonnes per annum[147] (as opposed to the millions of tonnes used in the blast furnace).

TABLE 3.16
Comparison of current and projected iron and steel processing capacities (per annum)

	Current	Via DRI Path	DRI Path with ZCA 2020
Blast Furnace (MT iron)	7.7	0	0
DRI (MT Iron)	0	7.7	10.05
EAF (MT steel)	1.75	0	0
BOS (MT steel)	6.11	7.86	11.7
Additional Electricity (TWh)	—	3.34	4.6
Additional Gas (PJ)	—	71.6	93.4

In Australia, the steel making industry generally revolves around an integrated mill. That is, the blast furnace and basic oxygen furnace, which produce the raw steel, are incorporated with casting, rough rolling, product rolling facilities to produce rolled steel products. The proposed process modification does not render the remainder of the mill invalid. Retrofitting existing mills would utilise the existing capital, infrastructure and workforce availability. As mentioned above, the biomass and steel making facilities can be considered to be independent. As such, the biomass and syngas facilities could be produced either as part of the onsite process, or piped from an offsite process.

The Australian steel making industry could be transformed into a zero emissions process. It would require transformation away from the emissions-intensive blast furnace toward a process utilising biomass-based syngas in the production of Direct Reduced Iron, and use of electric arc furnaces. Current production can be met competitively, using only 15% of the wheat crop residue, as an energy feed stock, and an additional 3.34 TWh of electricity.

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Part 4

Modelling of ZCA2020 Renewable energy supply

Contents

4.1 The ZCA2020 Grid Model

In order to assist with the Stationary Energy Plan, Jack Actuarial Consulting Pty Ltd (JAC) undertook to model, at fine time scales, the correlation of renewable resources (solar and wind) with demand.

To confirm that the proposed system can reliably meet the projected demand, modelling has been carried out on the proposed ZCA2020 generation mix on a half-hourly timescale, with data (insolation, wind and NEM demand) from 2008 and 2009.

The modelling results show that the 50 GW of wind and 42.5 GW of concentrating solar thermal (CST) alone can meet 98% of the projected electricity demand. The combination of existing hydro and biomass generation as backup at the CST sites can meet the remaining 2% of total demand, covering the few occasions where periods of low wind and extended low sun coincide. The model found that biomass backup equivalent of 10 GW(electrical) on the CST should be sufficient to ensure reliable energy supply in most realistic low wind and sun periods, however the ZCA2020 Plan has allowed for 15 GWe biomass backup for conservatism.

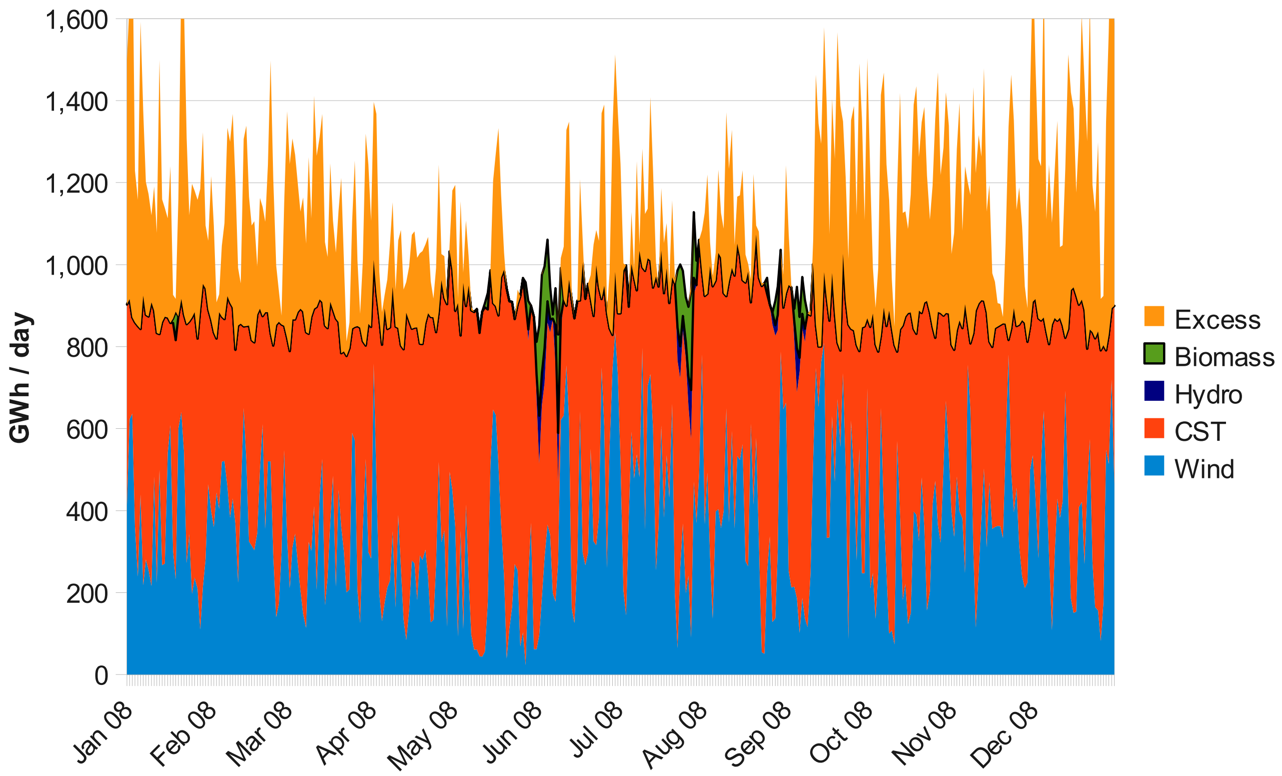
A further result of the modelling is that the ZCA2020 generation mix allows for elasticity of demand with more than 90 TWh per year of excess energy available from the specified renewable energy system.

Explanatory Notes for Figure 4.1 and Figure 4.2

Light Blue, [Wind] is electrical output from wind power. This is based on actual output from existing wind farms across southern Australia, published by the Australian Energy Market Operator, which has been scaled to represent the 50 GW of wind power specified in the Plan. Note that this model does not currently incorporate data from other regions, such as Western Australia and Queensland. As a result, the scaled wind output data has higher variability than would be expected under the proposed system and occasionally drops to a lower output value than would be expected from the total number of 23 wind sites proposed. If, as discussed in Part 3, the geographically diverse wind power can be relied upon for 15% of rated capacity at all times, total wind output would not drop below 7,500 MW, whereas in the model it actually does drop below this figure on occasions. Therefore this modelling is conservative, compared to what could be modelled if more region-specific data was available.

Dark Orange Shading, [CST] is the electricity dispatched from the CST plants. This is calculated from satellite derived solar data from each of the 12 ZCA2020 sites, sourced from the Australian Bureau of Meterology. The raw solar data has been used to estimate the electrical output from the solar thermal plants. This takes into account such values as the mirror field collection efficiency, steam cycle efficiency and other parameters. Underlying this data is the calculation

FIGURE 4.1
ZCA2020 Grid Model, 2008 (Results shown in daily averages, underlying model on half-hourly data)



of the amount of energy sent to the heat storage tanks each day for later dispatch.

Black Line, [Demand] projected electrical grid demand based on actual data from the National Electricity Market (NEM). This has been adjusted to take into account electrification of transport and industrial and space heating. The current baseline demand has also been reduced to allow for efficiency improvements. After these adjustments, the demand totals 325 TWh/year.

Light Orange Shading, [Excess] shows the excess electricity that would be available from the solar sites, but is not required by the demand.

Dark Blue Shading, [Hydro] shows electricity dispatched from the 5 GW of existing hydro capacity in periods of supply shortfall.

Green Shading, [Biomass] shows the electricity required from the biomass backup system in periods of low sun and wind availability. This is adjusted to reflect electrical output, though in reality the biomass system provides thermal energy to the heat storage tanks of the CST plants.

4.2 Detailed Overview of the ZCA2020 Grid Model

4.2.1 Introduction

This model enables assessment, at a high level, of whether or not the proposed generation mix is a plausible means of meeting the projected demand. It uses fine time scales to correlate renewable energy resources (solar and wind) with electricity demand.

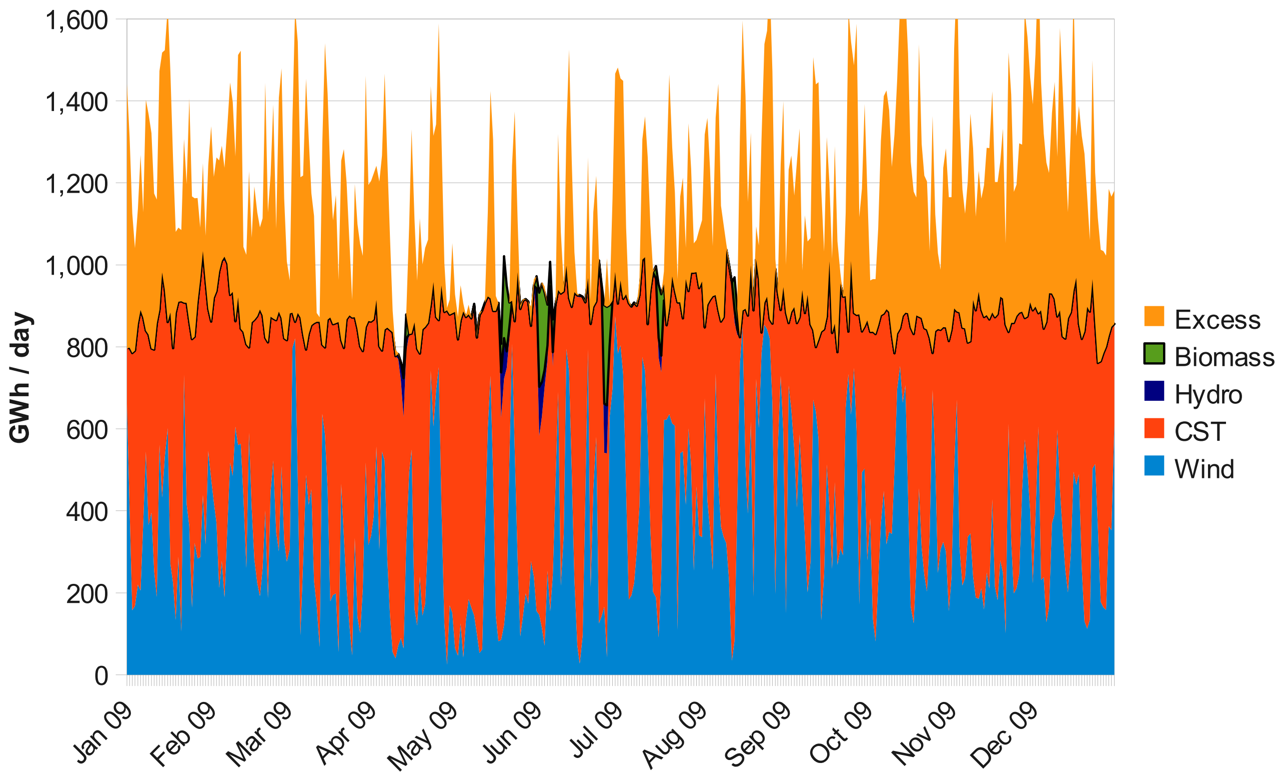
Although demand and supply have been modelled, no allowance has been made for transmission constraints or losses.

4.2.2 Proposed Generating Mix and Demand

The ZCA2020 Stationary Energy Plan proposes a stationary energy sector with the following components:

- 325 TWh projected annual demand for grid supplied electricity;
- 40% grid supply from 50 GW of wind generators installed at 23 sites;
- 60% grid supply from 42.5 GW of concentrating solar thermal (CST) power stations installed at 12 sites;
- 5 GW of hydro generation (the current mainland hydro capacity); and

FIGURE 4.2
ZCA2020 Grid Model, 2009 (Results shown in daily averages, underlying model on half-hourly data)



- Biomass fired boilers to supplement heating of the CST thermal reservoirs when required.

Critical aspects of the CST design are the solar multiple and thermal storage capacity. The standard CST design proposed by this Plan is a 217 MW (net) solar tower with a solar multiple of 2.6 and thermal storage of 17 hours.

The solar multiple is the ratio of the amount of power (electrical equivalent) that can be captured at peak insolation to the turbine capacity. Accordingly, a solar multiple of 2.6 in the context of a 217 MW plant, where 217 MW is the turbine rated peak output, could collect solar energy at peak insolation at a rate of 2.6 multiplied by 217 MW, giving 564 MW. A solar multiple greater than 1 allows thermal energy to be collected and stored for later use even if the turbine is operating at full capacity.

Thermal storage of 17 hours indicates that a thermal reservoir can store enough thermal energy to run the 217 MW turbine at full capacity for 17 hours. As a result, thermal storage for about 3.7 GWh(e) is modelled at each 217 MW CST plant.

The demand used here has a profile based on National Electricity Market (NEM) demand. The total demand has been increased to allow for electrification of transport and industrial and space heating, while the current grid demand has been reduced to allow for efficiency improvements, as explained in Part 2 of this report. Based on these adjustments the projected annual demand is 325 TWh.

4.2.3 Method and Characteristics of the Model

The model has the following characteristics:

- Daily global horizontal insolation (GHI) estimates derived from satellite images from the Bureau of Meteorology (BoM) are converted to estimated daily direct normal insolation (DNI) at each of the 12 ZCA CST sites.
- The daily DNI from the GHI is converted to an amount of energy available (for each CST site) either for dispatch or storage and spreads this through each day.
- A factor is applied for the mirror field as the heliostat field is not a perfect DNI receiver. This mirror field efficiency is based on the NREL Solar Advisor Model.
- NEM wind energy data is converted from 9 existing wind farms in South Eastern Australia to hourly capacity factors. Data from operating wind farms is publicly available for viewing and download.
- CST and wind sites are weighted with specified generating capacities of 50 GW for wind and 42.5 GW for CST (with associated solar multiples and storage)
- Potential output from solar and wind generators is compared to the projected demand.
- All available wind power and, if possible, sufficient CST power are dispatched to meet demand.
- Hydro, if necessary, is dispatched after wind and CST, to meet demand.
- Firing of the biomass boilers, to heat the CST thermal storage reservoirs, is triggered if these reservoirs, in total, fall below a specified level.
- All intermediate variables (eg demand, reservoir storage, wind generation, CST dispatch, unmet demand) are stored for later analysis.

For the purposes of this analysis the ZCA2020 generation mix has been used with data (insolation, wind and NEM demand) for calendar years 2008 and 2009.

Analysis of the resulting time series readily identifies whether or not the specified generation mix can meet the projected demand and, if not, the extent of the deficit and the 'reason' for the deficit. A subsidiary model fires biomass boilers which charge the CST thermal reservoirs. This backup thermal charging is done when total thermal stored energy drops below a specified level (e.g. 8 hours storage remaining). The biomass backup model is used to assess the boiler capacity and reservoir trigger required to meet the energy deficits identified in the main model. As the biomass will keep firing until the reservoir is back above the trigger level, this may result in short periods where biomass energy is firing even though hydro is not being dispatched.

4.2.4 Examples of Model Behaviour for Summer and Winter Periods

Summer — Curtailment due to excess supply

Figure 4.3 shows a selected period in February that demonstrates the 'normal operation' of the proposed generating mix. Insolation is high (typically in the range 50 GW to 100 GW) during the day. Wind is around 20 GW for much of the period, albeit with low periods during the middle of the day on both 13 and 14 February. With the high summer insolation, the reservoir is maintained at a high level, being charged during the daylight hours when insolation and wind added together significantly exceed demand and being drawn down overnight when there is no insolation and the wind does not meet demand. The reservoir energy varies in the period shown between about 580 GWh and 724 GWh. The upper limit, 724 GWh, is the storage capacity of the overall CST reservoir system. When this limit is reached, otherwise potentially harvestable energy is lost. This is evident in the flat section of the reservoir contents during the high insolation period on 12 February.

Winter — Insufficient wind, insolation and hydro, therefore biomass backup is used

The first few days of June 2009, shown in Figure 4.4, display a typical period of integration of wind, solar, hydro and biomass. First, with no allowance for biomass, there is unmet demand as wind and insolation are relatively low. The unmet demand, of some 25 GW on 2 and 3 June, is evident in the Figure 4.4 as the gap between the sum of the supply components (wind, CST and hydro) and the demand line. Note that the reservoir drops to zero on both 2 and 3 June.

FIGURE 4.3
Hourly dispatch with excess supply in February 2009

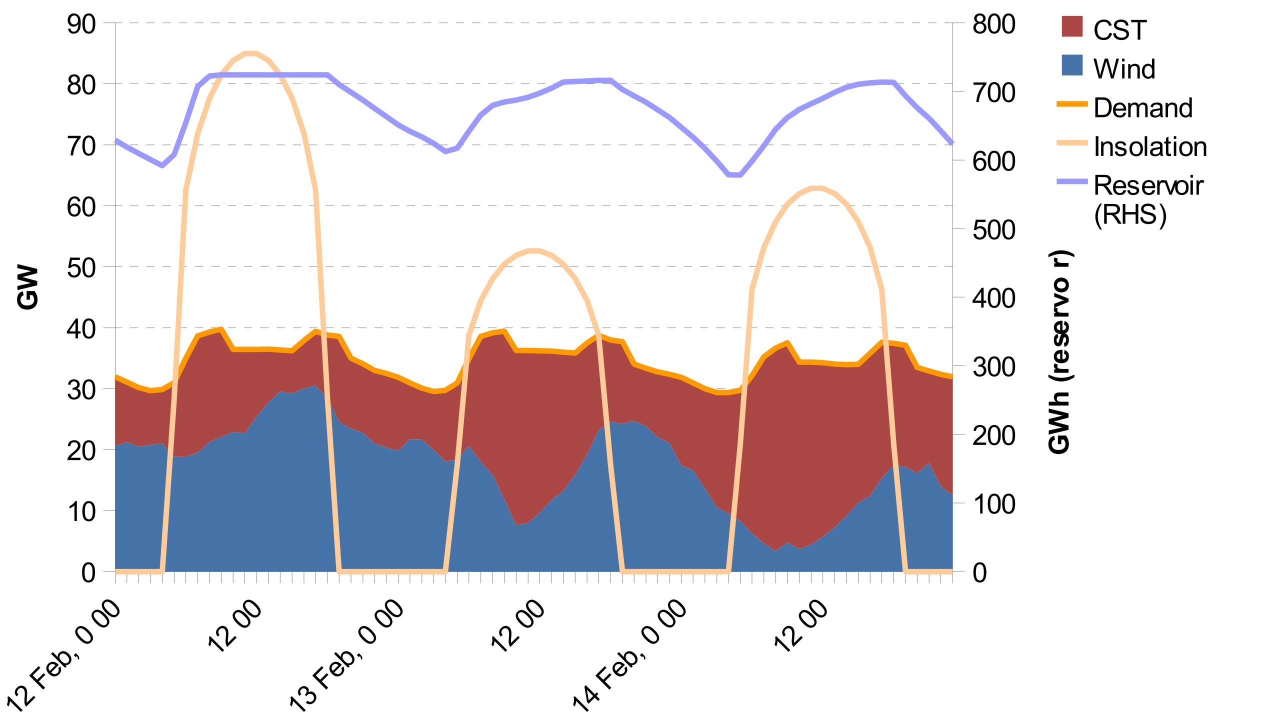


FIGURE 4.4
Hourly dispatch without biomass—June 2009

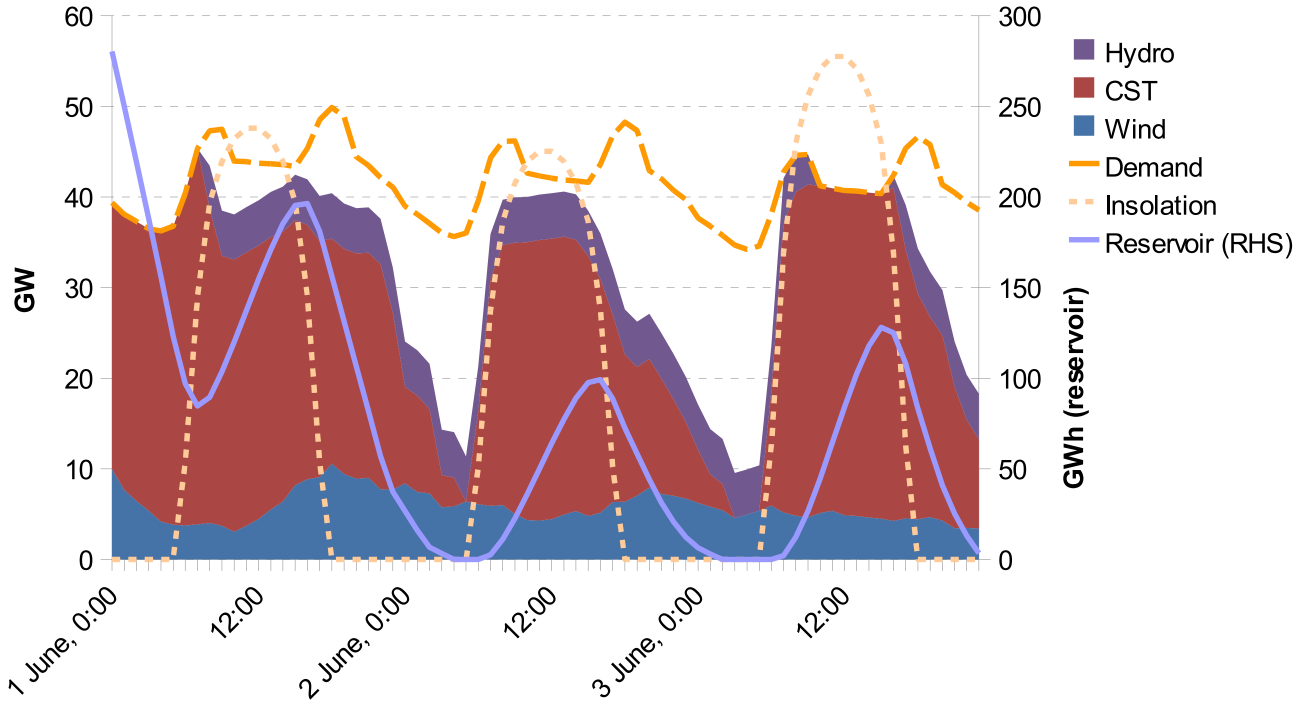
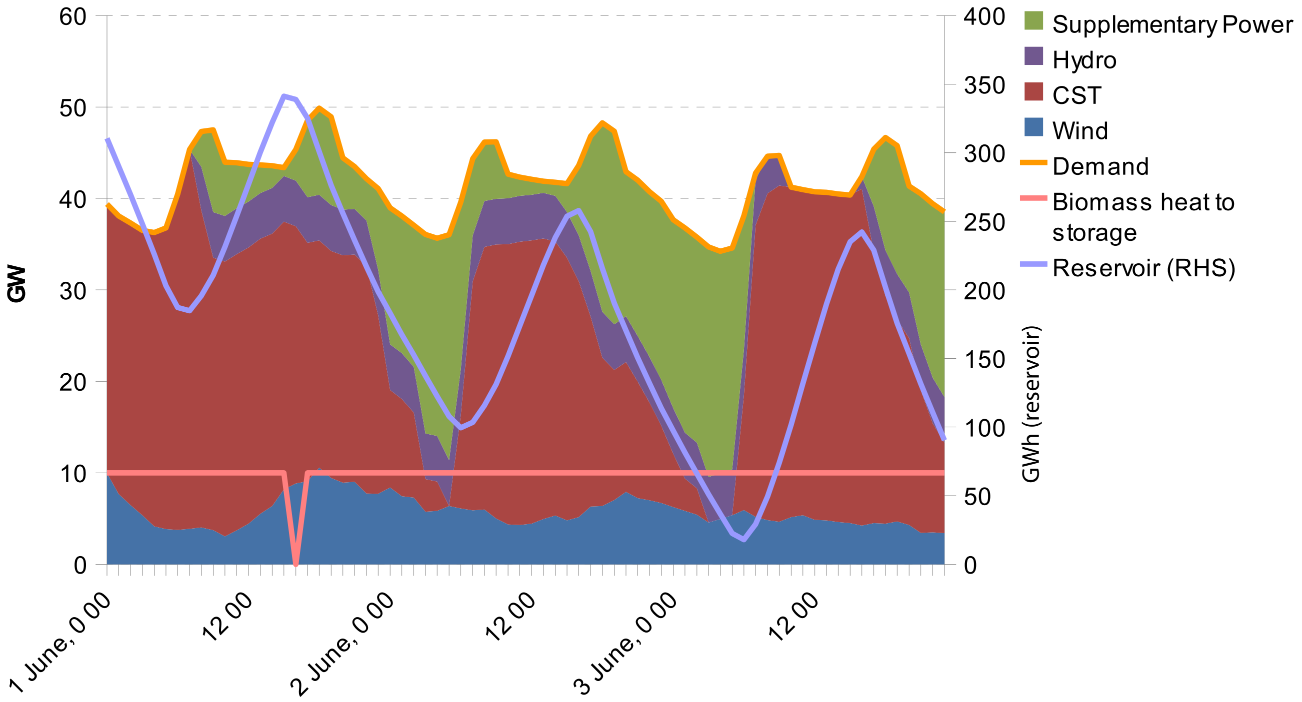


FIGURE 4.5
Hourly dispatch with biomass during June 2009



In this example the biomass is fired when the reservoir drops below 8 hours storage (about 340 GWh). Comparing Figure 4.5 to Figure 4.4 it is possible to see the additional supply possible from the CST plants due to charging the reservoir with biomass. During the times when the CST plants are using the reservoir to supply the supplementary power, the stored heat energy (RHS) can be seen to be decreasing. Biomass firing is a flat 10 GW(e) over the period apart from one hour on the morning of 1 June. It is clear that on the morning of 3 June the reservoir is nearly, though not in fact, exhausted. This situation would require the equivalent of 10 GWelectrical biomass heaters (25 GWthermal) distributed across around 25 GW(e) of the CST plants. The 25 GW(e) of turbines have partial biomass backup, not full backup.

Worst-case scenario

The period of lowest wind and sun over the modelled time period occurs on 27 June 2009 (early hours). This event arose after a single day of very low insolation (371 GWh on 26 June compared to next lowest for the month of 441 GWh and daily average for June of 690 GWh) and with very little wind overnight, dropping to almost no output. This low-wind situation would not be expected to actually eventuate in the proposed ZCA2020 grid, as geographical diversity suggests the system will have a realistic minimum wind output of 7,500 MW. (Refer to Section 3.2 for more information.) However, this example shows that using 15 GW of biomass backup is conservative: potentially only a smaller backup system would be required as the broader geographically diverse wind resource would reduce the variability of the wind output.

4.3 High Level Modelling Results

The outcomes of the high level modelling regarding the proposed generating mix (50 GW wind, 42.5 GW CST with 17 hours thermal storage) are as follows:

- The solar thermal and wind generating mix does meet about 98% of projected demand without biomass backup
- The generating mix can meet all of the otherwise unmet demand with hydro capacity of 5GW and biomass boiler capacity of 15 GW
- The generating mix sheds approximately 35% of total harvestable solar energy.

Monthly Supply Breakdown over 2008 and 2009

Figure 4.6 shows the monthly projections of supply breakdown if the generation model was used for data over the 2008 and 2009 calendar years. (Note that both the unmet and hydro components of this figure are too small to appear at this scale.)

There is a high level of consistency of the results between the two years, as shown in Table 4.1. Note that the CST values represent dispatched energy, not inclusive of excess energy that is discarded, mainly in the summer.

Curtailment is primarily the excess energy available from CST but also includes small components of biomass and wind. This arises from biomass being used to charge thermal reservoirs but then not being required or wind exceeding total demand. The values in Table 4.1 are for the case where there is 10 GW(e) of biomass capacity and this

FIGURE 4.6
Monthly supply breakdown over 2008 and 2009

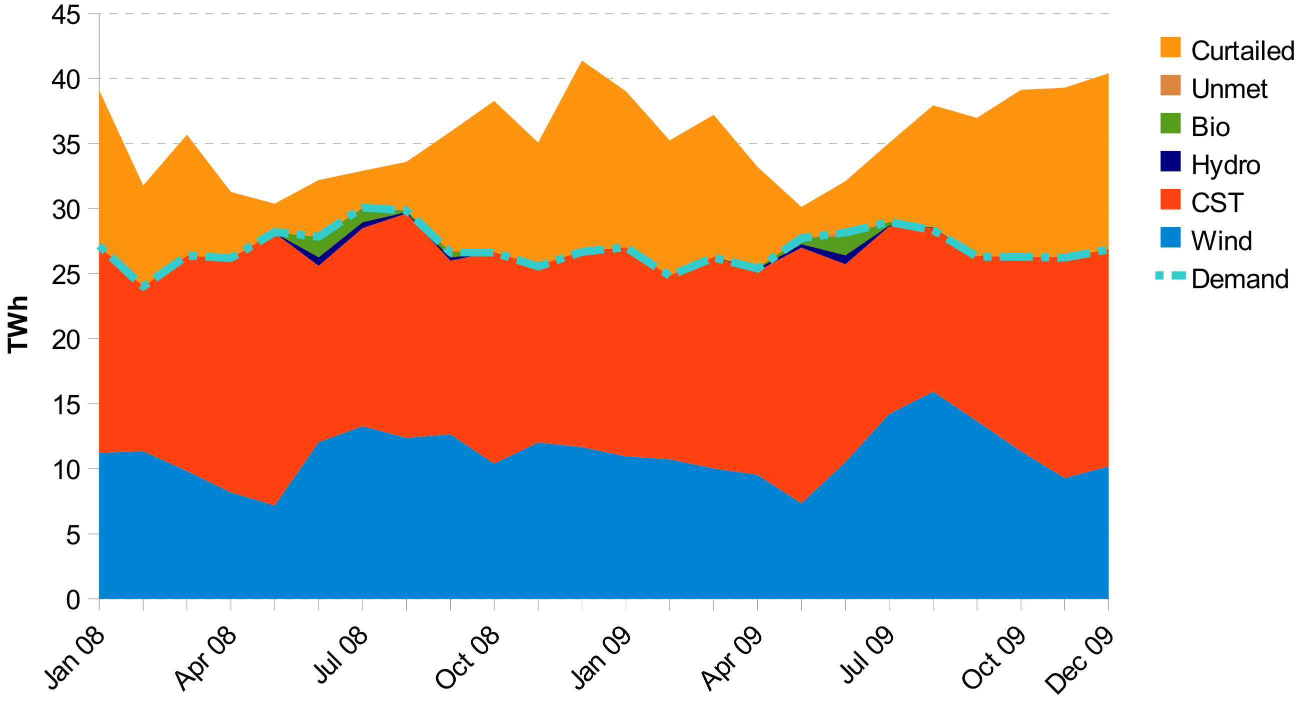


TABLE 4.1
Supply Breakdown Comparison between 2008 and 2009

Supply Component	2008 TWh	2009 TWh
Wind	132.2	133.8
CST	188.4	185.2
Hydro	1.5	1.3
Bio	3.4	2.7
Total	325.6	323.1
Demand	325.3	322.5
Unmet	0.0	0.0
Curtailed	95.7	116.6

is triggered when the reservoir, in total, is down to 5 hours of storage (5 multiplied by 42.5 GW, or 213 GWh).

With a biomass backup capacity of 15 GW and a firing trigger of 8 hours remaining storage, there is no unmet demand. Such early firing would be very likely if forecasting (particularly the poor wind) were allowed for. Various combinations of boiler capacity and boiler trigger were modelled. The results of this modelling, averaged over 2008 and 2009, are shown in Table 4.2 and Table 4.3.

The extra cost of using the earlier trigger for biomass firing (e.g. 8 hours of storage rather than 5 hours of storage) is high relative to the amount of energy supplied. Nevertheless it is, arguably, quite low in absolute terms. For example, considering the 10 GW(e) biomass capacity case, an additional 1.9 TWh(e) of biomass energy is used (5.7 TWh less 3.8 TWh from Table 4.3) for a decrease in unmet demand to 0.1 TWh from 0.2 TWh (from Table 4.2).

TABLE 4.2
Unmet demand (annual average) after use of hydro and biomass backup (TWh)

	Boiler Capacity			
Boiler Trigger (hrs of storage)	5 GW(e)	10 GW(e)	15 GW(e)	20 GW(e)
2 hours	1.8	0.9	0.4	0.2
3 hours	1.6	0.6	0.2	0.1
5 hours	1.2	0.2	0.0	0.0
8 hours	0.9	0.1	0.0	0.0

TABLE 4.3
Biomass energy (electrical equivalent) (annual average) (TWh)

	Boiler Capacity			
Boiler Trigger (hrs of storage)	5 GW(e)	10 GW(e)	15 GW(e)	20 GW(e)
2 hours	1.4	2.4	3.0	3.3
3 hours	1.7	2.9	3.5	3.7
5 hours	2.5	3.8	4.3	4.5
8 hours	3.8	5.7	6.4	6.8

4.4 Conclusions

The proposed generating mix would have been adequate to meet the modelled demand using 2008 and 2009 data. The demand modelled incorporates current demand, efficiency improvements and electrification of transport, industrial and space heating.

It appears that 17 hours of thermal storage is sufficient to allow for the absence of insolation overnight and for most cloud events that occurred during the period under analysis. To meet other deficiencies, 15 GW biomass backup is sufficient when combined with 5 GW hydro. With improved forecasting and demand management, a lower biomass capacity would likely be sufficient.

The seasonal correlation of supply and demand means there is excess energy in summer periods. Although the CST plants could run at around 75% capacity in the absence of supply constraints (meaning, if all that could be produced could be dispatched to meet demand), the overall capacity factor derived from the model is around 50%. So approximately one third of the total solar energy available is lost through curtailment, and this occurs mostly over the summer period.

4.4.1 Limitations and Future Work

The modelling has been done at a very high level and with several limitations. Many of these have the effect of making the model more conservative vs what would actually occur. Although the high level conclusions are deemed broadly valid, further research is necessary in order to develop a more sophisticated model and thereby further confirm the adequacy of the proposed stationary energy plan. Some of the limitations of the model include the following:

Transmission

The ZCA2020 Grid Model provides for substantial investment in transmission infrastructure. The present work has not allowed for the transmission capacity proposed by the ZCA2020 Project, rather it has assumed that there are effectively no transmission constraints. As the proposed demand of 325 TWh has been based on the output in the NEM, there is, accordingly and effectively, some allowance for transmission losses at similar levels to those in the NEM.

Insolation model

Satellite image derived daily global horizontal insolation (GHI) has been converted to half hourly direct normal insolation (DNI) using a correlation reported in the literature for the GHI to DNI conversion and a heuristic diurnal shape for the half hour allocation within each day. Given the large storage capacity assumed, the latter is unlikely to introduce errors or bias. The GHI to DNI conversion is thought to be quite reasonable on average however, further work is required to assess the appropriateness of its use in the context of the modelling reported here. It is possible that the daily pattern of DNI used may be sufficiently different from reality to introduce some errors.

Wind data

The wind data used is only from from existing wind farms, publicly reported generators within the NEM, only in South Eastern Australia. This Plan proposes a wider geographic spread than that covered by the NEM. Accordingly, it is likely that the current model overstates the variability (i.e. understates the benefits of geographic diversity) of power available from the wind component of the proposed generation mix.

Thermal losses

There is no allowance for thermal losses from the CST reservoirs. In fact, the CST modelling is very simplistic. However as the thermal storage is 99% efficient (there is 1% loss of stored thermal energy per day), the effect of this is considered negligible.

Demand management/smart grid

Other than that embodied in the NEM demand pattern, no demand management has been allowed for. Particularly with electrification of transport and space heating, there is a high capacity for short term demand management in the Plan. Accordingly, it is probable that the proposed wind and solar capacities are greater than required for a reliable and secure grid using active demand management.

Demand

Allowances for heating, ventilation, cooling, industrial and transport demands are high-level averages. Although the total energy demand modelled matches the demand proposed by this Plan, the pattern may be somewhat different.

Extended data timeframe

The two years modelled data offer a good insight as to the capability of the system as designed. Modelling over more years of data would improve the reliability of the results. This has been limited by the wind data only being available in recent years.

Part 5

Grid and Load Management—Creation of a National Grid

Contents

The ZCA2020 Stationary Energy Plan proposes a comprehensive upgrade to Australia's electricity grid to allow full utilisation of the distributed renewable energy network.

The centrepiece of this upgrade is the interconnection of the three main grids across Australia that supply electricity to consumers, to form one single "National Grid". This is achieved with High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC) transmission lines.

The upgrade also requires the reinforcement of interstate connections within the National Electricity Market (NEM) grid, to overcome existing capacity constraints.

Transmission lines are also specified to connect the new renewable energy sources to this grid.

The total cost of this upgrade is $92 Billion, which is considered an important investment in Australia's future energy security.

Whilst peak demand will be reduced by the electrification of heating and cooling, demand and supply will be managed across the network via a Smart Grid system.

The Engineering firm Sinclair Knight Mertz has reviewed the connection to the transmission network of the generation scenario proposed in the ZCA2020 Stationary Energy plan.

The review found *"that the transmission scenario proposed is technically feasible in terms of capacity and reliability. In addition, the proposed transmission uses mature technology with proven capability around the world."*

"The transmission concept is to use the existing network wherever possible and to develop major HVDC hubs in South Australia, Victoria and New South Wales (at Port Augusta, Mildura and Mt Piper respectively). The HVDC transmission will provide full access to the Solar Thermal generation located across a number of time zones. HVDC at voltage levels in excess of +/-500kV is used extensively throughout the world and is considered a 'mature' technology."

The location of the hubs has not been optimised but they are viable locations, given the "sources of generation (Solar and Wind) and the underlying transmission network. "

"Where HVDC is not practical ... 500kV HVAC transmission has been used (e.g. for wind farms across South Australia). 500kV HVAC is currently employed in both Victoria and New South Wales and is being proposed for Queensland."

"In addition, AEMO (Australian Energy Market Operator) has recently published reports entitled 'Network Extensions to Remote Areas: Parts 1 and 2'. In these reports, the concepts of major enhancements to the 500kV grid are examined, as well as using long-distance HVDC to connect remote renewable generation and upgrading interstate transmission capability. To some extent, these reports validate the transmission concepts proposed for the various renewable energy sources."

IMAGE: SPACEMAN[1]

"The costing of the proposed transmission connections has been carried out using figures derived from past projects but no formal evaluation has been made in this regard. It is recognised that the costs presented are very high—but not unrealistic if the development timeframe is considered. The costs could amount to $10B/year over a 10 year development horizon with much of the cost 'back-ended'."

— **SINCLAIR KNIGHT MERZ, 2010**

5.1 Upgrading the Grid

The ZCA2020 Plan calls for a nationally connected electricity distribution grid.

The creation of a national grid is an essential public infrastructure project that will make the supply of 100% renewable energy more economical and help ensure Australia's energy security into the future. The proposed interconnections and transmission upgrades allow full utilisation of the distributed renewable energy resources.

Currently three main grids supply electricity to Australian consumers[1]. The Plan calls for these three grids to be combined into one National Grid. The existing three grids are shown in the map in Figure 5.1.

- The National Electricity Market (NEM), which supplies the majority of the population, covering Queensland, New South Wales, Victoria, South Australia and Tasmania.
- The South West Interconnected System (SWIS), which supplies Perth and southern Western Australia.
- The North West interconnected system (NWIS), which covers the north of Western Australia and accounts for the added load from mining activities in that area.

In addition, there are some separate small grids to supply Darwin, Alice Springs and some intensive mining areas in Western Australia and west Queensland. The Plan does not, at this stage, propose linking these into the National Grid. Nonetheless we have included in the total system costs estimates for solar thermal plants and biomass systems to supply these isolated grids and "off grid" areas, but have not done the detailed modelling of where they would be located. This will be dealt with in a future report. More detail on the costings can be found in Part 7.

Creation of the new National Grid requires four main upgrades to the existing grid:

1. Extend the existing grids to enable transmission of power from solar and wind energy plants proposed in the Plan.
2. Interconnect the three main existing grids—NEM, SWIS and NWIS.
3. Upgrade connections within the existing grids to provide resilience and reinforcement
4. Introduce more centralised grid management including active load management via a Smart Grid.

The new high-voltage transmission links have been designed to connect into the key high-voltage distribution nodes of the existing grid. This means that the proposed upgrades

FIGURE 5.1
Australia's existing electricity grid

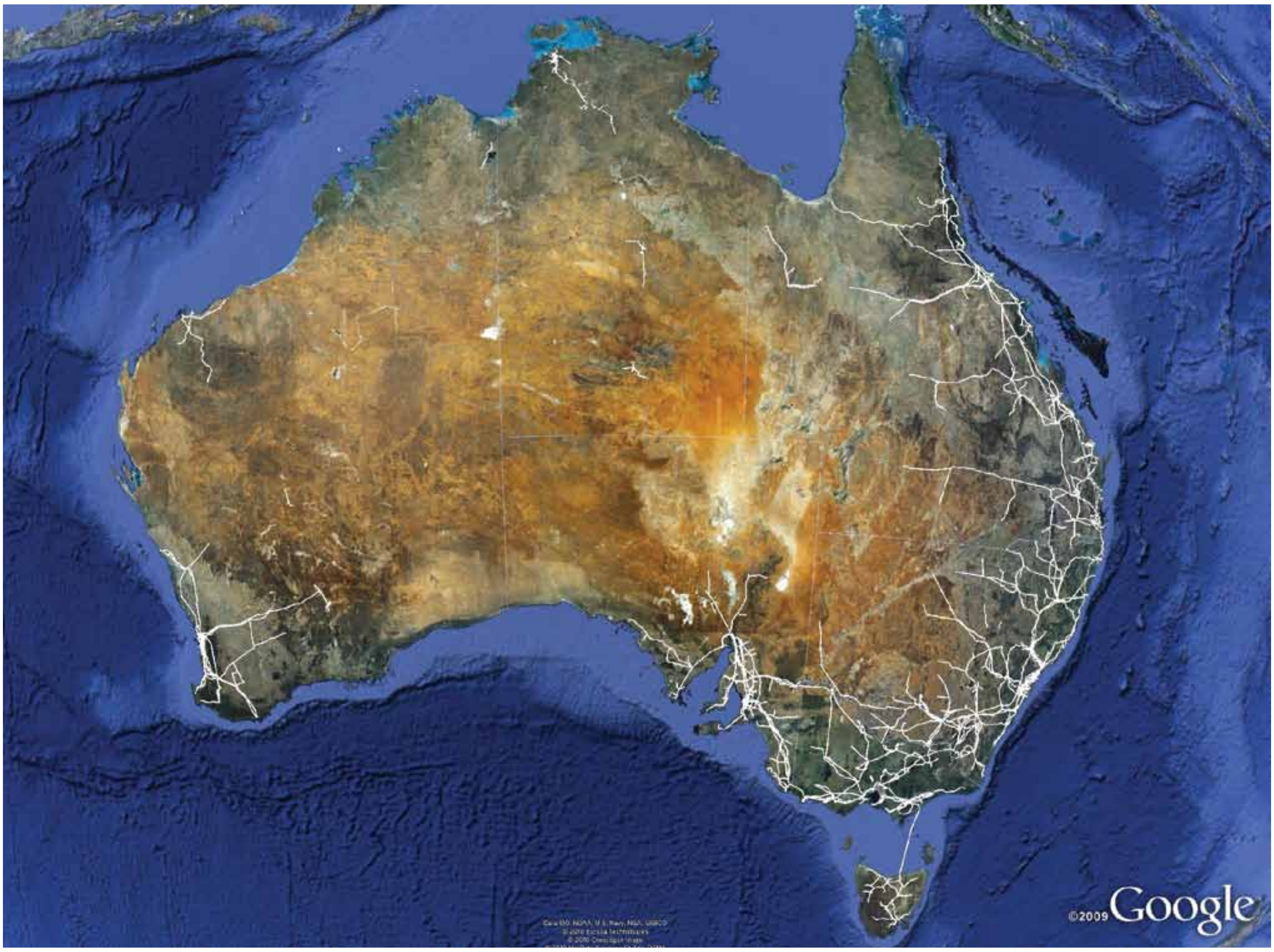
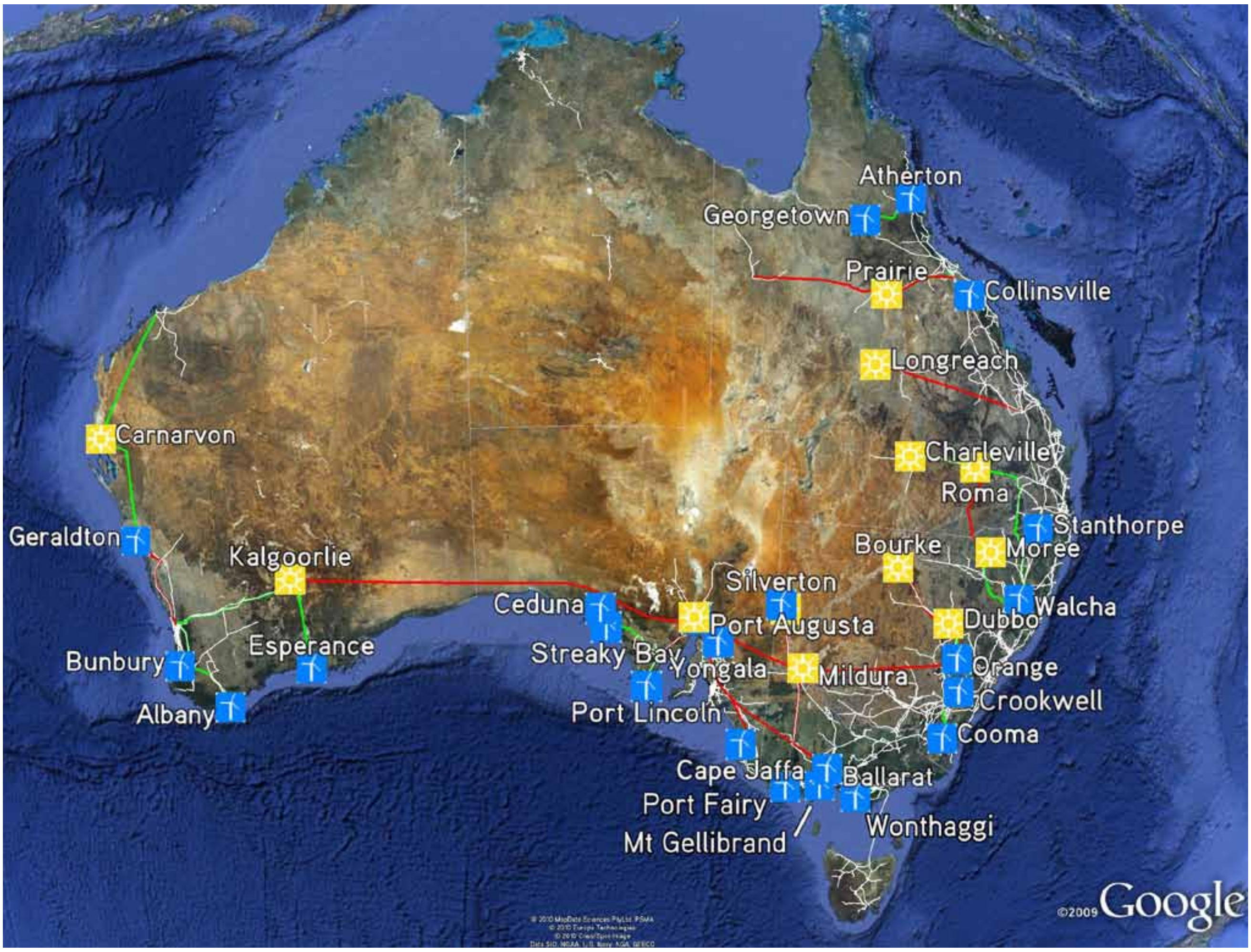


FIGURE 5.2
Proposed ZCA2020 National Grid
Solar sites are shown as yellow icons. Wind sites are shown as blue icons.
HVAC links are shown as green lines. HVDC links are shown as red lines



will easily merge with the present grid infrastructure and enhance the secure distribution of electricity around the country.

These new transmission links are shown in Figure 5.2 and Table 5.1, and discussed further in the sections below.

Table 5.1 shows all the proposed new transmission links, separated into categories of:

1. "Solar Plug-ins" and "Wind Plug-ins"—links required to connect the new renewable energy generator sites into the grid
2. "Grid Upgrades"—new links to improve the resilience and power flow through the existing NEM grid
3. "Inter-Grid"—links to interconnect the three main existing grids

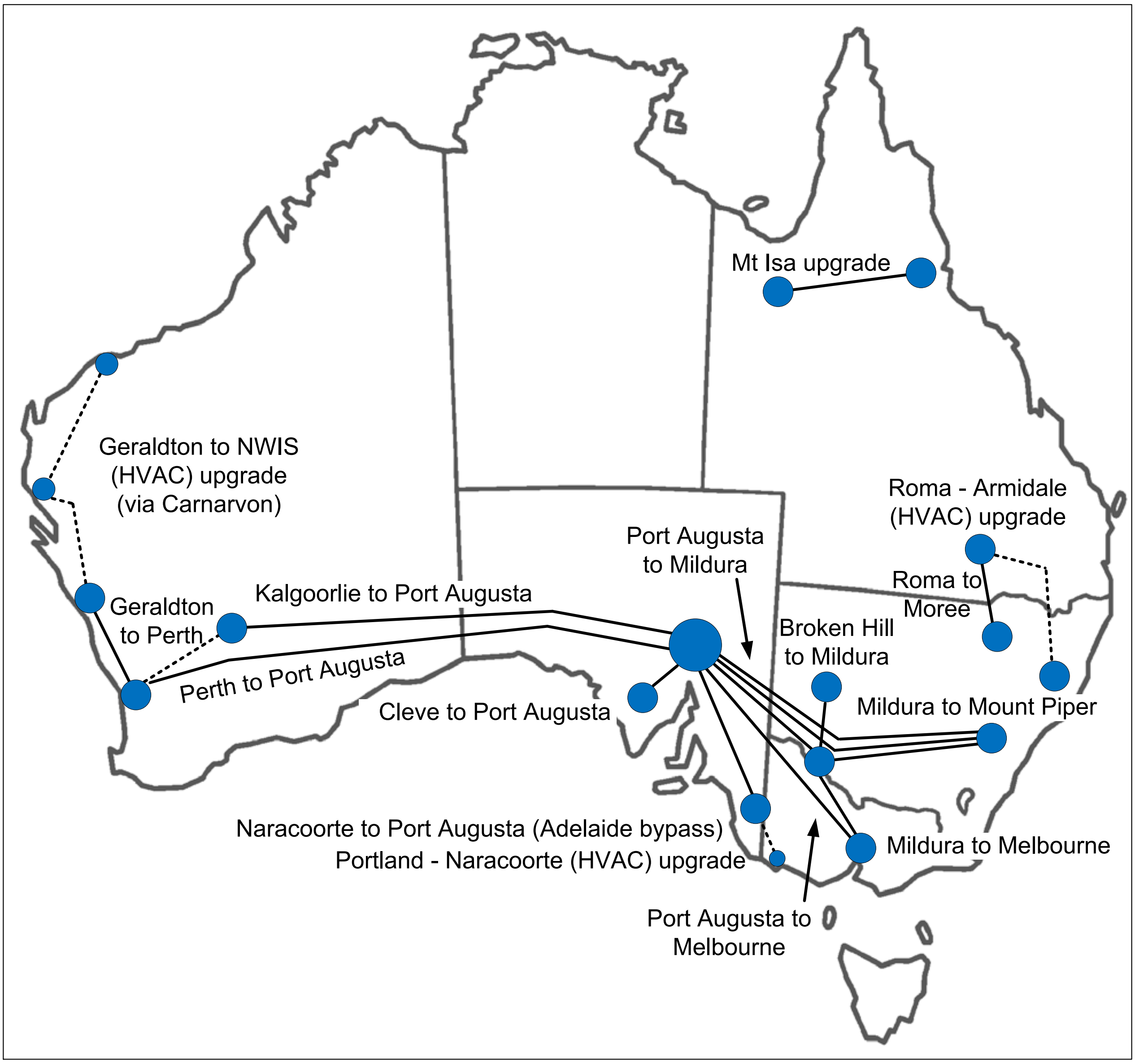
Role of High-Voltage Direct Current Transmission in ZCA2020 Grid

High-Voltage Direct Current (HVDC) is the most economical technology for long-distance bulk power transmission links. There are two parts to the cost of a link: cabling, and AC-DC converter stations (for inter-connections to the rest of the AC grid). HVDC links have relatively low cabling cost (approximately AU$1.2 million per kilometre [3]), and relatively high converter cost. Because of this, HVDC is more economical for long links, and HVAC for short links. However HVAC lines are also sometimes preferred for longer links, if multiple connections to the existing AC grid are needed along their length—this is because of the high cost of multiple converter stations.

The map of Figure 5.3 shows the proposed HVDC connections and long distance HVAC lines This shows how the HVDC lines are used for connection to remote solar generation sites and for grid interconnections.

The Plan requires the roll-out of some 23,300km of high-voltage transmission. These are summarised in Table 5.1 and explained below. Note that some corridors contain two parallel transmission lines, so the distances specified in Table 5.1 add up to less than 23,300km.

FIGURE 5.3
ZCA2020 proposed high voltage grid upgrades



5.1.1 Grid extension—connecting renewable energy plants into the grid

As outlined in Part 3, the ZCA2020 Plan proposes that solar and wind generators be located at sites chosen for optimal solar or wind resource, together with their proximity to major load centres and consideration of environmental and social factors. These sites need to be connected to the existing grid to deliver power to consumers. Table 5.1 shows the required grid extensions to connect the new renewable energy sources. The proposed capacity for each CST site is just less than 4,000 MW, so the transmission links connecting these sites to the grid are designed to carry 4,000 MW. The proposed capacity for wind sites is 2,000-3,000 MW, so the transmission links are designed to match.

The wind and solar sites at Port Augusta and the solar site at Mildura have not been specified with dedicated plug-in transmission links. This is because their final location would need to be worked out. However they are in close proximity to major transmission hubs, which are sized to meet the load from these generators.

5.1.2 Connecting NEM, SWIS and NWIS to form a National Grid

The creation of the National Grid (by interconnecting the NEM, SWIS and NWIS grids) will improve its resilience, by harnessing the geographical and energy supply diversity of the generators, and add redundancy (duplication providing alternate transmission paths in case of failure). A national integrated grid will smooth peak electricity demands across the geographical expanse of three time zones, whilst providing increased security of supply to consumers.

The two essential transmission projects to interconnect the NEM, SWIS and NWIS grids are:

1. The Western Australia-South Australia SWIS-NEM Connection - 2,146 km of 4,000 MW capacity HVDC. Despite the considerable length of this link, the estimated losses in worst case transmission scenarios would be six per cent. Another link via Kalgoorlie also serves as a connection point for the Kalgoorlie solar thermal power plant—1,586 km of 4,000 MW HVDC from Kalgoorlie to Pt Augusta, and 560 km of 6,000 MW HVAC from Kalgoorlie to Perth.
2. The SWIS-NWIS Connection - 561 km of 4,000 MW HVAC. This also connects the Solar Thermal plant at Carnarvon to the SWIS and NWIS grids. This has been specified as HVAC to allow plug-ins along the way, however the option of making this HVDC could be further investigated.

TABLE 5.1
Detail of ZCA2020 Transmission Lines

	Line name	Type	Length km	Power MW	Total Cost AUD$M
Solar Plug-ins	Carnarvon to Geraldton	HVAC	499	6000	$3,610
	Kalgoorlie to Perth	HVAC	560	6000	$3,895
	Broken Hill to Mildura	HVDC	262	4000	$1,936
	Bourke to Mount Piper	HVDC	567	4000	$2,293
	Dubbo to Mt Piper Direct	HVAC	249	3000	$1,220
	Moree to Armidale	HVAC	364	6000	$2,980
	Prairie Plug-in	HVAC	296	6000	$2,660
	Longreach Plug-in (direct)	HVDC	654	4000	$2,395
	Charleville to Roma	HVDC	311	4000	$1,993
Wind Plug-ins	Albany Plug-in	HVAC	430	3000	$1,643
	Esperance Plug-in	HVAC	363	3000	$1,487
	Geraldton to Perth	HVDC	440	4000	$2,144
	Bunbury Plug-in	HVAC	10	3000	$662
	Cleve to Port Augusta	HVDC	201	8000	$3,729
	Ceduna Plug-in	HVAC	327	3000	$1,403
	Yongala Plug-in	HVAC	125	3000	$930
	Port Lincoln Plug-in	HVAC	121	3000	$921
	Cape Jaffa Plug-in	HVAC	54	3000	$765
	Streaky Bay Plug-in	HVAC	269	3000	$1,267
	Port Fairy Plug-in	HVAC	61	3000	$780
	Ballarat Plug-in	HVAC	79	3000	$823
	Mt Gellibrand Plug-in	HVAC	56	3000	$769
	Wonthaggi Plug-in	HVAC	96	3000	$862
	Crookwell Plug-in	HVAC	86	3000	$839
	Dubbo-Orange-Mt Piper	HVAC	93	3000	$854
	Walcha Plug-in	HVAC	35	3000	$719
	Cooma Plug-in	HVAC	122	3000	$923
	Silverton to Mildura	HVAC	287	3000	$1,310
	Stanthorpe Plug-in	HVAC	98	3000	$867
	Atherton Plug-in	HVAC	62	3000	$783
	Collinsville Plug-in	HVAC	18	3000	$680
	Georgetown Plug-in	HVAC	272	3000	$1,274
				Subtotal, plug-ins	**$49,416**
Grid Upgrades	Roma to Moree	HVDC	417	4000	$2,117
	Port Augusta to Mount Piper	HVDC	1169	8000	$5,994
	Mildura to Mount Piper	HVDC	708	4000	$2,458
	Mildura to Melbourne	HVDC	544	8000	$4,533
	Port Augusta to Mildura	HVDC	461	4000	$2,169
	Port Augusta to Melbourne	HVDC	886	4000	$2,666
	Port Augusta to Naracoorte	HVDC	560	4000	$2,285
	Naracoorte to Portland	HVAC	216	6000	$2,286
	Roma to Armidale	HVAC	662	6000	$4,372
				Subtotal, grid strengthening & upgrades	**$28,879**
InterGrid	Mt Isa upgrade	HVDC	847	4000	$2,620
	Perth to Port Augusta	HVDC	2146	4000	$4,140
	Kalgoorlie to Port Augusta	HVDC	1586	4000	$3,485
	SWIS-NWIS Connection	HVAC	561	6000	$3,900
				Subtotal, national grid interconnections	**$14,145**
				TOTAL for ZCA2020 Grid	**$92,440**

Geographical Diversity

The increased geographical diversity of the new National Grid will have several major benefits for energy security:

- **Weather diversity:** For CST sites, the geographical diversity reduces the likelihood of extended cloud cover over several sites at the same time, and for wind sites it significantly increases the minimum reliable instantaneous power output available from the combined system.
- **Seasonal variability:** A mix of northern and southern latitude CST sites offsets the seasonal lows in solar radiation. The summer monsoon in northern latitudes is offset by high solar incidence in more southerly latitudes, and conversely, lower winter incidence in southern latitudes is offset by higher incidence in the northern latitudes during the dry season. Similarly, the seasonal variability between wind patterns along the southern coast and northern regions is minimised by the integration of all wind farms into one single grid.
- **Time differences:** The linking of CST plants in different time zones helps to extend the overall generation capacity of solar thermal. For example, Western Australian solar power can help to meet the early evening peak demand in the eastern states.

5.1.3 Increasing reinforcement and resilience within the existing grid

Network resilience is the ability of the network to continue providing service in the face of faults or unusual levels of demand. Network reinforcement is a term for additions to an existing network to improve its capacity or reliability.

Within the existing NEM eastern seaboard grid, there are significant capacity constraints on the interconnecting transmission lines, particularly between states.

The ZCA2020 Plan proposes upgrades to address these exisiting constraints. The upgrades are also designed to improve the flexibility and security of the network, by allowing capacity to ship significant power from one area to another. To maintain security of supply under the Plan, it is necessary to be able to readily send power from one region to another. This can help lower electricity costs by eliminating the need for localised peak generation units, such as gas power plants, as power can flow from a region of high reserve capacity to regions of low capacity and high demand. Under the Plan, due to the large wind and solar resource, and the gain from diversity, power generally is sent eastward. This contrasts with today's NEM grid where a net surplus of power is typically sent west to South Australia.

- **Portland to Port Augusta upgrade**: It is recommended that the existing 500kV transmission line from Melbourne, which terminates at the Portland Aluminium Smelter, be upgraded with an extension to Naracoorte in South Australia and then a HVDC line to Port Augusta. This will be achieved with a 560km 4,000 MW HVDC line between Port Augusta and Naracoorte, and continued with a 216km 6,000 MW HVAC line between Naracoorte and Portland.

- **Port Augusta to Hunter Valley (Mt Piper) link**: It is recommended that 1,169km of 8,000 MW capacity (2 x 4,000 MW) HVDC transmission line be built to allow wind and solar power generated in the west to be shifted east to supply the major demand centre in Australia (Wollongong—Sydney—Newcastle). The transmission line will run from Port Augusta via Mildura across South Western NSW to the existing generation hub in the Hunter Valley.
- **QLD-NSW import/export upgrade**: Currently the connection between the Queensland and New South Wales grids has a capacity of only about 1,150 MW. This is provided by the QNI and Terranora interstate connections [4]. However there is significant export potential southwards from Queensland (16,000 MWe of solar thermal and 13,000 MW of wind power). To allow greater flow of electricity between these two states, the Plan recommends a 417 km link of 4,000 MW HVDC from Roma-Moree and a 662 km link of 6,000 MW HVAC from Roma-Armidale.

5.2 Control of Supply and Demand

The creation of a national grid and the integration of country-wide renewable energy generators will require some management and control mechanisms for forward organisation of supply and demand correlation.

Under the current electricity system, baseload generators provide power for most periods of the day, however peakload power is needed for a few short periods when power demand increases significantly. A typical cause of these peaks is when air-conditioners are switched on simultaneously in mid afternoon in summer.

The ZCA2020 Plan combats this variation in demand both through system design and active load management, using Smart Grid technologies. The Plan also requires the active monitoring of country-wide weather events to choose the proportions of power supply source (wind, CST, biomass, hydro) utilised to maintain energy supply.

The Plan involves the retrofit and redesign of commercial and domestic buildings to minimise the need for heating and cooling, while also converting from gas heating to electric heat pumps. This will help to reduce peak energy demand and also allow for control over the timing of heating and cooling during non peak periods.

SmartGrid[5] is an umbrella term for a set of modern grid management technologies which can be combined to coordinate the control of demand and supply across a national grid. It is an information and control system, which can send information and commands from generation to load and vice versa. The term was developed to highlight the shortcomings of conventional grids, which provide very little real-time information to controllers and consumers, and hence are insufficient to deal with the emerging complexity of modern electricity networks.

5.2.1 Minimising Peak Demand

The ZCA2020 Plan involves a system design in which the overall extra generating capacity needed to meet peak demand is reduced relative to the current requirements. A major cost in the existing electricity system is the installed capacity needed to meet peak demand. Figure 5.4 shows the large difference between current average demand and the total installed capacity to meet the peak demand.

The ZCA2020 Plan makes these changes to the energy demand pattern:

- Reduction in total stationary energy demand, through building efficiency programs which reduce the overall need for heating and cooling.
- Conversion of gas heating to more efficient heat pumps, which reduces overall energy demand, while increasing total electricity demand. However, given that a large part of total current gas use is for industrial applications, which is a relatively stable demand, this reduces the variability (ratio of peak to average) of electricity demand.

In addition the electrification of heating, in conjunction with an active load management system, enables the deferral of heating and cooling load to smooth out peaks in demand. This significantly reduces the overall installed capacity required to meet peak demand, as the load is distributed across a longer time frame, flattening the instantaneous peaks generated when consumers turn on air-conditioners or heaters simultaneously. Deferral of electric vehicle charging also provides a form of load management.This is discussed in section 5.2.4.

A simplified presentation of the components of energy supply and demand is shown in Figure 5.4.

Here the total current annual energy demand (213 net TWh/y) is converted to an average power figure (24 net GW). The current installed capacity to meet maximum demand is 45 GW. The difference (21 net GW) is then considered power for meeting the demand for intermediate and peak loads only.

This is compared with the components that make up the demand under the ZCA2020 Plan. These components are:

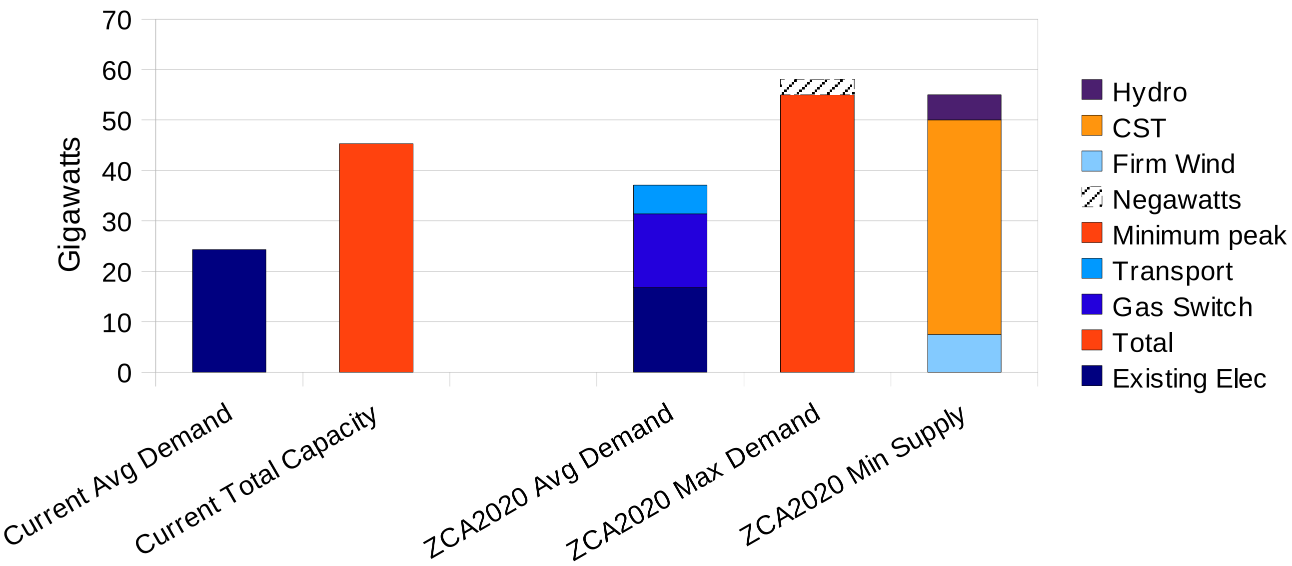
- The present average electrical energy demand, reduced by 30%, which is the projected contribution from energy efficiency programs and distributed solar PV generation. The annual average of this demand is shown as 'Existing elec' in Figure 5.4.
- The expected increase in average electricity demand due to the conversion of industrial gas applications to electricity (shown as 'Gas Switch').
- The extra average amount of electrical power needed to charge electric vehicles and for increased public transport (shown as 'Transport').
- The additional provision for meeting peak loads is initially assumed to be equal to that for the current demand pattern (21 GW on top of the average of 37 GW), but this is reduced by a 3 GW allowance for 'Negawatt' reductions in peak demand, to give an overall maximum demand of 55 GW.

With a normal wind output, there is a comfortable excess of installed generation capacity to meet peak demand. In the worst case scenario of low wind and low sun, there is a minimum of 55 GW reliable capacity. It is projected that 15%, or 7.5 GW, of wind power will always be available. The 42.5 GW of solar thermal turbine capacity can be called upon at any time, with up to 15 GW of this turbine capacity backed up by biomass heaters. The 5 GW of existing hydro capacity is also available on-demand.

Negawatts can be conceptually understood as real decreases in necessary installed generating capacity, due to real reductions in overall peak energy demand [6]. In the ZCA2020 Plan, Negawatts are achieved through energy efficiency programs which have the effect of lowering both overall energy demand and peak electricity demand, and the time shifting of loads due to active load management. Normally wind energy will operate somewhere between the minimum firm amount and the maximum peak output amount, so the reliance on Negawatts will only arise on a few occasions during the year. The economic incentive for these Negawatts is that they cost less than the extra installed generating capacity that would otherwise be required for only a few short periods in the year [7].

It should be stressed that this is only a simplified representation of the real peak and non-peak demand requirements of the system. Future work needs to be conducted to determine the actual peak demand expected in the proposed renewables grid, and the amount of reduction in peak demand that can actually be achieved. The latter will be dealt with in the Buildings and Industrial Processes Reports. However, the demand values assumed here are considered to be conservative.

FIGURE 5.4
Illustration of peak and average generation capacity for current and projected demand



5.2.2 Supply Side Management

The variable nature of the wind and solar resource will require active monitoring of Australia-wide weather events to plan the proportion of power supplied from the different energy sources in the grid.

For example a weather pattern providing good consistent wind resource at a number of wind farm sites would allow the CST plants to keep more heat in storage. On the other hand a large storm front hitting the south eastern states could cause a sharp loss of power, as wind turbines are shut down at high wind speeds to avoid any damage. In this circumstance wind turbines would go from producing at maximum output to producing nothing in the space of minutes. Such an event would need to be planned for in advance, with CST plants ready to dispatch power to ensure supply continuity. If this event coincided with a forecast period of low solar incidence, the biomass boilers would need to be switched on a few hours in advance so that they are operating at sufficient capacity to heat the molten salt storage tanks to meet the loss in supply. Hydro-electric power can also be rapidly dispatched in situations of unexpected change in weather conditions, to provide an additional back-up.

In most cases the system will operate with a reserve capacity, either stored energy in the molten salt storage tanks, or via curtailed wind turbines to avoid power oversupply. This reserve power can be rapidly deployed to increase the total energy supply, during peak periods. For example, during periods of high wind resource, curtailed wind turbines can act as a form of 'spinning reserve' [8] (reserve turbine capacity in terms of today's baseload plants), because wind turbines temporarily turned out of the wind can be rapidly returned to full power generation.

5.2.3 Demand Side Management

Smart Grid can allow reductions in peak load, either by bringing forward some expected demand, based on advanced forecasting, or by delaying load from non-essential services, or by load shedding, during demand peaks. Currently the price of electricity increases sharply during high demand periods (see Part 2) and decreases during low demand but these variations in price are absorbed by the electricity retailer, and ultimately passed on to the consumer. Thus, the incentive for consumers to adjust demand is lost.

Smart Grid allows demand-side management. If consumers are equipped with smart grid tools, they can make price-based decisions not to use heating and cooling, charging of cars, etc. during times when the demand would otherwise be high, or when supply is low. This provides an incentive to ease system congestion and reduce the need for new infrastructure.

In the future, incorporating technology that allows common appliances to communicate with smart meters may offer the opportunity for innovative ways of managing the load to help smooth the peaks in demand.

FIGURE 5.5
Hypothetical Daily Demand Profile Including Storage

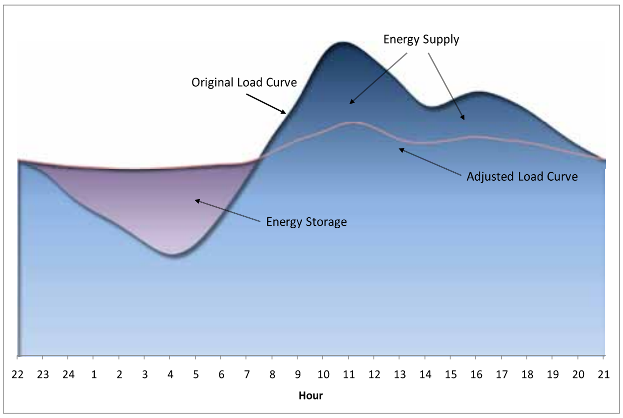


Figure 5.5 shows an illustrative example of smoothing the load peaks, in an area of the network where demand from commercial buildings in Summer peaks around midday. The "Original Load Curve" shows normal demand peaking before lunch. The "Adjusted Load Curve" (pink line) shows a reduction in the peak, that might be created by bringing forward the demand from some loads[9]. Some examples of loads that could be re-scheduled for peak smoothing are given in the next section. All of these examples have some form of energy storage, and so have the potential to be intelligently re-scheduled either earlier or later in time.

General Electric estimates that installing smart meters in 25% of American homes would be an equivalent energy reduction to removing 1.7 million cars from the roads[10].

5.2.4 Examples of Scale

Some examples of the scale of the proposed contribution to load management are:

Cars—The ZCA2020 Transport Plan involves a significant modal shift from private passenger vehicles to shared electric rail vehicles, with the car fleet reducing by around 50%. The result is that the average car travels 8,000 km per annum instead of 15,000 km today. It is estimated that, across Australia, there would be six million pure electric, plug-in hybrid electric, and battery swap electric vehicles. These can be charged using standard domestic power sockets. Off-peak charging could reduce peak demand on the electricity system by 650 MW or more (where 650 MW is the average charging rate for a full vehicle fleet - see Part 2.2.4).

Usually vehicles are left plugged in for an average of 22 hours per day (at work and home), meaning that charging can be scheduled for any time during that period. Electric car charging would only be scheduled for non-peak times, and assuming that the cars are trickle-charged over a period of 13 hours (so excluding morning and evening peaks), this would require 2,000 MW of capacity. Some or all of this 2,000 MW could be shed at a moment's notice to help deal with peak electricity loads. It has also been suggested that another potential benefit of electric vehicles is the possibility that car batteries can be used to feed electricity *back into* the grid, to increase peak electricity availability (Vehicle-To-Grid charging). However, this is not yet commercial, and the leading electric car infrastructure supplier, Better Place, is not considering this as an option for their cars in the near-term[11].

The most desirable option is to time the charging of cars to coincide with the periods of greatest solar and wind resource, thus helping with load management. When a correlation of high wind and solar incidence occurs across the geographically diverse grid, charging can be used as a "dump load". In this case the "dump load" is useful, profitable and valuable, both to society and to electricity consumers.

Space Heating—Space heating aims to heat buildings to a constant, comfortable temperature, typically 20°C. Under the ZCA2020 project, traditional gas space heating can be converted to electric heat pumps. Suitably equipped households and businesses can have their heating re-scheduled to non-peak times, using low-priced surplus electricity. For example, demand forecasting can be used to predict surplus electricity generation, and buildings can be preheated to 24°C during the lower demand period before the peak arrives, and then allowed to cool slowly over several hours during the high demand period.

Hot water systems—Hot water systems that use heat pumps or direct electric-boost could also be useful for load management, by accepting redirected surplus electricity. Assuming, for example, 5 million households with hot water heat pumps and typical power consumption of 500-1,000 W each[12], the potential flexibility in peak load is 2,500-5,000 MW. This is an extension of traditional off-peak hot water where households had separate meters for peak and off-peak power consumption.

Refrigeration—Existing refrigerators could be supplied from dedicated smart meter circuits to allow for central grid management, and new smart refrigerators can progressively replace the existing stock to interact more directly with the network, pre-empting and deferring refrigeration loads while keeping temperatures within acceptable tolerances. Domestic refrigeration can be switched off during periods of high demand or low supply, with limited impact on performance. Commercial refrigeration systems can be adapted to make ice for 12 to 16 hours per day and then melt ice for 8 to 12 hours per day in order to smooth the overall demand.

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Part 6

Resourcing the Transition — Implementation

Contents

The transition to 100% renewable energy in ten years is achievable, given Australia already has a large industrial capability. Our human and material resources are far in excess of those required to implement the ZCA2020 Stationary Energy Plan.

The ten-year timeline has been mapped out taking into account a gradual scale-up of the renewables industry, which would see most of the proposed infrastructure completed in the second half of the decade.

The large-scale conversion to renewable energy technologies globally will require large amounts of material, technological and human resources. In Australia, we are in an enviable position to exploit renewable energy sources, given not only our abundance of wind and solar resource, but also an abundance of the raw materials needed to construct wind and solar plants.

The bulk of raw materials required for the construction of a 100% renewable grid are not in short supply domestically or globally. Over 99.5% of all materials required to construct new renewable energy systems are "basic construction materials and metals abundantly available"[1]. Studies in the Australian context indicate that the supply of core materials will not be constrained during the construction of the ZCA2020 Plan, because the resources required only represent a fraction of Australia's total production capacity.

At the peak of installation, the Plan would require over 80,000 construction workers, only 8% of Australia's existing construction workforce, which has already shown it is capable of ramping up at a faster rate than called for by the Plan.

The Plan calls for expansion in our manufacturing industry to include the production of heliostats and wind turbines. This would create over 30,000 new jobs, setting Australia up with new renewable industries, ready to take part in the global clean energy economy.

In transitioning from an energy industry based on extracting and using fossil fuels to an energy industry based on solar plants and wind farms, more jobs will be created than lost. Renewable energy power plants, in most cases, are somewhat more labour intensive in their operation and maintenance than fossil fuel power plants, which is offset by not having fuel costs. The Plan will require over 45,000 ongoing people in operations and maintenance jobs. This compares with current employment of approximately 20,000 people in producing stationary energy from fossil fuels.

The amount of greenhouse emissions due to constructing the new system are not insignificant, but these emissions are recovered in only 2 months of operation of the new system, because the new system avoids the continuing emissions of the present fossil fuel system.

6.1 Implementation Timeline

The implementation of the ZCA2020 Stationary Energy Plan will require a scale-up of construction and manufacturing capability. It is recognised that with any moves to new industries, changes do not happen overnight, and this has been taken into account in the modelling of the ten year implementation period.

The timeline for installation under the Plan has been modelled over the period January 1, 2011 to December 31, 2020, representing a ten-year transition period. An initial ramp-up in the first few years leads to a constant rate of construction in the later years until completion of the Plan. The modelling has been carried out over 6-monthly intervals. Alternative scenarios could see a slow growth rate in earlier years with continued higher growth in later years.

Significant economies of scale and efficiencies can result from the planned roll-out of modular equipment. The engineering for solar power towers does not need to be repeated for each single unit. Once the design and planning is complete for one of the 13 Solar 220 modules that will be built at each of the 12 solar sites, all that is required is the replication of the same construction job another dozen times. As the companies and workforce scale up and gain experience, it is expected that the installation timeline will become faster and more efficient.

A constant pipeline of projects ensures that component factories for producing wind turbines and heliostat mirrors can run with continuous output, making the most efficient use of their capacity, as opposed to stopping and starting for individual projects. Sourcing of some components that are cheaply and easily transported from overseas may be an economical option, however there is significant advantage to be gained from doing a portion of manufacturing onshore. Large components such as 60-metre wind turbine blades (in 30-metre sections) and 12m x 12m heliostats are well-suited to being assembled close to their point of installation to minimise transport. It is also expected that as other countries ramp up renewable energy installations, there will be greater demand and competition for overseas components. Onshore manufacturing will ensure greater reliability for sourcing components on time. As domestic installation declines, Australia would be well set-up to export components and skills to the rest of the world, positioning itself as a renewable energy leader.

FIGURE 6.1
Windpower Installation Timeline

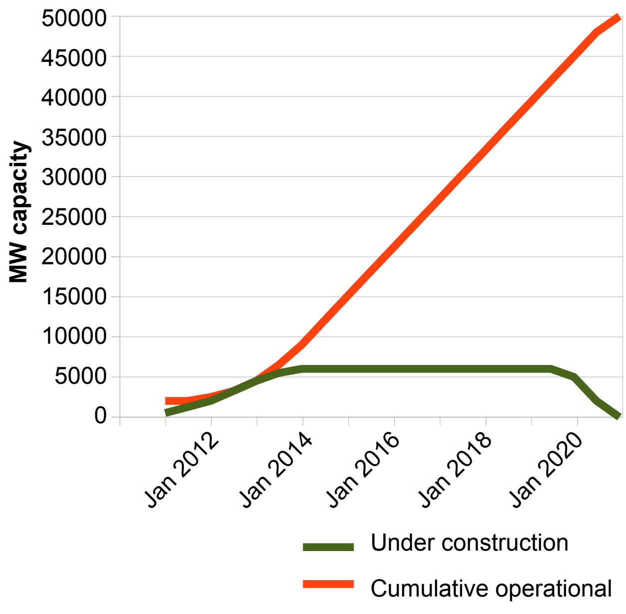
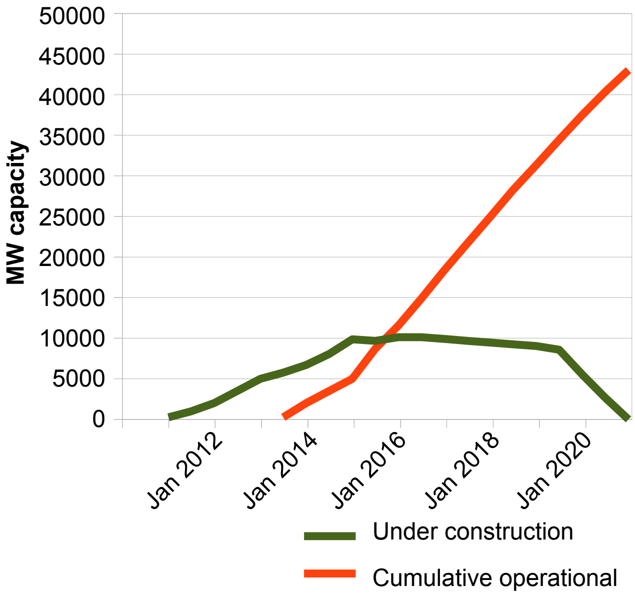


FIGURE 6.2
Solar Thermal Installation Timeline



6.1.1 Wind Power Timeline

The proposed installation timeline for wind turbines is described in Part 3, and summarised in Figure 6.1. This shows the capacity under construction at any one time (green line), and the cumulative completed capacity (red line).

By January 2015, operational wind capacity will be 15,000 MW (which meets 14% of total electricity demand). From 2014 onwards, the installation rate is 6,000 MW per year. This equates to 800 turbines of 7.5 MW capacity per year. Currently in Australia the operational wind power capacity is 1,700 MW[2]. With the addition of projects currently under way this capacity will be around 2,000 MW by the end of 2010. As noted in Part 3, coordination is required with the 11,000 MW of wind projects already at various stages of development and planning around Australia, many of them with projected completion dates in the period 2011-2014[3].

6.1.2 Solar Thermal (CST) Power Timeline

The proposed timeline for on-grid CST is shown in Figure 6.2. CST capacity is projected to grow initially at a slower rate than wind capacity. By January 2015, the operational CST capacity (on-grid) will be 5,000 MW (which meets 11% of total electricity demand). From 2015 onwards, the installation rate is constant at about 10,000 MW per year at the 12 main sites.

In addition to this on-grid CST, the Plan calls for construction of 4,475 MW of CST capacity at off-grid sites during the 2015-2020 period.

The early timeline allows 2.5 years for the construction of a plant, as with the Solar Reserve projects. The later part of the timeline allows 1.5 years construction timeline per CST plant, as with the Andasol projects[4]. At the peak of construction, this will require the installation each year of 30 large concrete towers, and 600,000 148 m^2 heliostats.

6.1.3 Transmission Installations

The Plan requires construction of 23,300 km of high-voltage 500 kV transmission line (HVAC and HVDC) by 2020, as some of the proposed transmission lines are double-circuit. The highest priority is for lines that allow connection of the new solar and wind sites to the grid—7,500 km of lines, which need to be completed by 2015. From that time onwards, the Plan calls for 4,500 km/year of new line.

6.2 Material Resources

6.2.1 CST — Concrete, Steel and Glass

The main resource requirements for large-scale CST plants incorporating power tower technology and molten salt storage are:

- Concrete
- Steel
- Glass
- Sodium/Potassium Nitrate Salt (Fertiliser)

All of these materials are already produced in very large quantities in Australia and globally. The Stationary Energy Plan would require on average 7% of Australia's annual output of concrete, for construction of solar thermal and wind plants. Australia's construction industry already uses over 60 million tonnes of concrete per year. The Plan would require only minor growth in concrete production, or alternatively a small re-scheduling of activities.

Over 95% of the materials in a solar thermal plant are contained within the heliostat field[5]. The type of heliostat currently specified in the Plan consists of a large mirror surface of around 50–150 m^2, mounted on a steel pedestal which is held in the ground with concrete foundations. Large heliostats of this type tend to be more resource efficient and cheaper than smaller heliostats (with the notable exception of the eSolar type racked heliostat field). The resource requirements for the Plan have been calculated using available data for the ATS 148, a 148 m^2 heliostat designed by Sandia Laboratories[6].

Though costing and design is based on the conventional large heliostat model, for comparative purposes the resource requirements for eSolar mirror fields have been calculated as well. This very innovative approach to heliostats uses much less in the way of materials, land and installation labour. While the eSolar technology is currently only used for daytime direct-steam generation in small modules (46 MWe), if their mirror field design could be adapted for large-scale molten salt power towers, it could significantly save on resource requirements, installation time and ultimately cost.

For the entire 47 GWe of concentrating solar thermal installations under the Plan, the total basic resource requirements are shown in Table 6.2.

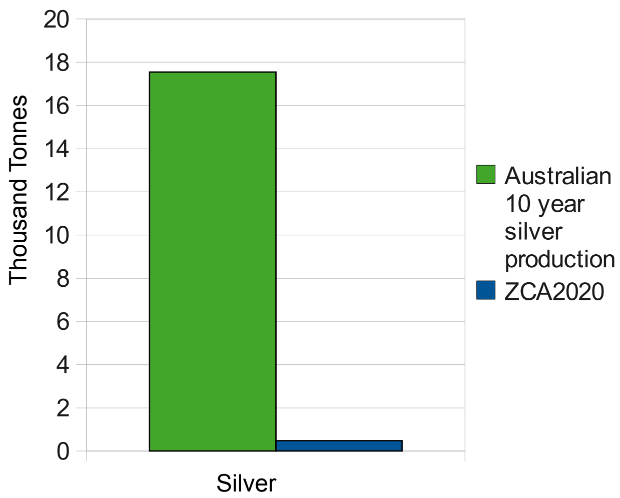
TABLE 6.1
Heliostat Resource Requirements

Heliostat resource requirements kg per mirror square metre		
	ATS 148	eSolar
Steel	31.9	15.8
Glass	10.0	7.8
Concrete	31.0	23.9

TABLE 6.2
Total CST Resource Requirements

Total CST resource requirements Millions		
	ATS 148	eSolar
Steel (tonnes)	18.2	9.0
Glass (tonnes)	5.7	4.5
Concrete (tonnes)	21.8	17.8
Concrete (m^3)	9.1	7.4

FIGURE 6.3
CST Silver Requirements



Mirror Silver

Mirrors are manufactured with a thin film of silver on the back of the glass. However the silver requirements are very low. Even high-quality precision glass, specially made for concentrating solar power, only requires 75mg of silver per square foot of glass[7]. Australia was the world's 4th largest producer of silver in 2008 with 62 million ounces[8], or 1,755 tonnes per year. In context, the ZCA2020 Plan would require only 460 tonnes over the ten years.

Solar Salt

Solar salt is a mix of 60% sodium nitrate with 40% potassium nitrate. These materials are very common—nitrate salts are made by the oxidation of ammonia, one of the world's highest volume production chemicals, while sodium and potassium are also very common components of the Earth's crust. Initial CST projects use a two-tank molten salt system, with separate hot and cold tanks. However Sandia Laboratories have run successful trials on a single tank thermocline system, where the layering effect due to density differences keeps the hot salt floating on top of the cold salt. Low cost quartzite is used as a filler for thermal mass, displacing a significant amount of the salt required with even more

TABLE 6.3
Material resources for 2 MW wind turbine installed in La Rioja, Spain[10]

			Materials (t)							
Component	**Sub-component**	**Weight (t)**	**Steel**	**Concrete**	**Iron**	**Resin**	**Fibreglass**	**Copper**	**Silica**
Rotor	Three blades	19.5				11.7	7.8		
	Blade Hub	14			14				
	Nose cone	0.31				0.186	0.124		
Foundation	Footing	725		700	25				
	Ferrule	15	15						
Tower	Three sections	143	143						
Nacelle	Bed frame	10.5			10.5				
	Main shaft	6.1	6.1						
	Transformer	5	3.3					1.5	0.149
	Generator	6.5	4.29					2	0.195
	Gearbox	16	8		8				
	Nacelle cover	2				1.2	0.8		
	Total	**962.91**	**179.69**	**700**	**57.5**	**13.086**	**8.724**	**3.5**	**0.344**

readily available materials. This system uses only 32% of the salt of a regular two-tank molten salt system[9]. The ZCA2020 Plan would require 17.5 million tonnes of nitrate salts if two-tank systems were used, or only 5.6 million tonnes for thermoclines. The Plan recommends the use of thermocline systems for this reason.

6.2.2 Wind — Concrete and Steel

The main raw materials required in the construction of wind turbines are steel and concrete. Relatively smaller amounts of glass fibre reinforced plastics (fibreglass) and resin are also required.

Studies are available quantifying the raw resources (tonnes) needed for wind turbines. However, due to market maturity, comprehensive data is only readily available for 2 MW turbines. The results of one study into the requirements of a 2 MW wind turbine are in Table 6.3.

6.2.3 Transmission Lines — Concrete, Steel and Aluminium

The ZCA2020 plan requires construction of 23,300 km of high-voltage 500 kV transmission line by 2020. This is made up of 16,700 km of HVAC, 9,600km of HVDC and requires 39,000 transmission towers.

The main resources required for manufacturing transmission lines are concrete, steel and aluminium. A summary of the required resources is shown in Table 6.4.

Further detailed information on Resource Requirements can be found in Appendix 8.

TABLE 6.4
Transmission Resource Requirements

	Transmission materials
0.67	million tonnes steel for transmission
0.18	million tonnes aluminium for conductors
1.81	million tonnes concrete for transmission

FIGURE 6.4
Aluminium Requirements

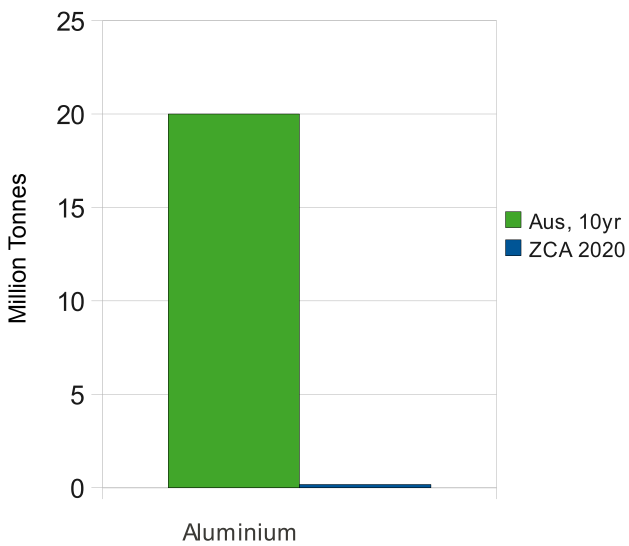


FIGURE 6.5
ZCA Concrete Requirements

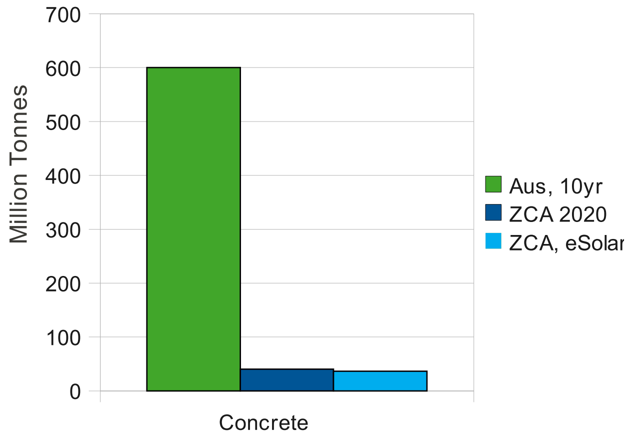


FIGURE 6.6
ZCA Steel requirements including Steel and Ore Exports

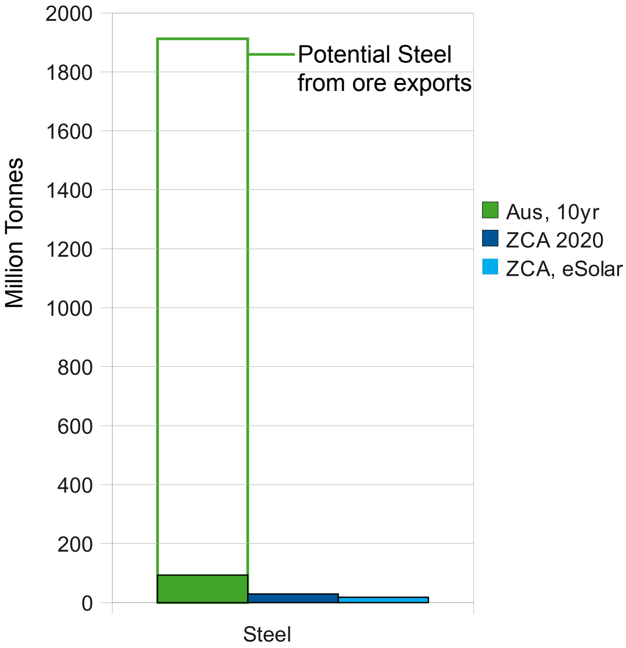
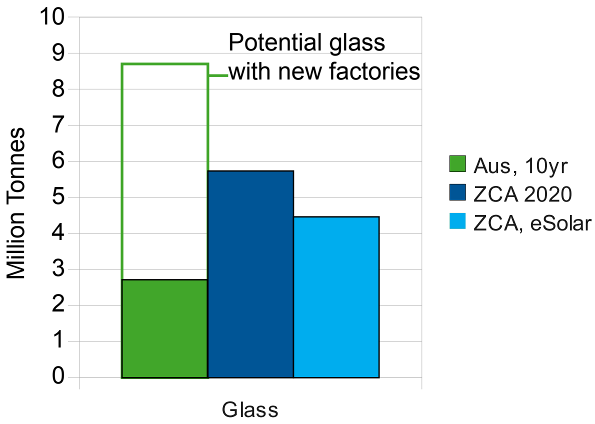


FIGURE 6.7
CST Glass Requirements including new factories



6.2.4 Total Concrete, Steel and Glass

The following results show the total material resources required for CST, Wind and Transmission lines.

Concrete

Australia currently produces 25,000,000 cubic metres of concrete[11] (60,000,000 tonnes) per year. Over the 10 year period of construction, the ZCA2020 Plan requires 40,500,000 tonnes. This comprises the concrete for CST plants, wind plants and transmission lines. This total is only 6.8% of Australia's total concrete production over the 10 year time frame. It is therefore realistic that the required amount of concrete could either be supplied from current production, or by a small expansion of production capacity.

Steel

Australia currently produces 7,860,000 tonnes per year of steel[12]. Therefore, over ten years, it is assumed that at least 78.6 million tonnes could be produced. Construction of solar thermal, wind power plants and associated transmission lines for the Plan requires 24.6 million tonnes of steel (or 15.8 million tonnes if eSolar-style mirror fields were deployed—this demonstrates the value of investing more R&D into exploring the eSolar heliostat option). While the Plan may appear to require a sizeable proportion (20%-30%) of Australia's steel production, it must be pointed out that some of this requirement could be met by imports, or by expanding the domestic industry. Australia exported 267 million tonnes of iron ore in 2007 alone[13], which would eventually be smelted into 183 million tonnes of steel[note 1]. When taking this 'potential steel' into account, it is clear that meeting the ZCA2020 steel requirements from domestic and international sources should not impose any significant constraint.

Glass

The amount of glass required for manufacturing heliostats under ZCA2020 is large compared with current domestic production. The Australian glass industry however is relatively small, with Viridian (CSR) being the single major manufacturer (270,000 tonnes/year[14]). The required quantity of 5.8 million tonnes (or 4.5 million tonnes for the eSolar heliostats) could be met from the output of two large (300,000 tonne/yr) glass factories, similar to that recently announced by glass manufacturer Saint-Gobain in India at a cost of INR 10 billion, or $AU250 million[15].

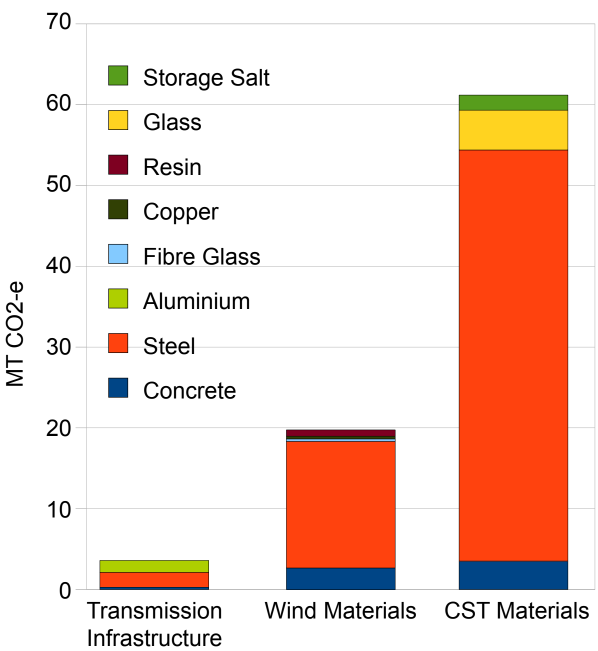
6.3 Emissions Resulting from Construction

Stationary energy, including electricity, is responsible for more than half of all Australian emissions[16]. Implementing this Plan could therefore reduce Australia's emissions by more than half. The total emissions produced in commissioning the Plan (materials, construction, etc.) are only a fraction of the overall reductions achieved—a tiny "emissions-investment" with a huge return in emissions-saving.

For conventional fossil fuel energy sources, most of the lifetime emissions originate from the fuel that is consumed in operating the plant. The emissions are produced in mining, processing and transporting the fuel to the plant, and then in the final consumption of fuel in the plant. In contrast, wind and CST sources need no fuel for their operation. Therefore their emissions per kWh are low (see section 2.5.9), with over 90% of their lifetime emissions coming from manufacture of the required construction materials. The remainder comes from transport of the materials, and from plant construction and ongoing maintenance.

The bulk of the materials-associated emissions are due to the iron/steel and concrete requirements for both wind and CST. Minor contributions come from resin, fibre glass and copper (for wind), and glass and the thermal storage salt (for CST), as well as materials for the transmission infrastructure. The contribution from other building materials (such as plastic insulation, protective paint, silver and other metals, etc.) is marginal by comparison[10,17,18].

FIGURE 6.8
Manufacturing Emissions



6.3.1 CST Related Emissions

Using the data for the ATS 148 heliostat design (slightly more materials intensive than the eSolar design) and the thermal storage requirements for the proposed 47 GW of CST power, the material manufacture results in emissions of some 60 Mt CO_2-e. The majority of this is due to the steel requirements of the mirror fields which could be reduced as proposed by the eSolar option.

TABLE 6.5
CST Materials and Associated Emissions

Materials	Mt required for 47,000MW	$t(CO_2\text{-e})/t(\text{material})$	Mt CO_2-e
Concrete	22.1[6]	0.159[19]	3.51
Iron and steel	18.5[6]	2.75[19]	50.88
Glass	5.8[6]	0.85[19]	4.93
Storage salt	5.6[9]	0.33[20]	1.85
		Total	61.17

6.3.2 Wind Related Emissions

Based on the data available for the material requirements of the above mentioned 2 MW facility in La Rioja, Spain, and scaled to meet the proposed additional construction of 48,000 MW of wind power, the manufacture of the materials would result in some 20 Mt CO_2-e.

TABLE 6.6
Wind Materials and Associated Emissions based on 2MW facility in La Rioja, Spain

Materials	Mt required for 48,000MW	$t(CO_2\text{-e})/t(\text{material})$	Mt CO_2-e
Concrete	16.8[10]	0.159[19]	2.67
Iron and steel	5.69[10]	2.75[19]	15.66
Resin	0.31[10]	2.5[19]	0.79
Fibre glass	0.22[10]	1.53[19]	0.33
Copper	0.08[10]	3.83[19]	0.32
		Total	19.75

6.3.3 Transmission Infrastructure

The linking of CST plants and wind farms to the grid, as well as the requirements to upgrade the existing grid, involve the building of new transmission line infrastructure. The emissions resulting from this are mainly associated with the required steel and concrete, as well as the aluminium used for power transmission lines.

6.3.4 Combined Total

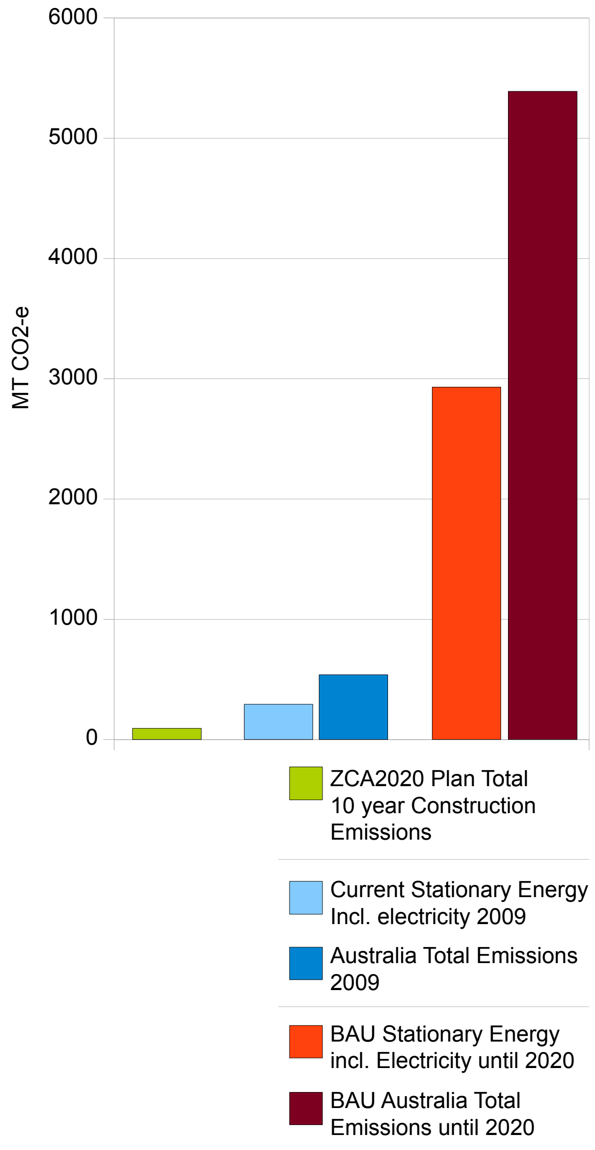
The combined emissions resulting from the manufacture of the listed materials in the sections above are therefore around 85 Mt CO_2-e. Assuming that the above mentioned numbers amount to 90% of all of the emissions, the construction of all wind farms, CST plants and the required transmission upgrades as outlined in this Plan would result in around 94 Mt CO_2-e. This obviously is a significant amount of emissions, but should be seen in context with emissions that would be emitted under the BAU scenario, due to the continued burning of fossil fuels, and the construction of new conventional power plants. These BAU emissions would be several tens of times higher.

Considering that Australia's current annual emissions are around 540 Mt CO_2-e,[16] the proposed 10 year roll-out corresponds to about 2 months of current Australian emissions (or 6 days of emissions per year for 10 years—i.e. 1.6%). Because electricity and stationary energy are currently responsible for over half of Australia's emissions, the final result of these "investment" emissions is that Australia's emissions are reduced by more than half. All of this can be achieved using technology that is currently available.

TABLE 6.7
Transmission Infrastructure Materials and Associated Emissions

Materials	Mt required	t(CO_2-e)/ t(material)	Mt CO_2-e
Concrete	1.81	0.159[19]	0.29
Iron and steel	0.67	2.75[19]	1.84
Aluminium	0.18	8.24[19]	1.48
		Total	3.61

FIGURE 6.9
Comparison of Emissions[15]



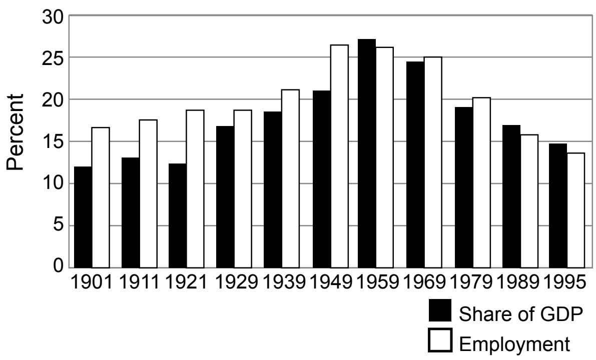
6.4 Manufacturing

Australia's domestic manufacturing capacity will need to be ramped up quickly to enable the broad-scale roll-out of a 100% renewable electricity grid. The manufacture of CST and wind components domestically has the potential to create thousands of job opportunities in areas that currently rely on coal- or gas-fired power plants, and coal or gas extraction, for direct and indirect job benefits. Unlike the construction, operations and maintenance jobs in CST plants and wind farms, jobs in factories are not tied to regions with high solar or wind incidence. The factories can therefore be sited strategically for smart regional development.

In the 1960s manufacturing accounted for approximately 25% of our GDP. Since then it has been steadily decreasing as seen in Figure 6.10[25]. The last decade has been no exception, with Australia's manufacturing industry currently accounting for approximately only 10% of our GDP[26]. This has led to the closure of numerous factories, as manufacturing overseas becomes a cheaper alternative. The movement has left factories empty, and an estimated 100,000 jobs lost from the sector in the past 10 years[27]. This gives Australia excess capacity that can be utilised by the ZCA2020 Plan. The Australian Federal Government supports this view when it states that:

"There is no doubt that clean energy development and manufacture represents a significant opportunity for Australia, building on existing strengths in research, innovation and production technologies."[28].

FIGURE 6.10
Australian manufacturing as percentage of GDP[25]



6.4.1 CST Manufacturing Capacity

The ZCA2020 CST system has been designed based on Solar-Reserve/Torresol power towers, receivers and molten-salt-as-working-fluid technologies, with 148 m^2 heliostat mirrors. At the peak of construction activity, installation of the CST infrastructure will require the following quantities of component parts:

Torresol Gemasolar solar thermal power tower under construction, May 2010 SOURCE: TORRESOL ENERGY

- 30 concrete towers per year
- 30 receivers per year
- 600,000 ATS 148 heliostats per year
- 30 steam turbines and associated ancillary equipment per year, readily available from industrial suppliers
- 60 insulated tanks for molten salt storage system per year

The concrete towers use exactly the same continuous-pour system that is currently employed to construct smokestacks for conventional powerstations—the company employed to construct Torresol's Gemasolar tower already has years of experience in the conventional fossil industry[21]. One tower would take a crew of ten workers about 2 months to complete, once the ground is prepared along with all the other associated civil works[22].

Existing factories can be re-tooled and refurbished to manufacture CST component parts. The first factory manufacturing CST components in the United States was opened in an old furniture factory in 2008 by Ausra. The Ausra plant will produce 700 MWe of solar electricity equipment each year, including reflectors, absorber tubes and other components for Ausra's Compact Linear Fresnel Reflector system. While employing only about 50 people, the factory supports over 2,500 jobs in construction[23].

For SolarReserve's newly announced project in Alcazar, Spain, as well as the 750 jobs for direct construction of the

Enercon rotor blade factory in Viana do Castelo, Portugal[32]

project, a new heliostat production facility is built nearby to employ an additional 50 skilled workers and introduce new technology manufacturing to the region[24].

The modelling for ZCA2020 has assumed that 50% of the heliostat production is done in Australia. This could also reflect having some components (such as individual mirror panels) manufactured overseas and having the final assembly carried out onshore to reduce the transport of bulky heliostats. Manufacturing industries are generally broken down into two groups—elaborately transformed manufactures (ETM) and simply transformed manufactures (STM)[25]. Whilst heliostats would still be classified as an ETM, the manufacturing process is nowhere near as complex as that required for a car. In 2008 Toyota Australia manufactured over 140,000 vehicles[29] and in comparison with overseas plants the automotive manufacturing plants in Australia are relatively small. In 2009 over 500,000 vehicles rolled off the production line at the Audi plant in Ingolstadt[30]. It is therefore reasonable to expect that a single manufacturing plant in Australia, when equipped with the correct tools could easily produce and assemble the 300,000 heliostats suggested for local manufacture, and possibly even the full 600,000 required.

Based on the manufacturing labour requirements detailed in studies from Sandia National Laboratories[31], the production of 300,000 heliostats per year could create another 7,000 manufacturing jobs. If Australia then positions itself well with manufacturing expertise, we could continue to produce components for export after the surge of domestic CST installation declines.

6.4.2 Wind Manufacturing Capacity

The ZCA2020 wind system design is based on the Enercon E-126 wind turbine. This turbine has a nameplate capacity of 7.5 MW, is 138m high and has a rotor diameter of 127m. The quantities of component parts of the Enercon E-126 wind turbines for the ZCA2020 Plan at peak installation rates are:

- 800 turbines per year
- 2400 blades per year
- 800 nacelles per year
- 800 towers per year

These parts can all be manufactured in fairly conventional factories after the requisite re-tooling.

There are examples, globally, of wind turbine manufacture being ramped up quickly. Enercon has established a manufacturing hub in less than two years for wind turbine manufacture in Portugal. In the harbour of Viana do Castello, a rotor blade factory and a concrete tower factory are producing 250 towers and 600 rotor blades (for the E-82 turbine) each year. In nearby Lanheses, the production lines have all been set up with the completion of plants for generator manufacturing, e-module assembly and final assembly. Eventually Enercon expects to export 60% of the production output from these factories, hence their harbourside location.

As mentioned in Part 3.2 the Chinese have begun construction of the world's largest wind farm dubbed the "Three Gorges on the Land", in Gansu Province[33]. The wind farm will have 20 GW installed capacity by 2020 and 40 GW eventually (representing just under two-thirds of the

Enercon rotor blade manufacturing in Magdeburg[35]

Inside the Enercon permanent magnet factory[35]

ZCA2020 overall wind requirement). A series of wind turbine and blade manufacturing plants are being built by the Chinese government to remove supply constraints on the project and keep costs down[34].

In the United States, Vestas has completed the world's largest wind turbine tower factory in Pueblo, Colorado. The factory is producing 900 towers a year. Vestas' first America-based wind turbine blade factory opened in 2009 with a capacity of 1,800 wind turbines per year[36]. While these Vestas factories are producing wind turbine equipment of smaller capacity than the 7.5 MW turbines recommended for the Plan, it must be pointed out that manufacturing is a modular process that can be scaled up by simply installing more equipment. Enercon E-126 turbine blades are actually transported as two separate sections which are shorter than the blades of smaller model turbines.

These international examples indicate how it is possible to install a large manufacturing base very quickly, even under a lukewarm regulatory environment. Vertical integration appears to aid a speedy roll-out. The large companies favour vertical integration in order to lower costs, maintain quality and ensure that project timelines are not disrupted by production line problems. However the ZCA2020 Plan represents such a broad scale construction and implementation project that vertical integration may be a strategy that could be debated for the Australian context.

To manufacture the required wind components for the ZCA2020 Plan, Australia would require slightly more than the equivalent production capacity of the Vestas tower factory in Colorado USA (which produces 900 towers a year), and less than double the capacity of the existing Vestas blade manufacturing plant in Windsor, Colorado (which produces 1,800 blades a year), or 1.5 times the manufacturing capacity being installed by China in just Gansu province alone over the next decade.

Of course, Australia would not need to produce all these turbines domestically. Many of the turbines and component parts could be imported, particularly to take advantage of lower-cost turbines being produced in China. However there are significant advantages in developing a substantial

Enercon E126 under construction

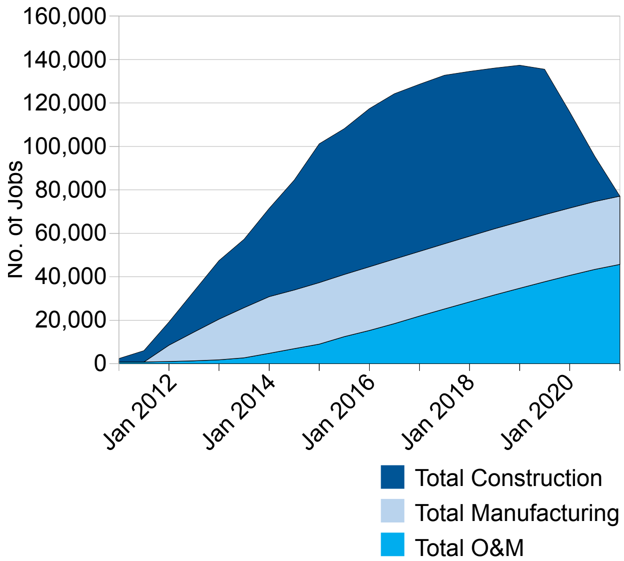
turbine manufacturing industry in Australia: to be a part of the global boom in renewable energy technology, and to develop domestic jobs, expertise and capacity. The Plan recommends a mix of locally manufactured and imported turbines. Factories producing wind turbine components could be geographically dispersed throughout Australia, depending on labour market capacity and proximity to rail transport.

6.5 Jobs

ZCA2020 modelling shows that many more jobs are created with the construction of a 100% renewable energy grid than are lost with the phasing out of coal and gas from the stationary energy supply chain (see Appendix 7). In this modelling only the direct jobs are included, and so the model estimates are considered conservative. From 2010 to 2020, the ZCA2020 Stationary Energy Plan will create just over 80,000 jobs from installation of renewable energy infrastructure at the peak of construction, plus over 45,000 continuing jobs in operations and maintenance, which will continue for the life of the plant (see Appendix 7). These jobs will be in a diverse range of fields including, but not restricted to, construction, manufacturing, engineering, trades and plant management. Over 30,000 jobs would also be created in manufacturing of wind turbines and heliostat mirrors, assuming for this scenario that 50% of manufacturing is done onshore. If Australia moves to export these components as domestic demand begins to taper off towards the end of the transition decade, we can ensure that we are well-positioned to be a leader in the global renewable energy economy. These figures refer only to direct jobs involved in the renewable energy systems.

In comparison, around 20,000 jobs in stationary energy production from coal and gas will be lost in the same period, including those in the extraction of coal and gas for electricity production and end-use gas for heating[37,38,39] (see details in Appendix 7). The job creation figures are broadly consistent with the findings of a recent study by the Australia's CSIRO[40], which estimated overall job growth of 230,000—340,000 jobs over the next 10 years in making the transition to an environmentally sustainable society. The loss of 20,000 jobs is comparable to average monthly fluctuations in employment levels, for example the change of 19,480 jobs in January 2010[41].

FIGURE 6.11
Overall construction, manufacturing and O&M jobs directly created by the ZCA2020 Plan



As can be seen from Figure 6.11, over half of the jobs created in the installation of the renewable energy plants under the Plan will be ongoing after the construction phase is complete. The decline in construction jobs at the end of the period is to be expected, as all individual construction projects have a short lifetime, and people employed in this industry are used to transitioning from one job to the next.

Australia's solar thermal and wind industry would then be well-placed to export expertise and skills to assist other countries around the world in the shift to a renewable energy future.

Construction workers installing heliostats at a Brightsource solar thermal power tower[42]

FIGURE 6.12
Jobs created by the ZCA2020 CST plants.

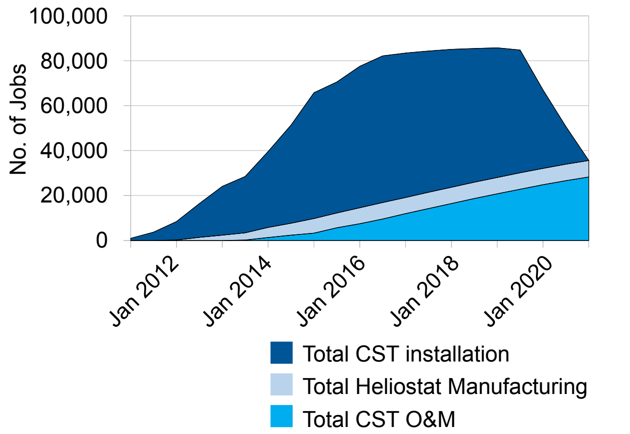
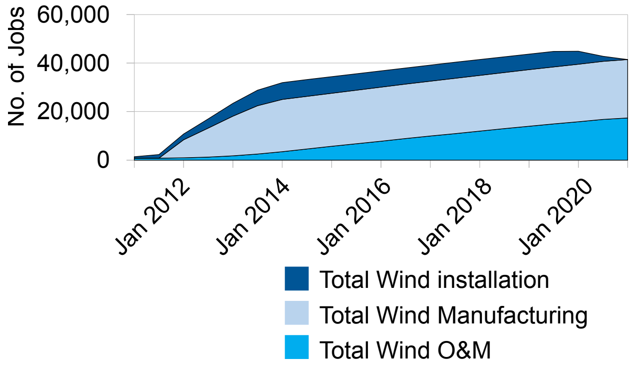


FIGURE 6.13
Jobs created by the ZCA2020 wind component.



6.5.1 Current Employment in Stationary Energy Production

It is estimated that there are just over 20,000 people directly employed in the production of stationary energy (electricity and heat) from fossil fuels currently. Most of those (just under 8,000) are employed in coal mining (not including coal for export). 6,300 are directly employed in fossil-fuel-fired power stations and around 6,100 are employed in the extraction of natural gas for domestic purposes[38,39]. The majority of Australia's coal and natural gas reserves are extracted for export. Only the people employed in the extraction of these resources for stationary energy production domestically have been included in this study.

6.5.2 Jobs in Solar

The construction and operation of the CST plants will create many high-quality skilled and unskilled jobs. Due to the geographical diversity of the CST sites these job opportunities will be dispersed throughout Australia. By coincidence many of the sites with high solar incidence where CST plants will be installed are in regions that support a great deal of mining activity. This means that many jobs lost in the mining sector can be replaced by jobs in the new solar power industries. The construction and O&M jobs for CST have been based upon real-world employment figures for SolarReserve's announced molten salt power tower projects in Rice, CA[43] and Tonopah, NV[44].

As shown in Figure 6.12, construction of the solar plants will create around 65,000 direct jobs in the peak installation phase (2017), after a ramp-up of manufacturing and construction capacity[note 2].

Assuming that half of the heliostat manufacturing is done in Australia, a further 7,000 jobs could be created in this industry, which can then be directed to offshore exports as domestic demand declines [note 3]. Once plants are brought online, over 28,000 people will be employed in operation and maintenance. This includes both grid-connected and off-grid CST (see also Appendix 7).

6.5.3 Jobs in Wind

The best wind sites in Australia are located along the coast. This means that many of the wind sites chosen under ZCA2020 are situated in areas close to population centres. During the construction phase of the ZCA2020 wind component this will be convenient in terms of tapping into large labour markets. Traditionally, construction and maintenance jobs in the wind sector can be very well-paid due to the heights at which some of the work is done.

Manufacturing of wind turbines and components is the most significant source of jobs in wind power[46]. Assuming 50% of the turbines are manufactured domestically, over 22,000 manufacturing jobs could be created by the time the installation rate reaches 6,000 MW per year. The ZCA modelling has assumed that the wind manufacturing industry continues to grow at 1.5% p.a., as Australia begins to export high-quality wind turbines.

During the construction and installation phase, up to a further 7,000 jobs in installation will be created after the initial ramp-up to 2014, then a continuous steady rate of installation until completion in 2020. This matches the ramp-up that has been achieved in other areas internationally, such as Texas[47,48].

Over 17,000 permanent jobs will be created in the ongoing operation and maintenance of the wind farms (see Appendix 7).

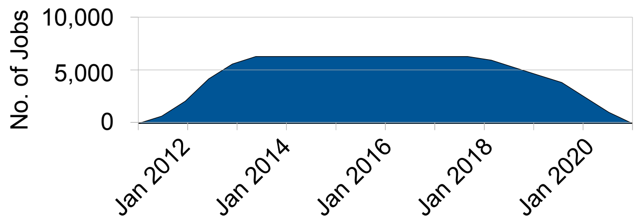
Wind farms can bring a range of benefits to local communities and families. They create a significant change in the dynamics of local towns, offering employment and more secure, steady incomes, supporting population growth instead of decline, and allowing families to stay together. They can help to reverse the trend of people leaving rural areas at times of drought and hardship on the land. Many can now enjoy a rural lifestyle without the hardships of toiling on the land.

SUZLON—POWERING A GREENER TOMORROW[49]

6.5.4 Jobs in New Transmission Lines

Jobs required in the construction of transmission lines are shown in Figure 6.14. The priorities in installation are, first to connect new generator sites into the grid, and second to create the interconnects for the complete national grid. The job numbers are based on employment rates reported for two 500 kV transmission line construction projects in the US[50,51].

FIGURE 6.14
Jobs created by the ZCA2020 transmission lines

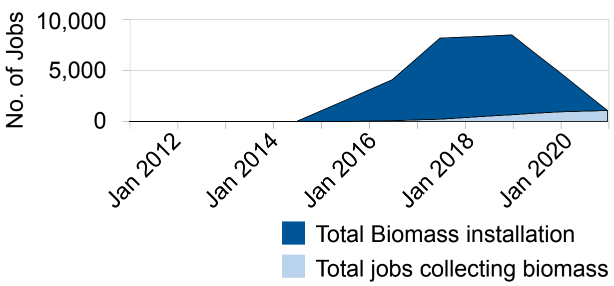


6.5.5 Jobs in Biomass

The biomass plants will be installed alongside the CST plants so that biomass can be used to co-fire the boilers (when there is concurrent low-wind and low-solar incidence). Due to the biomass back-up being installed as supplements to the CST plants, the installation of the total 15 GWe of biomass heaters will occur at the same rate as, and in conjunction with, the CST plants. Over 8,000 jobs will be created during the construction, manufacturing and installation phase, which for biomass will begin in 2015, as the large-scale Solar-220 plants are being built. The extra labour force for construction of biomass heaters will be located mainly at the southern-latitude CST sites.

It is expected that the biomass backup will only operate for 1-2 weeks each year, for example during winter, when low solar incidence may coincide with low wind incidence and high electricity demand. Since the backup will only be used on the CST sites when solar thermal activity is low, it is expected that its contribution to overall O&M labour will be relatively small (assumed to be zero here). The more significant job numbers are in biomass fuel collection and general CST plant O&M labour. The biomass plants proposed under the ZCA2020 Stationary Energy Plan consist of large-scale pelletised biomass boilers (very similar to existing pulverised coal boilers). As an illustrative example, each 220 MWe CST turbine with biomass backup can be likened to one-eighth of Victoria's eight-unit, 1540 MWe Hazelwood power station, in terms of output capacity and operational labour requirements.

FIGURE 6.15
Jobs created by the ZCA2020 biomass component



6.5.6 Ramp-up and Comparison with Current Employment

The ZCA2020 Plan will create an ongoing 77,000 jobs in manufacturing and O&M. At the peak of construction, there will be over 80,000 people employed in installation of the solar, wind, transmission and biomass sites. The bulk of these will be in construction, these figures are not necessarily inclusive of all jobs in engineering, financing, management and administration.

The graph of Figure 6.17 compares the labour requirement of the ZCA2020 Plan with the size of the existing Australian workforce—showing a selection of industries that are relevant to the jobs in the Plan.

Actual industry figures up to 2009 are shown to the left of the dotted line. This includes a flat line in job growth after the Global Financial Crisis of 2008. To the right is the projected growth in jobs, published by the Department of Education, Employment and Workplace Relations. The total job requirements for the ZCA2020 Plan are shown in blue.

FIGURE 6.16
Total Jobs created by the ZCA2020 Plan

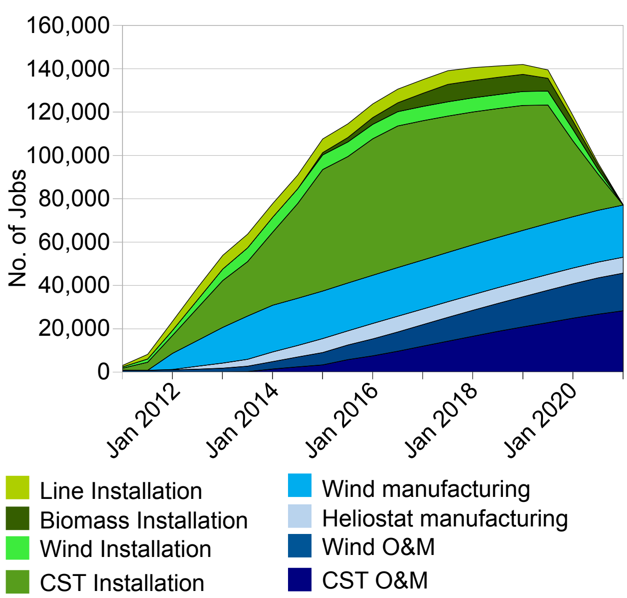
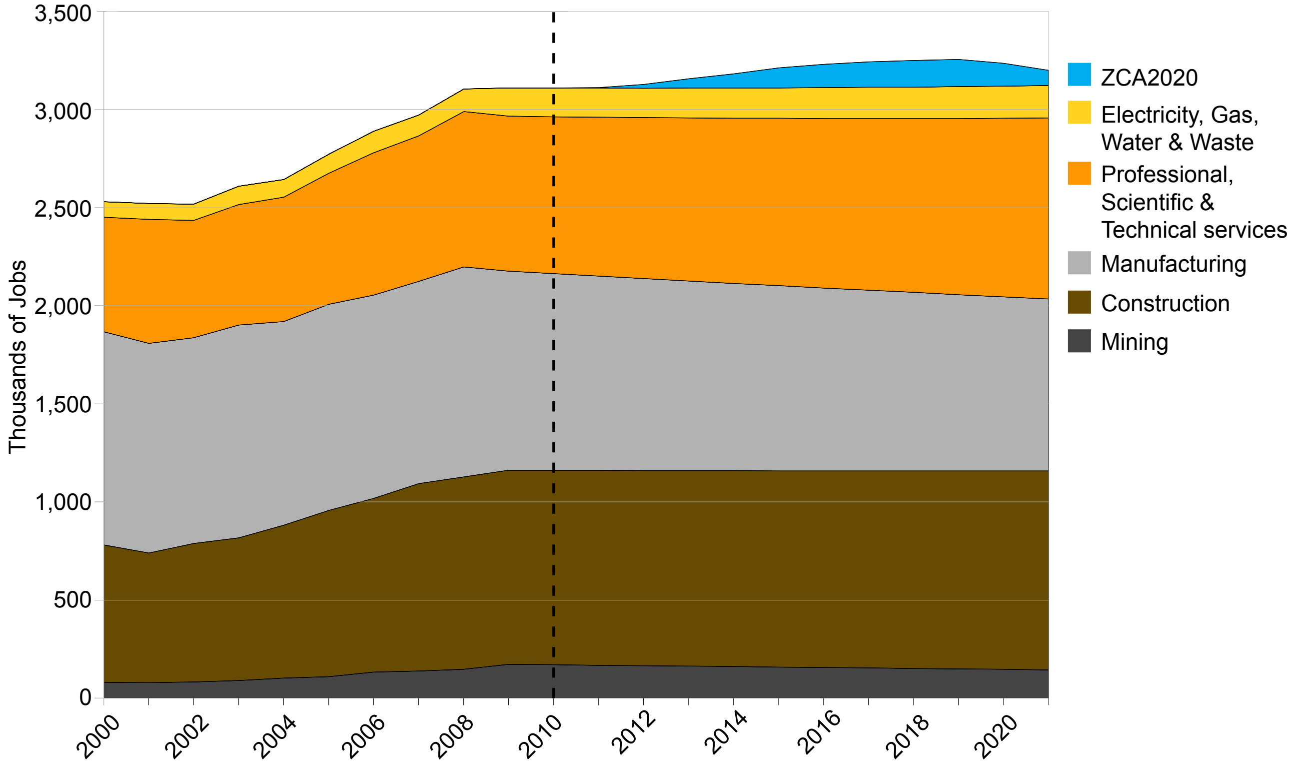


FIGURE 6.17

Jobs in context. Jobs prior to 2010 are actual figures from DEEWR[52] for relevant sectors, with official mid-term projections post 2010, and total ZCA2020 jobs from Figure 6.16 shown in blue.



Already one million people are employed in construction in Australia, with a further one million in manufacturing. In the five years before 2008, the number of construction jobs was growing at 50,000 new jobs per year[52]. The construction jobs component of the Plan requires an average of 9,000 new jobs per year (ranging from 8,000 to 13,000 with a peak in 2015). This appears to be entirely achievable in the context of Australian industry capabilities.

People employed in existing industries can readily switch and adapt to the new jobs in renewable energy, says Kevin Smith, CEO of the U.S. company Solar Reserve. He was recently interviewed about the rapidly expanding green economy, and was asked how a company like his can deal with the crucial aspect of training. He discussed the issue of finding appropriate people as the business goes through a rapid expansion—doubling or tripling in 6 months. People can be recruited with broad skills in business and engineering, and trained in 6 to 12 months. The dynamics are much the same as any normal expansion phase in the economy[53].

6.6 Conclusion

The ZCA2020 Plan is clearly achievable, using available technologies, and within Australia's currently available material, human and economic resources. We already have construction and manufacturing sectors that are large enough to supply the resources for the ten year transition period.

The material requirements for steel and concrete are a fraction of Australia's current annual production. Production of float glass for the heliostats would need a significant increase in capacity—of approximately 600,000 tonnes per annum—but this is equivalent to a couple of new factories of 300,000 tonnes/year capacity[15].

The manufacturing requirements are well within Australia's capabilities. The Plan calls for several new factories to produce components for wind turbines and solar thermal plants, of similar size to factories that already exist overseas.

The Plan would require only a fraction of Australia's existing cosntruction and manufacturing workforce, and yet would create more ongoing jobs in renewable energy than would be lost in old fossil fuel industries.

Footnotes

1. Australian iron ore is primarily hematite (Fe_2O_3) and magnetite (Fe_3O_4), ~70% elemental iron (Fe), by weight steel is >98% iron.
2. Job numbers are based on total 700 job-yrs/MW for Rice SolarReserve, a 450,000 GWh/yr solar power tower plant (normalised to 75% capacity factor), but for plants with a shorter construction time of 1.5 years, the number of construction jobs/yr has been increased. i.e. total manpower has been kept constant at 700 job-yrs/MW, so for a shorter timeframe, more people are needed at any one time. Total job-yrs has been calculated from average construction numbers (not peak numbers), because the average gives the more meaningful total for job-yrs, which can be adjusted to different timeframes, and it is not specified how long peak construction takes place. As there will be many plants under construction in various places at any one time, peaks will occur at different times.
3. Heliostat manufacturing data[31]. For a heliostat size of 148 m^2, the manufacturing workload is 46 man-hrs per heliostat. This is based on factories running at 223 production days per year (like an Australian Toyota factory), see Electric Vehicle section in Part 2. Single 8-hour shift per day is modelled. See further details in Appendix 7 Manufacturing 50% of the heliostats in Australia would create just over 7,000 jobs.

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Part 7
Economic Comparisons

Contents

A commonly cited reason for stalling action on climate change is the cost of mitigation, even though we are warned that the eventual cost of adaptation will be far higher. While implementation of the ZCA2020 Stationary Energy Plan will require a higher upfront investment than Business-As-Usual, it avoids future fuel costs. Moreover, when measured over the long term, the ZCA2020 Stationary Energy Plan has an approximately equal net present cost to the Business-As-Usual scenario.

The purpose of Part 7 is to detail the financial dimensions of the ZCA2020 Stationary Energy Plan and examine whether the economic arguments for inaction have any merit. In particular, this section:

- provides an economic comparison of the ZCA2020 Plan with a modelled Business-As-Usual (BAU) scenario.
- identifies the economic challenges of implementation and their potential solutions.
- contextualises the scale of expenditure required by the Plan by comparing it against other areas of past and present Australian economic activity.

"...a solar thermal power plant has no fuel cost, but it does have a high initial cost because you basically, once you build the plant, you have all the fuel for the 30 or 40 years of the design life. If you had to buy 30 or 40 years of coal, along with your coal plant, the price might be quite a bit different..."

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7.1 Summary of Economic Findings

The ZCA2020 Stationary Energy Plan (the Plan) requires a total capital expenditure of $AU370 billion over the 2011-2020 period, in contrast to a BAU capital expenditure of $AU135 billion. While the Plan's up-front investment is relatively high when compared to BAU, its lower ongoing cost results in dramatically reduced expenditures in the long-term. In fact, over a longer timeframe (2011-2040), the ZCA2020 Stationary Energy Plan and BAU have an approximately equal Net Present Cost (taking into account capital, operations, and fossil fuel costs).

The savings expand significantly if the broader benefits of the Plan on the economy are included. The use of electricity to power transport instead of oil realises fuel cost savings under the Plan of $AU1,170 billion. Furthermore, a conservative estimate of the savings realised by avoiding CO_2 emissions charges suggests that the Plan could negate the need for a further $AU370 billion of expenditure, raising total savings to almost $AU1,550 billion. Most importantly of all, if the Plan helps to stimulate global action on climate change mitigation, then the Stern Review suggests that by 2050, 20% of GDP will be saved annually ($AU240 billion/yr)[2].

The average annual capital investment to fund the Plan over 2011-2020 amounts to $AU37 billion per year, approximately 3% of Australia's GDP. As this section demonstrates, the financial scale of the Plan is comparable to several other areas of large public and private expenditure suggesting that the Plan is within the capacity and capability of the Australian economy. Furthermore, the additional $AU260 billion of up-front investment required by 2020 under the Plan, when divided by 21 million Australians over ten years, only equates to $AU3.40 per person per day and moreover this expense is readily recouped in future years by avoiding fossil fuel costs.

Although the Plan does require a high degree of up-front investment, in the longer term it aims to release Australia from the twin threats of rising fuel costs and the potentially immense expenditure associated with future climate change. There are no roadblocks to implementing the Plan given Australia's economic capacity.

A preliminary analysis of the potential impact on electricity prices indicates that the renewable energy system proposed would raise the price of electricity by 6.5c/kWh over today's levels by 2020. This is based only on one potential funding scenario, and as such should not be taken as a recommendation of the Plan. However, it gives a benchmark of the likely relative cost of the Plan, with this price increase amounting to only an extra $AU8 per week for residential households. This rate of electricity price rise is similar to what has already been experienced in Australia's electricity market.

7.2 Economic Comparison: The ZCA2020 Plan vs Business-As-Usual

To allow a valid comparison of Net Present Costs of the Plan versus the BAU scenario, economic models were constructed for both scenarios over the 2010-2040 period. The purpose of this section is to present and explain these models, analyse the results and discuss some other economic impacts of the transition that are excluded from the modelling. For comparison, both systems have been sized to meet an electricity demand of 325TWh/yr in 2020, which is enough to either supply BAU electricity growth with no efficiency or fuel-switching measures, or to supply all energy needs if these extra measures are implemented.

Section 7.2.1 introduces the modelling, explains the key assumptions and presents the key findings for each model; section 7.2.2 provides an analysis of the payback period of the Plan when compared to the BAU scenario; and finally, section 7.2.3 introduces the unmodelled impacts, primarily focusing on the benefits derived from transitioning oil-dependent transport to electrified transportation.

7.2.1 Modelling ZCA2020 and BAU: Which Provides Lower-Cost Energy?

Only the most fundamental and easily measurable economic impacts, such as fuel, capital and maintenance costs, are modelled quantitatively in this analysis. Social and environmental externalities arising from, for example, fossil fuel pollution, road trauma, and water use, are not included. Indeed, even climate change is excluded from the analysis, despite Stern's warning that it may reduce GDP by up to 20% each year by 2050[2]. Were these externalities to be included, their economic value would heavily favour the Plan.

In the BAU scenario, it is assumed that future growth in energy demand is met by conventional energy technologies, with electricity primarily generated from coal combustion, heating mostly derived from natural gas, and transport dependent on oil. The ZCA2020 Plan scenario is principally based upon wind and solar technologies that have high upfront capital expenditure but low ongoing costs. Both models explore the option of an increasing price on greenhouse gas emissions with a $AU10/tonne impost assumed for 2011 and rising thereafter. A discount rate of 1.4% is used as per the Stern report. A detailed examination of all the assumptions underlying the models is provided in Appendix 9.

Extra generating capacity and growth in electricity demand beyond 2020 is not included in either the BAU or ZCA2020 scenario. The analysis compares capital expenditure out to 2020, and the ongoing costs of the two 325TWh/yr systems out to 2040. The Plan assumes that beyond 2020, implementing energy efficiency measures, rather than installing new power generation, will be the most economically viable way to meet the increasing demand for services; even with such measures, Australia's per capita electricity generation will still be significantly higher than other developed economies (see Part 2). However, future demand growth is beyond the current scope of the analysis.

Modelling Business-As-Usual

To allow a fair and reasonable cost comparison between fossil fuels and renewable energy, this section examines the projected expenditure associated with sizing the Business-As-Usual model to generate 325TWh/yr of electricity from fossil fuel resources by 2020.

Under BAU, no significant adjustments in technology choices are made in response to rising oil or carbon costs. Thus, in order to supply the projected demand growth, additional conventional coal and gas-fired power plants are constructed and old coal-fired power plants are replaced as needed. The use of energy supply infrastructure remains inefficient, with large investments continuing to be made to supply energy during short demand peaks. Outside of peak demand times, more than a third of Australia's total electricity generation infrastructure is idled or throttled back.

While capital expenditure for fuel-switching and efficiency has not been included, the analysis shows the future costs of oil for transport and gas for heating that would be incurred, under either BAU or ZCA2020, if these switches do not take place and the extra electricity supply is used to meet a growing demand for current services with no efficiency measures. This future energy 'bill' can be considered a fund that is available for efficiency and fuel-switching investments.

Under BAU, resources such as natural gas are consumed in ever increasing quantities. The cost of natural gas is expected to nearly double, in real terms, by 2050[3]. The price of oil is also likely to rise rapidly, although for the purposes of this modelling, it is assumed that the oil price will plateau at $AU130 per barrel. This is based on the likely probability that oil price rises above this point would, under BAU, incentivise energy companies to undertake more costly and environmentally destructive ways of securing oil supplies, such as coal-to-oil technologies, tar sand processing, and oil from shale.

Modelling the ZCA2020 Stationary Energy Plan

As detailed in Part 3 of this report and in Table 7.1, the Stationary Energy Plan requires capital expenditure of $AU370 billion in the 2011-2020 timeframe. This will provide a new, renewable grid able to supply at least 325TWh/yr of electricity, 40% higher than today's electricity consumption. The Stationary Energy Plan excludes the costs associated with building retrofitting (to be described in the Commercial and Residential Buildings Sector Plan), electric cars and

TABLE 7.1
ZCA2020 Stationary Energy Plan Total Cost

Component	AUD$,Bn
CST	$175
Backup Heaters	$8
Bioenergy supply	$6
Wind	$72
Transmission	$92
TOTAL	**$353**
Off-grid CST + Backup	$17
"TOTAL + Offgrid"	**$370**

expanded public transport (to be described in the Transport Sector Plan) and industry retrofitting (to be described in the Industrial Processes Sector Plan).

With the Plan heavily reliant on freely available energy sources such as solar insolation and wind, there are no ongoing fuel costs. As such, the rising prices of oil and gas have only a marginal impact on the Plan during the transition period 2011-2020 as these fossil fuels are phased out.

A complete switch to renewable energy will leave the owners of fossil fuel infrastructure with stranded assets. The economic models do not include provisions for any compensation payments. The question of financial compensation to generators is a political one that is not addressed in this report however two points are made. Firstly, many fossil fuel power plants in Australia will be at least 40 years old and due for replacement during the time of the transition[4]. Given the age of these assets, they are fully depreciated[5]. Secondly, when many of these assets were privatised and purchased by the current owners, climate change and its implications for fossil fuel power generation were a known business risk. Due diligence by the purchasers of these assets at the time of acquisition would therefore have alerted them to the risk of these assets becoming stranded.

7.2.2 Comparing the Models

Figure 7.1 compares net present costs (2011— 2040) under Business-As-Usual versus the ZCA2020 Stationary Energy Plan. Net present fuel, operations, maintenance and capital costs required are approximately equal for both BAU and ZCA2020, at $AU500 billion. The ZCA2020 scenario is more capital intensive, while most of the costs under BAU are for purchasing coal and gas. The full results are shown numerically in Appendix 9.

However, if the net present costs of meeting Australia's BAU demand for domestic and foreign-sourced crude oil (~ $AU1,300 billion for 2011— 2040), gas for heating ($AU140 billion) and potential emissions permits (~ $AU420 billion for 2011— 2040) are included, this brings the total net present costs under BAU to approximately $AU2,350 billion.

The equivalent net present costs under the ZCA2020 Stationary Energy Plan bring the total to $AU800 billion (2011— 2040) representing a net present cost savings of nearly $AU1,550 billion.

These different scenarios are summarised in Table 7.2.

FIGURE 7.1
Economic Model Comparison

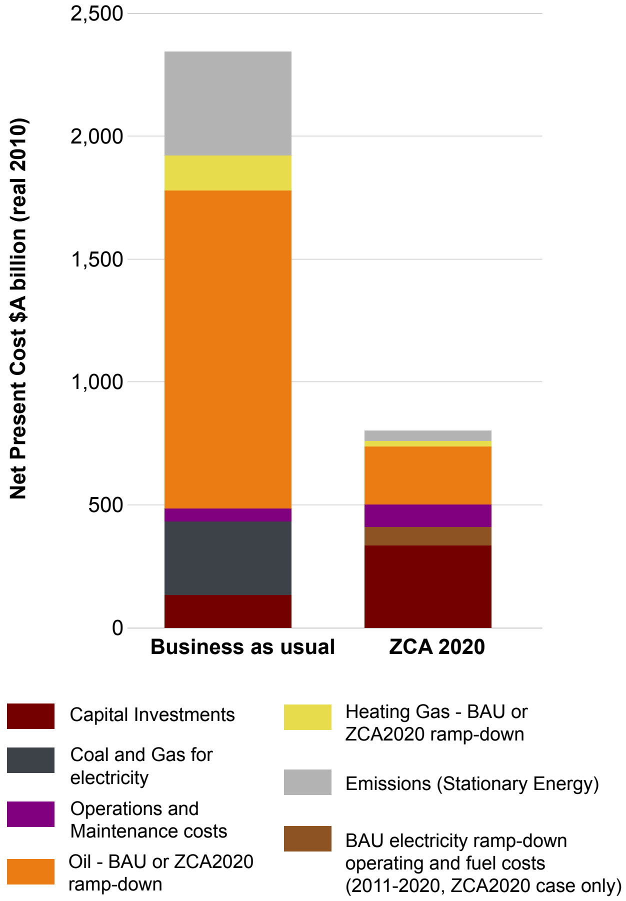


TABLE 7.2
Results of Economic Model (real 2010 $AU billion)

	BAU	ZCA2020	Difference
Total	$2,354	$806	$1,548
Sum Excl Oil & Gas	$914	$546	$368
Sum Excl Emissions	$1,930	$765	$1,165
Sum Excl Oil, Gas & Emissions	$490	$504	-$15

FIGURE 7.2
Net Present Costs: BAU minus ZCA2020

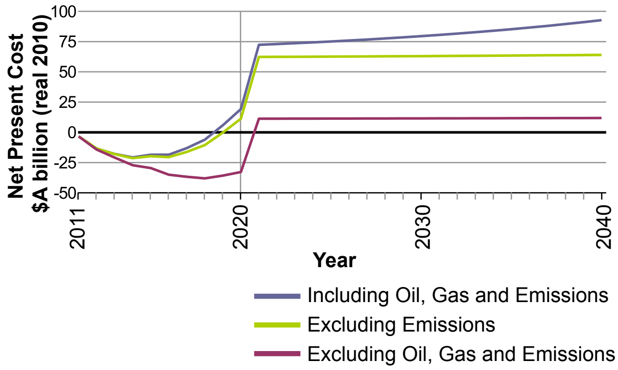
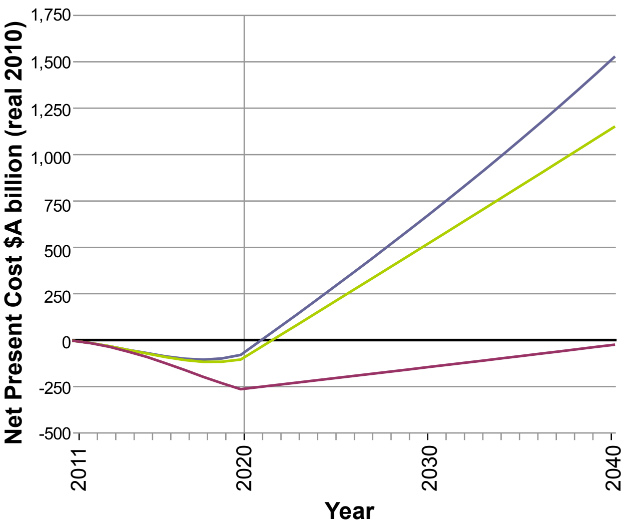


FIGURE 7.3
Cumulative Net Present Costs: BAU minus ZCA2020



Economic Payback Period

The Plan requires a capital expenditure of $AU370 billion over the period 2011-2020 as renewable energy systems are sequentially installed to provide Australia with an essentially new and expanded electricity supply system.

Over this same 2011-2020 period, the BAU scenario requires capital investment of $AU135 billion for electricity system expansion and ongoing replacement of fossil fuel plants. However, the BAU scenario incurs higher ongoing costs due to increasing coal and natural gas consumption over the full 2011-2040 modelling period whereas the Plan phases out the use of fossil fuels.

Figure 7.2 and Figure 7.3 show the range of various economic payback curves for the Plan scenario. In the narrow terms of capital and operating expenditure for electricity generation, the avoided costs of fossil fuels under the Plan allow the inital capital costs to be recouped by 2040. However, if the full potential costs for oil, gas and emissions are included, the Plan will have an economic payback time of only a few years after its completion in 2020.

Applying Different Discount Rates

As previously mentioned, the economic comparisons have been calculated using the Stern Review discount rate of 1.4% which is regarded as a representative measure for long term societal costs. However, similar results are produced when other discount rates are applied. For example, using either the Government bond rate of 6% or the standard infrastructure investment rate of 8%, the comparison reveals that the ZCA2020 plan is only marginally more costly than BAU when oil, gas and emissions costs are excluded - $AU 100 billion over the 30 years (refer to Appendix 9).

7.2.3 Other Unmodelled Economic Benefits

Transitioning to an electrified transport system of electric vehicles and expansion of the rail network will require investment in addition to the $AU370 billion for the Stationary Energy Plan, which will be outlined in the ZCA2020 Transport Plan. However, given the very large costs that the continuation of oil imports imposes on the Australian economy, transport electrification will be a very attractive investment.

Oil is not, however, the only cost of Australia's current transportation system. Establishing a transport network based around electric cars and electrified public transport brings many co-benefits in reducing the social and medical burdens imposed by today's oil-based transport system.

Soot particle pollution costs the Australian economy between $AU1.6 and $AU3.8 billion per year in premature death and disease[6]. Taking the central estimate of this range ($AU2.7 billion), this adds up to a cost of $AU80 billion (in 2009 dollars) between 2011 and 2040, without accounting for growth in vehicle and population numbers.

Medical, insurance, and the clean-up cost risks associated with the extraction, transportation and storage of oil are low in typical years (the cost of cleaning up oil spills in Australia was $AU5 million in 2007-2008)[7], but can be extremely high. A single large incident, such as the Exxon Valdez oil spill in 1989, cost ExxonMobil $US 3.8 billion in clean-up costs.[8] Such spills are always a risk when producing oil in, or transporting oil over, the sea.

Traffic congestion was estimated to cost Australian businesses $AU9.4 billion annually in 2005, rising to $20 billion per year by 2020[9]. Road construction costs are around $AU14 billion annually Australia-wide.[10] The level of expenditure required to maintain roads is largely dictated by the volume of heavy axle-weight vehicles. A doubling of axle-weight increases road-damage costs by sixteen times.[11] [12] Under the ZCA2020 Plan, heavy road freight and passenger bus transport are transferred to heavy and light rail. This change, combined with large reductions in the volume of traffic will significantly lengthen the period between resurfacing of roads. The modal shift to electrified rail will also eliminate the need for large extensions to the road network.

FIGURE 7.4
ZCA2020 Stationary Energy Plan capital cost compared to other economic activity

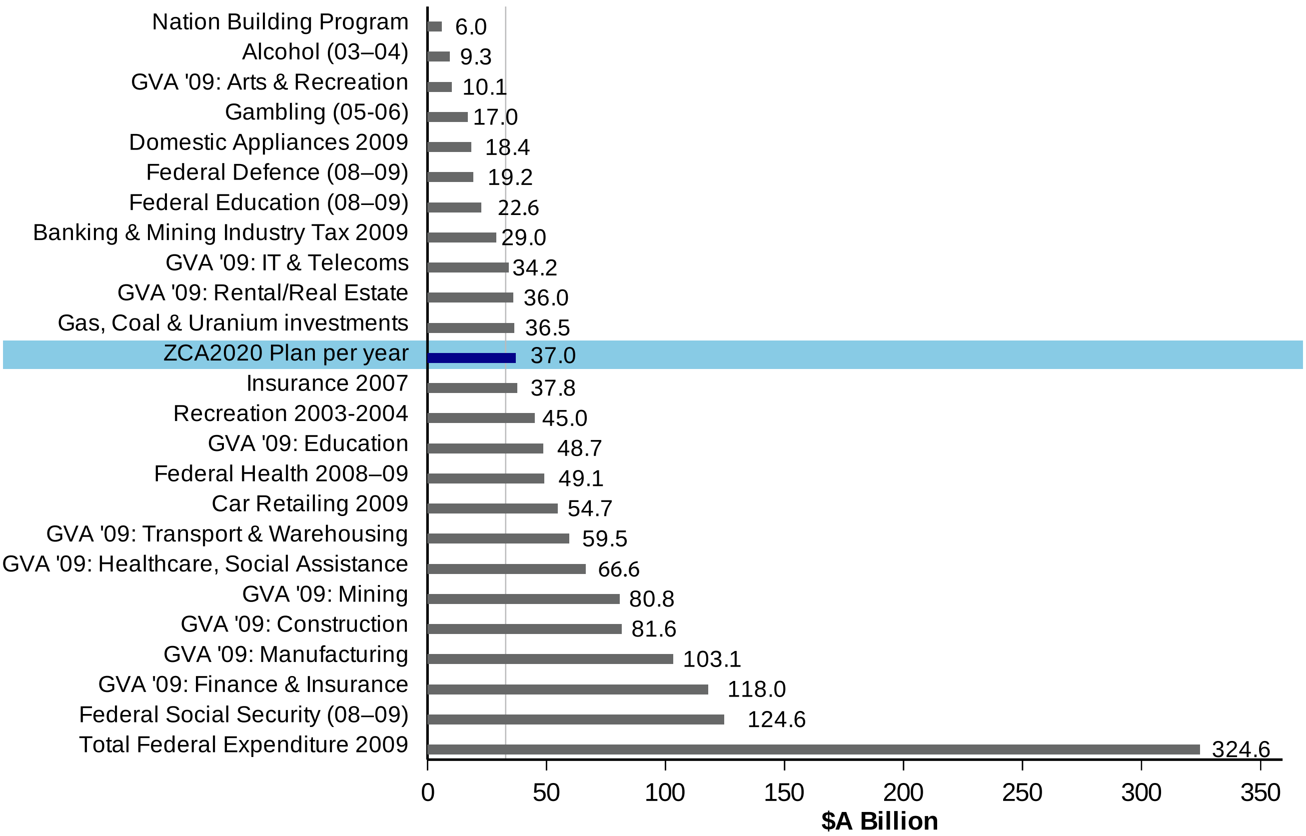
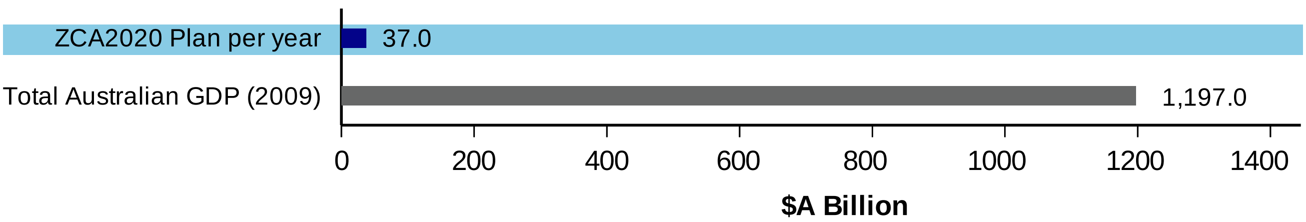


FIGURE 7.5
ZCA2020 Stationary Energy Plan capital cost compared to Australian GDP



In 2006, road trauma in Australia cost $AU17 billion annually, or 1.4% of GDP[13]. With a modal shift of passengers and dangerous heavy road vehicles to electrified rail, road trauma costs will be substantially reduced.

Co-benefits also exist for a phase-out of coal and natural gas extraction such as improved air quality and the associated benefits for health, agriculture and the natural environment.

7.3 The ZCA2020 Stationary Energy Plan Investment in the Context of Other Economic Activity

As outlined above, the implementation of the ZCA2020 Plan results in considerable savings when compared to Business-As-Usual over the coming decades. The initial expenses are recouped by eliminating fossil fuel costs and by reducing other externalities such as congestion, pollution and dependency on foreign oil imports.

Despite these evident economic benefits, the frequently quoted reason for not investing in large scale renewable technologies to reduce Australia's emissions is that this would be too expensive.

Certainly, the Plan's required up-front capital expenditure of $AU370 billion (averaged at $AU37 billion per year over the coming decade) is significant. However, when this is compared to other expenditures within the Australian economy, it becomes evident that this is neither unachievable nor unrealistic.

The required annual ZCA2020 investment will not originate from any single source but rather will be a combination of public and private investment. The goal of both sectors will be to benefit from being a part of this future industry, in the same way that others benefited from conventional energy production in the past.

Figure 7.4 compares a range of micro and macroeconomic annual figures from the Australian economy (see Appendix 9 for references) and shows that the ZCA2020 investment of $AU37 billion per year is not extraordinary when compared with other public or private spending. Of particular significance are the Gross Value Added (GVA) measures for Construction and Manufacturing. GVA represents the value of goods and services produced in a given area and can be seen as quantification of the size and production capacity of the sector. Figure 7.4 clearly shows that the scale of the Plan is fully within the capacity of the Construction and Manufacturing industries while at the same time it would contribute significantly towards both sectors.

At approximately 3% of the 2009 Australian Gross Domestic Product, the implementation of the Plan is not only within the capacity of the Australian economy but it would significantly contribute to it. Jobs and new industries will be created, dependencies on foreign oil imports will be minimised and Australian greenhouse gas emissions will be substantially reduced.

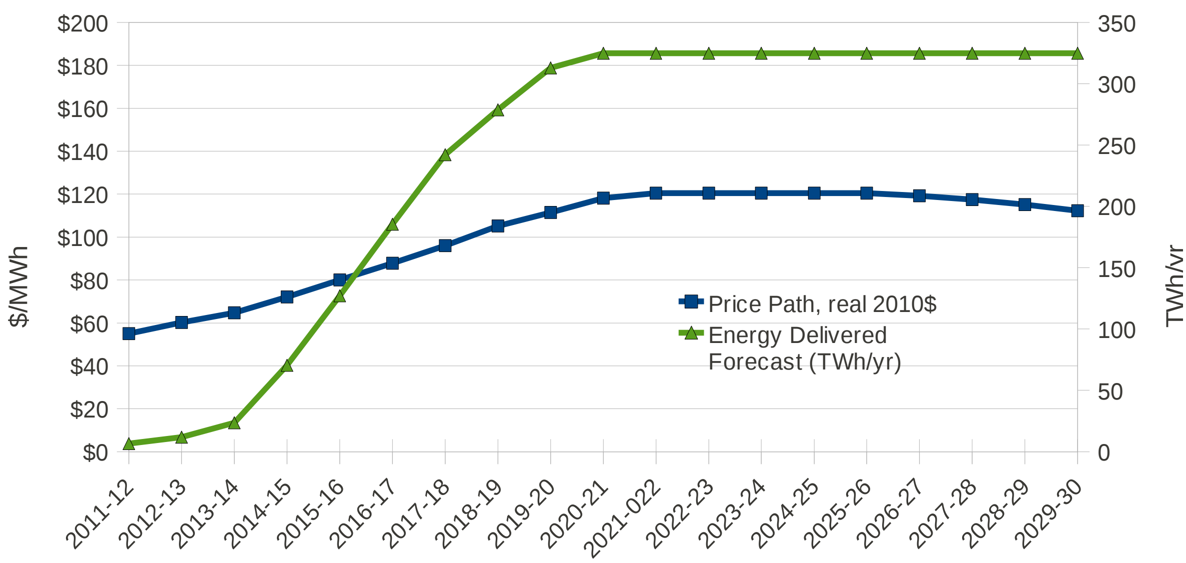
7.4 How much would electricity cost under ZCA2020?

Analysis of the proposed ZCA2020 renewable energy infrastructure based on current market financial parameters indicates that electricity prices would rise by approximately 6.5 cents per kWh (real 2010 currency) by 2020, or about 33% of the current domestic consumer price of 20c/kWh. While not prescriptive, this is indicative of the relative costs of the ZCA2020 Plan. 6.5c/kWh is a similar premium to today's cost of GreenPower, and would only impose an extra $AU8 per household per week in direct electricity costs. This rate of increase is similar to the price increase expected under Business-As-Usual. The wholesale electricity price would also increase for businesses and industry, creating incentives to increase their energy efficiency.

The $AU370 billion investment required for the installation of the 100% renewable energy grid under ZCA2020 is not a cost to the economy. It is an investment that will generate returns over the lifetime of the infrastructure. The exact impact of the investment on electricity prices depends entirely upon the financing mechanisms used, of which there are many. Some policies would allow for the infrastructure to be built with minimal impact on electricity prices. For example the current policies in the U.S.A. include a 30% Investment Tax Credit on new solar plants, which lower the initial cost of capital through a tax concession and thereby lowers the cost of electricity required for these projects to be profitable.

However, to aid understanding of how the impacts of the $AU370 billion investment are in fact spread over 30+ years, a single example is given below of one potential funding scenario, to gauge the actual costs that would be involved.

FIGURE 7.6
Projected electricity price path modelled for ZCA2020 Stationary Energy Plan



This investigates the potential impact on electricity prices if the ZCA2020 Plan was funded in the same way that existing power transmission and distribution assets are funded under current regulated market arrangements.

The price of electricity to consumers is made up of several components:

- wholesale price – the price of power dispatched from a power plant.
- transmission – charges for using the high-voltage transmission network to transport the electricity.
- distribution – charges for using the low-voltage network that conveys electricity to consumers, mainly residential and commercial (industrial customers often plug directly into the transmission grid).
- retail margin – charges from the electricity retailing companies.

Of the above four cost components, the natural monopolies of the transmission and distribution charges are regulated under determinations of the Australian Energy Regulator, according to agreed regulatory revenue models. These models are built up from payment for regulated return on debt and equity portions of invested capital, as well as operating and maintenance costs of the regulated transmission and distribution assets. The generation cost component of electricity in the National Electricity Market (NEM) is not determined by the AER but rather by a competitive auction process in which generators bid, are scheduled and dispatched under the central coordination of the Australian Energy Market Operator.

This study has modelled the long term wholesale cost of electricity which would apply to generation assets foreseen under the ZCA2020 plan, and transmission to nodes of the existing HVAC grid via the new ZCA2020 HVDC and HVAC upgrades. The model used has amalgamated the capital and operating costs of the new renewable generation assets and new transmission grid assets, and applied these costs to the AER regulated asset pricing model in conjunction with typical financial model parameters which have been used for recent AER price determinations.

It is recognized that generation businesses are not regulated assets, and would in practice use other economic models to determine their required revenue to achieve target economic performance. Nonetheless, the AER model's inclusion of terms for capital repayment, return on equity and debt, operation and maintenance costs and treatment of imputation credits is considered by this study to provide a reasonable estimate of long term marginal costs of power which would be required to finance the ZCA2020 generation and transmission grid assets.

The Australian Energy Regulator provides a publicly available 'post-tax revenue model' that is used to calculate electricity prices for regulated power assets[14]. This has been used to model the investment and ongoing costs for the ZCA2020 generation and transmission infrastructure. Financing parameters used for the ZCA2020 model were set as currently specified by AER in recent regulated pricing determinations for Victorian power companies , giving a "nominal vanilla" WACC (Weighted Average Cost of Capital) of 9.68%[15] (see Appendix 9 for details).

Current average NEM wholesale electricity prices are about $AU55/MWh, or 5.5c/kWh. It is calculated that funding the ZCA2020 renewable energy infrastructure including the extra high-voltage transmission lines would raise the equivalent wholesale price to $AU120/MWh (12c/kWh) after 2020. Figure 7.6 shows the projected price path in real (2010) dollars, as well as the nominal (inflation adjusted) price. On completion of the Plan the wholesale electricity price would be 6.5c/kWh greater than today.

The results of the modelling are consistent with the current cost of renewable energy in Australia.

While it is expected that the costs of solar thermal power would drop to 5-6c/kWh, this only applies to plants that are run at 70-75% capacity factor. Due to the extra capacity specified, under the Plan CST plants would only be required to run at slightly over 50% capacity factor. With further optimisation of the proposed infrastructure, it is expected that this over-design would become smaller and lower the overall costs.

The higher price of 12c/kWh also takes into account the costs for the new ZCA2020 high voltage transmission links, which are required to deliver the wholesale power to relevant nodes of the existing high voltage transmisson grids.

The price premium of 6.5c/kWh is equivalent to the current premium that already exists in Australia today for GreenPower, which ranges from 5-6.5c/kWh[16].

This increase is less than electricity price increases already experienced by household consumers. For example the Independent Pricing and Regulatory Tribunal in NSW has proposed annual tariff increases of between 7 and 10% over 3 years to June 2013[17]. This rise was motivated by the need to "enable higher levels of investment in the electricity distribution networks". The price increases mean that after 3 years the price of electricity will increase by up to 42% which equates to a 8.6 c/kWh increase.

With an estimated 9.8 million households in 2020[18], consuming 63TWh/yr of electricity under ZCA2020 (see Appendix 1), this price rise would impose a cost of around $AU420 per household per year, or $AU8 per household per week. The wholesale price rise of electricity for businesses and industry would also have a flow-on effect that has not been determined with this preliminary analysis, however, such a price rise would also create an incentive for them to improve their energy efficiency.

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Conclusion

Enercon wind turbines, Albany, WA[1]

Transitioning to a zero carbon future in Australia is achievable and economically feasible using the technology of today.

The ZCA2020 Stationary Energy Plan demonstrates that converting Australia's energy sector to 100% renewable sources by 2020 is achievable using commercially available technology. Wind, solar, hydro and biomass resources can be combined with energy efficiency measures to adequately meet Australia's projected future energy demand.

The strategic investment of $37 billion per year required to transition Australia's stationary energy sector to renewable sources, is equivalent to a stimulus of just 3% of GDP over 10 years. In the long term, however, the lower fuel costs of renewable energy recoup the upfront investments. Achieving the ten-year transition is well within Australia's existing industrial capacity. Adoption of this plan promises health benefits, long-term energy security, and significant economic benefits. The ZCA2020 Plan will position Australia as a global leader in the zero carbon economy of the 21st century – the economy required for effective mitigation of climate change.

Australia is ready for a zero carbon future. The challenge now lies firmly in the hands of decision-makers, who must put in place strong future-oriented policies that will allow this transition to occur – starting today.

Rapid action is essential to achieving the ZCA2020 goals: the 'ramp up' needs to begin by 2011 to achieve a 100% transition in ten years. Commercially available renewable energy technologies can be immediately utilised to supply 100% reliable baseload power without needing to wait for further research, development, or demonstration. Positioning solar thermal power generation as a critical component of this technology mix is important because there are no technical barriers to its deployment, and it is perfectly suited to Australia's geography and climate. Australia should follow the lead of other sun-drenched countries such as USA, Spain, Italy, United Arab Emirates, Algeria, Israel, Morocco and Egypt. These countries are currently operating or constructing solar thermal plants in order to exploit their most abundant natural resource.

Other mature technologies specified by the Plan are wind energy, high-voltage direct-current transmission, biomass from agricultural waste, small-scale photovoltaic and solar hot water, electrified rail and road vehicles and electrified heating and cooling with heat pump systems. All these technologies are proven, mature and ready to be rolled out on a national scale.

Currently more than half of all Australian emissions come from the stationary energy sector. The ZCA2020 Plan reduces these emissions to zero, by converting electricity production to 100% renewable energy, improving demand side efficiency and switching from less efficient oil and gas furnaces and engines with measures that are inherently more efficient, while delivering the same, if not better, services to the Australian public.

Modelling conducted by the ZCA2020 team and Jack Actuarial Consulting using two-years of actual half-hourly data found that the electricity generation mix will meet 100% of Australia's electricity demand for every hour of the year. Seasonal and daily variability is accommodated by geographic diversity of renewables sites and the flexibility of solar thermal's dispatchable-on-demand electricity. The combination of backup reserves from existing hydro power and biomass firing with solar thermal is able to meet the 2% yearly energy shortfall that the modelling indicates will occur during infrequent low sun and wind periods.

Upgrades to the electricity transmission grid with commercially available high-voltage direct current and alternating current (HVDC/HVAC) technologies will be used to connect the new wind and solar sites. Not only are these transmission upgrades viable and economically feasible, but they will also strengthen and modernise the grid.

The scale of the construction, manufacturing, resource, and workforce requirements is well within the capability of the Australian economy. For example, the 80,000 construction jobs which will be required at the peak of the Plan installation represent only 8% of Australia's present construction workforce. During the recent resources boom until 2008, new construction jobs increased at the rate of 50,000 per year – far in excess of the Plan's requirements. Jobs lost in the existing fossil fuel supply industry will be more than replaced by the many jobs created in renewable energy manufacturing, operations and maintenance.

The Plan's requirement for concrete, steel, glass and other materials is minor when compared with the quantities currently available. Furthermore, the life-cycle emissions resulting from the production of these materials, as well as those from the construction of wind farms, solar plants, grid upgrades, etc., are negligible. After an initial 'emissions investment', the payback time, in terms of emissions saving compared with business-as-usual, is approximately two months. Wind and solar thermal plants are built from components that can be mass-produced, and the resultant economies of scale that will develop during ramp-up will drive down the cost of renewable electricity. Furthermore, the Australian manufacturing industry will benefit from the growth in renewable energy and the potential for ongoing exports, providing tens of thousands of jobs.

The total investment to transition Australia's stationary energy sector to renewable electricity production is $370 billion over the next ten years, or an average of $37 billion per year. This is equivalent to 3% of Australia's $1,200 billion annual Gross Domestic Product. While this is about $260 billion more than the capital spending required under business-as-usual by 2020, this investment is easily recouped over the longer term as the costs of purchasing oil, gas, and coal are avoided. The net present cost of the ZCA2020 Stationary Energy Plan is approximately equal to the net present cost of business-as-usual to 2040. The economic cost-benefit analysis is therefore attractive, even without considering the enormous value of avoiding climate change costs which, as Sir Nicholas Stern warns, could reach 20% of yearly GDP by 2050.

As demonstrated by the electricity price analysis, which indicates that electricity prices may increase by only 6.5c/kWh, the ZCA2020 investment will ensure that the transition to 100% renewable energy is affordable. Whatever mechanism is used to achieve the Plan, a cost of $8 per household per week is an impressively low benchmark, considering the enormous benefits of making the transition.

In summary, transforming Australia's energy sector to 100% renewable electricity production in ten years is achievable using today's commercially available technologies, and is economically attractive. It would deliver the benefits of zero energy-related greenhouse gas emissions and eliminate dependence on foreign oil imports while strategically positioning Australia as a world leader in the emerging renewable energy economy. This plan offers a pragmatic and realistic vision for a zero carbon future. Converting this vision into reality requires an immediate commitment to change from Australian policymakers to deal decisively with these pressing climate and energy issues.

"The time has come to aggressively accelerate that transition... The time has come, once and for all, for this nation to fully embrace a clean-energy future."

— BARACK OBAMA,
PRESIDENT OF THE UNITED STATES OF AMERICA,
JUNE 2010[2]

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Appendices

Contents

Appendix 1
Energy Demand

Steps for converting 2006-07 Australian energy usage to ZCA2020 final energy use.

This outlines the top-down analysis that has been used to project 2020 energy and electricity demand under the ZCA2020 plan, taking into account efficiency measures and electrification of services currently provided by gas and petroleum. In summary, Australia's grid electricity demand will increase by 42% from 228 TWh/yr in 2008 to 325 TWh/yr in 2020, however the overall end-use energy demand will drop by more than half due to the increased efficiency of electrified services.

Figure A1.1, "Australian Energy Flows 2006-07 from the Office of the Renewable Energy Regulator"[1], is a graphical representation of the data found in ABARE's Energy in Australia 09 Report[2]. End-use energy consumption is shown as "Utilisation". This is used in Table A1.3 as a base for calculating energy demand under the ZCA Plan (see the columns referred to as "Set 1" for 2006-2007).

The energy values in columns "Set 2" are scaled up for 2007-08 using a 2% GDP growth rate, so that they can be crosschecked with the most recent ESAA Electricity Gas Australia 2009 Report, with data from 2007-08 (available in hardcopy[3]). This scaling of ABARE numbers crosschecks with ESAA—228 TWh of electricity generation in 2008, from on-grid electricity sources. **2008 is used as the benchmark year for this analysis** due to the availability of data at the time of working. However, while historically energy consumption has been tied to GDP growth, ZCA2020 intends to decouple energy use from GDP growth. Energy use per capita is used as a reference, taking into account medium-range population growth.

"Set 3" columns—adjusting industrial energy consumption to reflect the ZCA Plan.

In the "Set 3" columns, an adjustment is made for energy associated with the existing fossil fuel industry that does not require replacement under ZCA2020. In summary these energy savings arise from:

- fossil fuels used to generate off-grid and embedded electricity—there is an extra 4,810 MW of off-grid and embedded capacity in Australia (ESAA[3] p14), however in ABARE's accounting, the fuel used to fire these is counted as industrial primary energy use (ABARE09[2], p15, see footnote).
- parasitic electricity used by fossil fuel power stations to run their own processes
- coal used in smelting of iron ore (counted as industrial coal)
- diesel and electrical energy used in coal mining
- natural gas used domestically to process LNG for export—10% of exported natural gas energy

Parasitic electricity

ESAA[3] reports that 228.6 TWh of electricity was generated in 2007-08. However only 213 TWh was ultimately delivered to the grid - an average loss of 7% (15.6 TWh), due to the parasitic electricity requirements of power stations. In the ZCA2020 Plan, CST generation plant parasitic loads have been allowed for in the designed capacity of the CST facilities.

Off-grid generation

The actual electricity generated by the 4,810 MW of off-grid capacity is not reported in ABARE09[2], so the numbers in ABARE10[4] are used to crosscheck. This reports 265 TWh of total electricity generation in 2007-08, but only 229 TWh of this is on-grid[4]. Therefore the difference (36 TWh) is off-grid. Much of this off-grid electricity is generated by reciprocating engine and open-cycle gas turbine plant located at remote mine sites and off-grid towns. Assuming an average thermal efficiency of 35%, these are using 103 PJ of oil and gas to generate the 36 TWh of electricity. 103 PJ of oil and gas is therefore removed from the industrial energy usage column. The 36 TWh will be provided from solar thermal and dedicated biomass backup, costed into the Plan separately. In reality, some of this could also be provided from small-scale remote solar PV/battery systems. This is an area for further research..

Coal for smelting

Coal is used as the carbon source for smelting of iron ore to iron. As outlined in Part 3, preliminary work suggests that replacing coal blast furnaces with Direct Reduced Iron utilising biomass gasification is a feasible zero-emissions alternative.

ABARE09[2] lists 13.2 PJ of coal used in coke ovens, and 55.7 PJ used in iron and steel. However, this may not reflect the extra energy produced as a byproduct of the conversion of coal to coke. The ZCA2020 analysis uses data directly from the source to determine how much coal is entering the smelters. Illawarra Coal, a BHP subsidiary, supplies premium quality coking coal to the domestic and export markets. According to their reports, 4 million tonnes per year of coking coal are delivered to the Port Kembla and Whyalla steel works[5]. At an energy content of 27.7 GJ/tonne for black coal[6], this represents 110 PJ of coal energy

FIGURE A1.1
Australian energy flows 2006–07 (Petajoules)

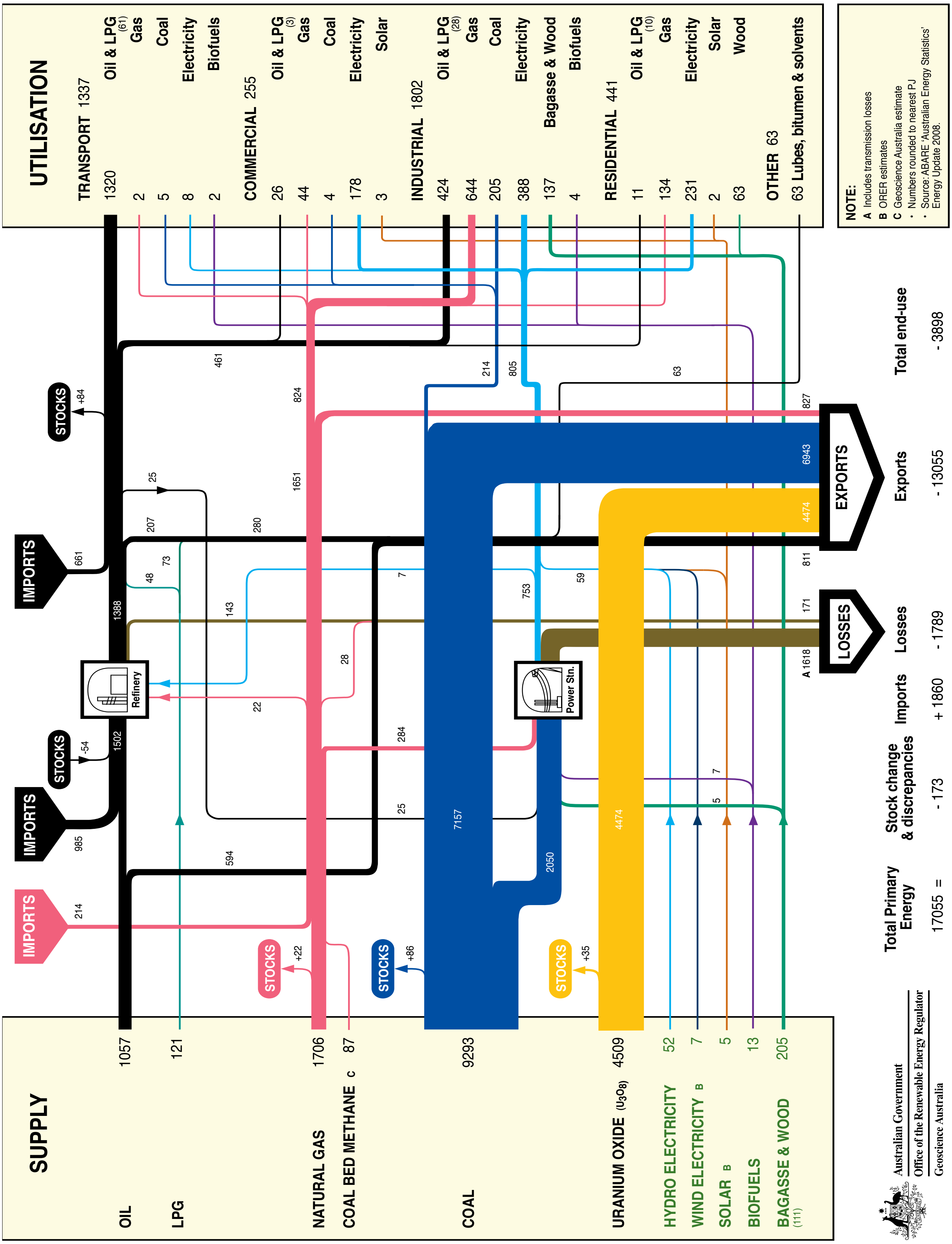


TABLE A1.3
Calculation detail for 2020 Energy Estimates

	SET 1		SET 2		SET 3		SET 4		SET 5		SET 6			
	2006-2007		Adjust for GDP Growth to 2008		Exclude gas for LNG export, smelting coal, offgrid fuel & power plant parasitics.		Electrifying Transport Adjustment		Other Fuel Switch Adjustments		Efficiency Adjustments and Onsite Solar Use			
	PJ/yr	TW-hr/yr	PJ/yr	TW-hr/yr	PJ/yr	TW-hr/yr	PJ/yr	TW-hr/yr	PJ/yr	TW-hr/yr	PJ/yr	TW-hr/yr	GW-hr/d avg	GW avg
Energy savings from each step					577		1132		269		278			
TOTAL	**3834**	1065	**3915**	1087	**3338**	927	**2206**	613	**1936**	538	**1659**	461		
Transport	1337		1365		1365		233		233		233			
Oil & LPG	**1320**		1348		1348		0		0					
Natural Gas	**2**		2		2		0		0					
Coal	**5**		5		5		0		0					
Electricity	**8**		8		8		180	**50**	180		180	50	137	5.7
BioLiquids for Transport	**2**		2		2		**53**		53		53			
Commercial	254		259		259		259		225		180			
Oil & LPG	**26**		27		27		27		0					
Natural Gas	**44**		45		45		45		0					
Coal	**4**		4		4		4		0					
Electricity	**178**		182		182		182		**223**		**161**	45	122	5.1
Wood	**1**		1		1		1		1		1			
Biogas	**0**		0		0		0		0		0			
Solar Heating	**1**		1		1		1		1		**18**			
Industrial	1802		1840		1263		1263		1094		928			
Oil & LPG	**424**		433		**209**		209		0		0			
Natural Gas	**644**		658		**391**		391		0		0			
Coal	**205**		209		**108**		108		0		0			
Electricity	**388**		396		**339**		339		**833**		**599**	167	456	19.0
Wood & Bagasse	**137**		140		**212**		212		**212**		212			
Biogas	**4**		4		4		4		**50**		50			
Solar Heating	**0**		0		0		0		0		**67**			
Residential	441		450		450		450		384		**318**			
Oil & LPG	**11**		11		11		11		0		0			
Natural Gas	**134**		137		137		137		0		0			
Electricity	**231**		236		236		236		**317**		**228**	63	174	7.2
Wood	**63**		64		64		64		64		64			
Solar Heating	**2**		2		2		2		**2**		**25**			
Electricity Subtotal	**805**	224	**822**	228	**765**	212	**936**	260	**1553**	431	**1169**	**325**	889	**37.1**

to be replaced by biomass-gasified DRI. From the working in Section 3, the replacement energy required is 72 PJ of biomass, as well as 3.3 TWh of electricity for Electric Arc Furnace smelting.

Gas used for export LNG

LNG requires a large amount of energy to compress, cool and liquefy natural gas. Typically, an extra 10-15% of the energy value of LNG is required for liquefying, which is provided by extra gas. 827 PJ of LNG was exported in 2008, therefore an estimated 10% (83 PJ) of gas was used in industrial onshore preparation processes. It is assumed that there is no place for LNG exports in a low-carbon future, so this has been removed from the analysis.

Energy used in coal mining

Brown coal mining uses electricity from the associated power plant to directly deliver coal using conveyor belts and equipment running on the plant's own electricity, which is already included in the 15.6 TWh of parasitics.

Australia produced 327 Mt of black coal in 2007-08[7]. Of this, 77% is from open-cut mines, with the remainder from underground mines[8]. Of this total, 135 Mt was export coking coal, for steel production. For this analysis, it is assumed that all domestic coal consumption is phased out by 2020, along with thermal coal exports. For conservatism, it is assumed that the 135 Mt coking coal exports may still be in operation.

Open-cut coal mining uses 0.23 GJ of onsite energy per tonne of coal mined, of which 90% is from diesel fuel[9], the remainder being mostly from electricity. Underground mines have similar extraction efficiencies[10], so this has been used as the basis for coal mining parasitics.

Phasing out of 190 Mt of coal mining for domestic and thermal coal exports will save 39 PJ of diesel and 1.2 TWh of electricity.

"Set 4" columns—Electrification of Transport

50 TWh is allocated for 2020 transport electrification - see separate explanation below.

"Set 5" columns—Electrification improves delivered energy efficiency

The energy currently provided by fossil fuels is replaced by electricity. However, the conversion efficiency is not 1:1, as electricity is inherently more efficient in energy delivery than combustion of fossil fuels. It is assumed that, to deliver the same services of heating, less electricity is required, with the following breakdown:

Commercial and Residential sector—x 0.55

Most fossil fuel use in the residential and commercial sector is for cooking and for space heating. Cooking with natural gas wastes heat that is lost to the surrounding air, not transferred to the pot. Electric induction stovetops directly transfer electrical energy to the metal base of the saucepan, a highly efficient process. Induction stovetops require only 50% to 80% of the energy of a gas stovetop to deliver the same amount of heat energy to food.

However, space heating using heat pumps is even more energy efficient. Heat pump heaters are like airconditioners run in reverse. They use only one unit of electricity to deliver three units of heat, as the refrigeration cycle is actually drawing energy from the surrounding ambient environment[11]. This means that switching from a gas heater to a heat pump would require less than 33% of the energy to deliver the same heating service. Under some conditions, heat pumps can achieve even higher efficiencies, however this has not been modelled.

Taking into account the fact that there is a mix of heating and cooking requirements with different conversion efficiencies, it is assumed that the switch from gas to electricity in commercial and residential use requires 55% of the original energy to deliver the same service.

Industrial sector—x 0.75

Most industrial gas and fossil fuel is used for high temperature heating in furnaces. These lose a lot of energy in the flue gases which are a by-product of the combustion. Old heaters may only be 60-70% efficient, newer heaters 70-85%[12]. Many industrial facilities in Australia are several decades old, and without modern monitoring equipment cannot be run with the tight parameters required for high efficiency operation[13]. In the ZCA2020 Plan, electrical resistance heating is used instead, which can directly transfer heat via efficient heating elements without the flue losses. A 25% energy reduction is considered reasonable given both the lack of flue losses, and the potential for some low-temperature applications to be met via heat pumps.

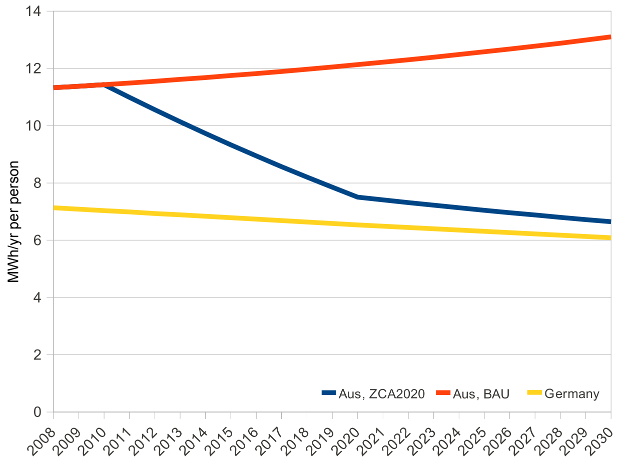
"Set 6" columns—Energy Efficiency in utilised energy—x 0.8, economy-wide

If 1 MJ of heat is delivered to a room, either by 1 MJ of gas, or by 0.3 MJ of electricity via a heat pump, much of that heat will escape if the room is not insulated properly. Based on a broad range of efficiency improvements, such as insulation, upgraded appliances, and improved industrial processes, the ZCA2020 Plan projects that, in 2020, total end-use of energy is reduced by 20% from 2008 levels. This translates to a per capita efficiency gain of 33%, taking into account mid-range population growth as project by ABS[14].

Per capita electricity

As shown in part 2, with a per capita efficiency gain of 33%, Australian electricity use per capita in 2020 will approach that of Germany. Germany has ongoing targets for reduction in overall electricity consumption. This particular dataset is based on standardised data from the IEA[15], and the official efficiency targets of the German Meseberg Report[16].

FIGURE A1.2
Per-capita electricity consumption, existing services only illustrating efficiency measures (IEA standard data)



This compares existing electricity uses **only** and ignores the ZCA2020 strategy of fuel-switch electrification for transport, residential and commercial heating (and others) as described elsewhere.

Onsite solar—x 0.9

It is assumed that 10% of the electricity requirements can be displaced through the use of onsite solar, over the commercial, residential and industrial sectors.

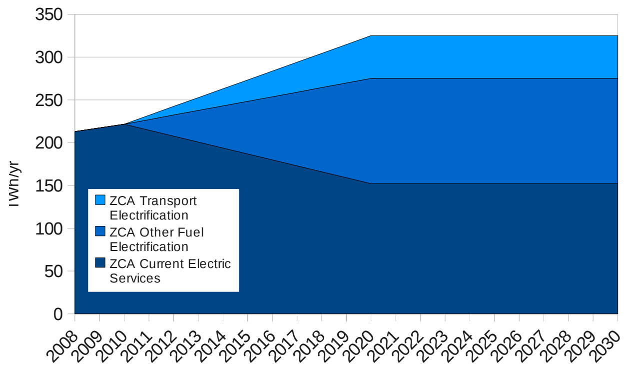
Use of solar PV onsite at the point of use avoids losses in transmission and distribution from centralised sources. Also low-temperature (< 100˚C) solar hot water is well suited to hybridisation with heat pumps. It is reasonable to increase the amount of solar energy at point-of-use, though this is still backed up by the 100% renewable grid.

What does this all mean?

This analysis has found that, with appropriate efficiency targets, Australia's energy requirements could be met with 325 TWh/yr of grid electricity in 2020 and beyond. Figure A1.3 shows how this electricity demand is made up of existing electricity services (which become more efficient over time), electrification of transport, and electrification of other services presently fueled by fossil fuels (especially natural gas). This 325 TWh/yr by 2020 is more electricity than would be required under BAU growth of 1.8%/yr (as reported in AERA) and with no fuel switch electrification. The ZCA2020 Plan 100% renewable energy mix has been sized to deliver this 325 TWhr/yr.

ZCA2020 does not propose expanding electrical generating capacity from 2020 through to 2030. Rather, continuously improving efficiency measures will counter demand increases caused by increasing population.

FIGURE A1.3
ZCA2020 Total Electricity Demand including fuel switching/electrification

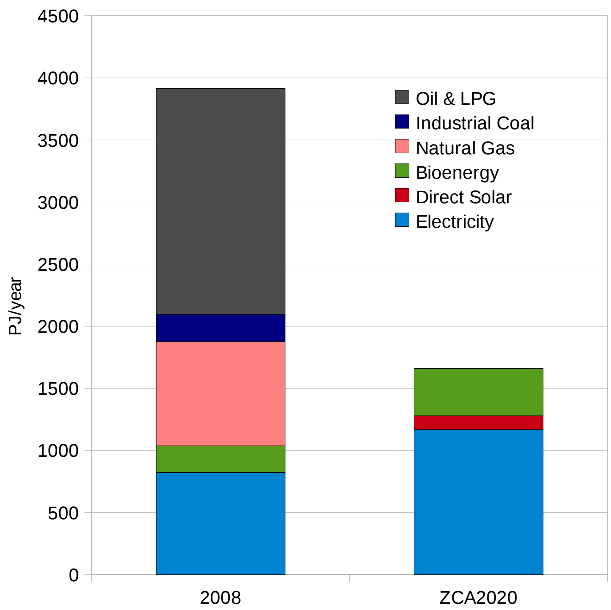


Transport electrification

This high-level analysis investigates the electricity requirements to supply the Australian transport function using electrified vehicles and rail. A small allowance (5%) is made for non-electrified transport services to be provided through liquid biofuels. Non motorised transport measures (e.g. cycling, walking) are not considered in this analysis, though modal switches of this kind would further reduce transport energy demand.

Energy and transport data is all sourced from Apelbaum Consulting's Australian Transport Facts 2007—latest data is for 2004/05[17]. Analysis has been on the basis of supplying the equivalent passenger-kilometres (p-km) and tonne-kilometres (t-km) of the existing transport system with an electrified system.

FIGURE A1.4
Australian End-Use Energy: Present and ZCA2020



Total end-use liquid fuel consumption in 2004/05 was 1301 PJ. All data has been scaled up to reflect the 1337 PJ used in 2007/08, as shown in Table A1.1. This analysis indicates that this could be reduced to 210 PJ for land-based transport using electrification, and with increased modal shift to electric rail for both passenger and freight, this could be further reduced to 160 PJ of electricity (45 TWh) for today's entire domestic passenger and freight task (including domestic aviation and shipping). **50 TWh of electricity is allocated for transport in 2020.**

TABLE A1.1
Transport Energy Use 2007/08 (scaled from 2004/05 data using a factor of 1.027)

Category	Urban (PJ)	Non-Urban (PJ)	Total (PJ)
Passenger Vehicles	474.2	181.4	655.6
Motorcycles	2.6	1.1	3.7
Light Commercial Vehicles	99.9	67.2	167.1
Rigid Trucks	55.3	32.4	87.7
Artic. Trucks	36.9	98.7	135.6
Other Trucks	1.7	0.7	2.4
Buses	15.2	6.9	22.1
Total Road	686	388	1074
Passenger Rail	0.3	2.2	2.5
Freight Rail		23.6	23.6
Ancillary Freight			6.3
Total Rail (liquid fuel)			32
Domestic Aviation			91.1
Domestic Shipping			19.4
Electric Rail (Light and Heavy)			6.5
TOTAL Domestic Liquids			1217.2
International Aviation			119.8
TOTAL Liquids			1337

Electrification of transport results in 5:1 energy reduction, due to the inherent efficiency of electric motor vs internal combustion engine[18]. Internal combustion engines are around 15-20% efficient under normal driving conditions, whereas electric motors are around 85% efficient at converting energy into motion.

However, switching from road vehicles to electric rail (light and heavy, passenger and freight) has the advantages of:

- steel-on-steel wheels to tracks reducing vehicle rolling resistance
- overhead electric cables eliminating the need for batteries—especially relevant for long-distance freight and passenger corridors
- higher loadings (passengers or freight-tonnes) per vehicle further increasing the efficiency of travel.

Modal switching to rail is best suited to cities where a lot of people are travelling along central corridors (e.g. commuting), and for long-distance travel between towns outside of cities. The following modal switches are assumed:

In this analysis, a further **5:1** efficiency gain is projected for modal switch to urban public transport. An electric vehicle operating at 22 kWh/100km, 1.5 average persons/vehicle, delivers 0.15 kWh/p-km. An efficient light rail public transport system can achieve 0.024 kWh/p-km[19], a ratio of more than 6:1 (based on the Siemens Combino tram in Switzerland, 1.53 kWh/vehicle-km, average passenger loading of 65 (out of crush capacity 180)).

Non-urban transport with high-efficiency highspeed rail, can achieve 0.07-0.08 kWh/km[20], a **2:1** efficiency gain over electric vehicles.

Freight rail can achieve 0.07 kWh/t-km[21]. Based on current energy intensities (derived from Apelbaum data), it conservatively modelled that freight rail has an extra efficiency gain per tonne-km of 3:1 (urban) and 2:1 (non-urban), versus electrified trucks. With the exception of Light Commercial Vehicles, which are a highly energy intensive way to transport goods—5:1 (urban) and 10:1 (non-urban) is assumed.

TABLE A1.2
Fraction of p-km shifted to electrified rail

Category	Urban	Non-Urban
Passenger Vehicles	50%	25%
Motorcycles	20%	20%
Light Commercial Vehicles	50%	80%
Rigid Trucks	50%	80%
Artic. Trucks	50%	80%
Other Trucks	50%	80%
Buses	100%	100%

Table A1.2 shows the fraction of passenger-km that would be shifted to an electrified rail transport (light and heavy) system under the ZCA2020 Plan.

International Aviation and Shipping is beyond the scope of this analysis. Domestic aviation and shipping is moved to electric rail. Domestic shipping freight task (excluding petroleum) is 86.8 billion t-km, primarily for ore. This is shifted to high-efficiency bulk rail, with the 0.02 kWh/t-km efficiency currently seen by ancillary rail in Australia (e.g. dedicated rail for iron ore transport in northern Western Australia). Domestic aviation is moved to high-speed rail, 41.8 billion p-km at an efficiency of 0.07 kWh/p-km.

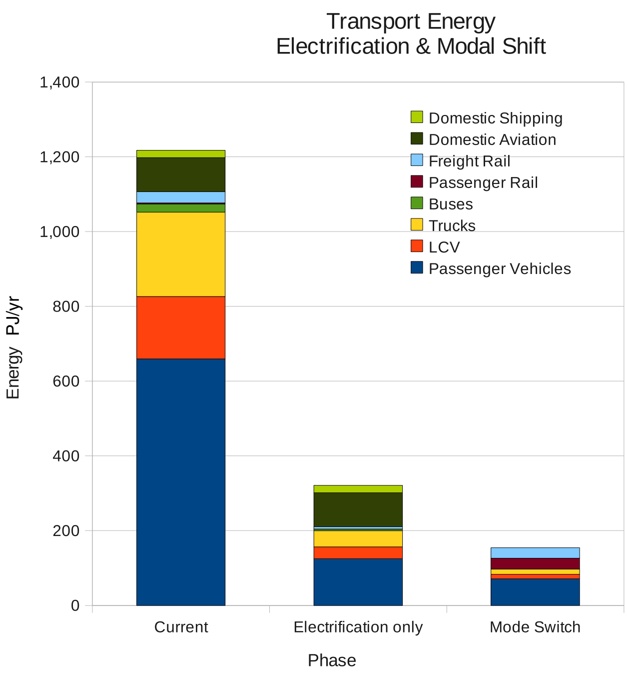
TABLE A1.4

Results of switching transport from liquid fuels to electric vehicles and rail

Final results (PJ)	Current		Electrification only		Rail Mode Switch	
	Liquids	Electricity	Liquids	Electricity	Liquids	Electricity
Passenger Vehicles	655.6		31.9	124.6	31.9	70.9
Motorcycles	3.7		0.2	0.7	0.2	0.6
Light Commercial Vehicles	167.1		8.1	31.7	8.1	12
Rigid Trucks	87.7		4.3	16.7	4.3	6.5
Artic. Trucks	135.6		6.6	25.8	6.6	7.3
Other Trucks	2.4		0.1	0.4	0.1	0.2
Buses	22.1		1.1	4.2		0
Passenger Rail	2.5			0.5		28.9
Freight Rail	23.6			4.7		28.3
Ancillary Freight	6.3			1.3		
Domestic Aviation	91.1		91.1			
Domestic Shipping	19.4		19.4			
Existing Elec Rail		6.3		6.3		6.3
Totals	1217	6	163	217	51	161

FIGURE A1.5

Transport Energy Electrification and Model Shift



The final transport energy requirement after electrification and mode switch is 160 PJ, or just under 45 TWh of electricity. Taking into account further population growth, **50 TWh** of electricity is allocated for Transport in 2020. A further 51 PJ of bioliquids is reserved for land transport that is not electrified, and some hybrid vehicles. This is additional to the 2 PJ of biofuels used currently.

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Appendix 2
System Design and Costing

Wind		
40%	percent	of annual electricity to come from wind
130	TWh/yr	from Wind per year
30%	percent	Annual average Capacity Factor (ref)
49,412	MWe	Total Wind Turbine capacity required
50,000	MWe	Proposed installed capacity
6	MWe	Nameplate wind turbine rating
15,768	Mwhe/yr	annual average per turbine
2,000	MWe	existing wind turbine capacity (end 2010)
48,000	**MWe**	**Actually installed new capacity**
8,000	no.	Number of 6MWe turbines
15%		Of wind capacity that is reliable & firm (i.e. 'baseload wind')
7,500	MWe	Wind capacity reliable at peak times
66	TWh/yr	Wind electricity that is 'baseload'

Solar Thermal - Based on Solar 220 plant with air-cooling		
12	sites	Number of geographically different sites
8,700	MW	Gross Capacity needed to achieve Solar 220 Cost reductions
725	MW	Amount of small-capacity CST at each of 12 sites
13	no.	Solar 220 modules per site excluding scaleup
3,585	MW	Total gross output per site (before air-cooling)
217	MW	Actual Solar 220 output (with aircooling)
3,537	MW	Net output with aircooling
156	no.	Solar 220 modules total
43020	MW	Total grid CST capacity without aircooling
42,461	**MW**	**Total CST capacity with aircooling**
60%	percent	of annual electricity to come from CST
195	TWh/yr	from CST
52%	C.F.	Actual capacity factor required (to meet 60% of energy)
72%	C.F.	Design capacity factor (annual average)
267.8	TWh/yr	Max annual electricity available
73.0	TWh/yr	Extra TWh available per year

Biomass Backup Basis		
7.0	TWh/yr	from biomass (TJ grids modelling)
40%	net turbine efficiency	
17.54	TWh/yr thermal energy	
85%	Heater thermal efficiency	
20.6	TWh/yr primary biomass energy	
74	PJ biomass stored energy for Australia	
4,475	MW of off-grid CST	
5.3	TWh thermal biomass stored energy for off-grid	
19	PJ energy for off-grid	
93	PJ biomass stored energy for Australia	
15.5%	of Australia's wheat crop waste	

Capital Costs Wind		
48000	MWe	New wind turbine capacity
71.68	AU$Bn	Billion Australian Dollars - Total Wind Cost
CST		
8700	MWe	Gross capacity needed to achieve Solar 220 Cost reductions
$60	AU$Bn	Cost of first 8700Gross/8587Net MWe
739.0	AU$M	Cost for Solar 220 plant, 2010 currency
3.41	AU$M/MWe	per unit MW
115	AU$Bn	Cost of Solar 220s
$175.4	AU$Bn	Billion Australian Dollars - Total CST Cost

Off-grid CST with biomass backup		
4,810	MWe	Gross off-grid
7.00%		parasitic energy (average from ESAA)
4475	MWe	net off-grid
$15.2	AU$Bn	Off-grid CST (not including biomass backup)
$500	AU$	AUD per kWe biomass boiler
$2.24	AU$Bn	Off-grid biomass backup
17.5	AU$Bn	Total off-grid cost, CST and biomass

Backup Heater Capital Cost		
15	GWe	biomass heater capacity required (TJ model)
0.5	AU$m/MWe	Million AU$ per MWe equivalent biomass backup heater cost [4]
7.5	$Bn	Total grid backup capability

Waste pelletisation plant costs	
9662754	tonnes of wheat crop residue required for 60 PJ
4	months - period of pelletisation after/during harvest (assumed)
2880	hours - pelletisation period
3355	tonnes/hr pelletisation capacity required
10	tonnes/hr average plant size [8]
336	10 tonne/hr plants required
8.3	AU$M per 10 tonne/hr plant [8]
2.79	AU$billion - total cost for all pelletisation plants

Air cooling Capital Cost & Performance adjustment			
Total Plant Capital Cost			
Wet cooling, $k	$267,747 [3]	US$k	
Dry cooling, $k	$279,120 [3]	US$k	
Difference, $k	$11,373	US$k	extra cost for air cooling
Plant size, MWe	80	MWe	
Aircooling, $/MWe	**$142.20**	**US$k/MW**	**(2005 dollars)**
CPI 2003-->2005	1.06 [5]	CPI	
Air cooling, $/MWe	$134.10	US$k/MW	(2003 dollars)
	$186.20	**AU$k/MW**	**(2010 dollars)**
Nominal Solar 220 plant size	220	MW	
Extra cost for air-cooling	$29,505	US$k	(2003 dollars)
Add 10% contingency (as per S&L)	**$32,456**	**US$k**	**(2003 $) extra capital for air cooling**
Initial Plant size	220	MW	With wet cooling
Air-cooled performance penalty	1.30%	(tower)	U.S. DoE Water Study
	217	MW	Net output with dry cooling
Capital costs for SunLab Solar 220 Solar Thermal Plant (Table E-1, Sargent & Lundy[1])			
Structures & Improvements	$7.20	US$M	
Heliostat field	$198.80	US$M	
Receiver	$34.40	US$M	
Tower & Piping	$24.30	US$M	
Thermal Storage	$57.20	US$M	
Steam Generator	$9.30	US$M	
Elec Power Block	$83.60	US$M	
Master Control	$1.60	US$M	
Balance of plant	$9.90	US$M	
Direct Cost	$426.30	US$M	
Eng, Mgmt, Dev (7.8%)	$33.30	US$M	
Land at $5000/ha	$7.00	US$M	
Contingency	$34.30	US$M	
Total Cost	**$500.00**	**US$M**	**The summed cost is $499.9 (Reference[1] presents $599.9 as the total.)**
Add in air cooling	$32.46	US$M	
Cost with air cooling (2003 US$M)	$532.36	US$M	
Consumer Price Index (2003 to 2010)[5]	1.18	CPI	
Solar 220 Plant Total Cost (2010 US$M)	**$628.18**	**US$M**	
Solar 220 Plant Total Cost (2010 AU$M)	**$739.04**	**AU$M**	**Assumed ForEx $0.85US = $1.0AU**

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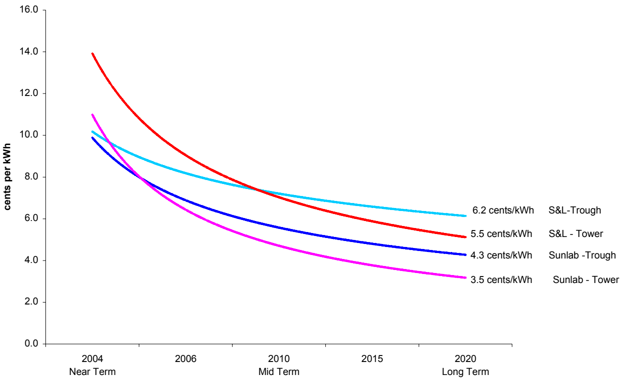
Appendix 3A
Scaling up Solar Power Towers

Cost reduction trajectories of power towers

Both the US Department of Energy's SunLab (Sandia/NREL) program, and the engineering consultancy firm Sargent & Lundy have modelled the economics of CST energy systems in the document Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts, compiled by Sargent & Lundy[1].

The cost reduction trajectory from the Sargent & Lundy report[1] is repeated in Figure A3.1.

FIGURE A3.1
Cost reduction trajectory for solar thermal power



The red curve on the chart above represents the Sargent & Lundy cost projection for towers, while the mauve curve represents the SunLab tower projection. The main difference between the two projections is the cumulative installed capacity assumed by each. In the original report, these were referenced to an installation timeline from 2004—2020, but the key factor in achieving the cost reductions was not the timeline but the total installed capacity.

The key finding from this was that the levelised cost of electricity would come down to $US3.5c/kWh (or 5c/kWh in 2010 Australian currency) once global installed capacity reaches 8,700 MWe of power towers. Most of these cost reductions would come from simple economies of scale—i.e. when the industry is able to build 75% capacity factor 200-220 MWe towers, it is much cheaper than the first-of-a-kind 10-50 MWe plants. There are also significant cost reductions to be achieved from mass-manufacturing of heliostats. The mirror field makes up about half the capital cost of a Solar Power Tower plant, therefore tooling up for large-volume production of these components on a continuous basis (as opposed to start-stop, one-off constructions) has a huge cost-reduction potential.

In summary, 49% of cost reductions from first-of-a-kind plants to more advanced 220 MWe plants comes from economies of scale, a further 28% of cost reductions from high-volume component production, and the remaining 23% from continuous technology improvements, for example from the continued R&D by Sandia Laboratories, and breakthrough innovations such as eSolar's low-cost mirror field design. Sargent & Lundy projected that as costs of towers come down, tower installed capacity would overtake trough installations. Given that troughs are a more mature technology with less scope for cost reductions than towers, and that tower installation capacity is already about to overtake troughs, building trough plants in Australia would not represent the best value for money.

Optimum Plant Size

In Spain, where there are ten solar thermal plants in operation and over fifty under construction[2] the Feed-in-Tariff only applies to plants below 50 MW. However, better economies of scale will come from plants larger than this. Designs are detailed by Sargent & Lundy and NREL for tower plants sized at 13.5 MW, 50 MW, 100 MW, 200 MW and 220 MW with storage. This progression of larger tower projects is being implemented at the time of writing by concentrating solar thermal companies, with Torresol's 17 MW Gemasolar tower with 15h storage currently in construction near Ecija, Spain and Solar Reserve's latest announcements comprising:

- 150 MW, 450 GWh/yr tower plant in Rice, California[3].
- 100 MW, 480 GWh/yr project at Tonopah, Nevada[4].
- And a 50 MW, 300,000 GWh/yr plant in Alcazar de San Juan, Spain[5].

The nature of progress in tower plants, however, is to build a larger plant than the last. For example, Abengoa built a 10 MW power tower, PS10, followed by a 20 MW tower, PS20.

The 220 MW tower described by Sargent & Lundy with 17 hours of storage is approaching the optical limits of a single mirror field to reflect sunlight onto a single tower—at the outer heliostats the reflected light is too diffuse to heat the solar receiver on top of the tower. However, to construct a larger power plant, for example 2,200 MW, you simply construct 10 modules of the 220 MW power tower. It is standard for a power station to consist of a number of smaller operating modules—for example, Hazelwood in Victoria's Latrobe valley has a total generating capacity of 1,680 MW (gross)[6], but this is actually composed of 8 separate 210 MW (gross) generating turbines.

Mirror Field Size and Electrical Output

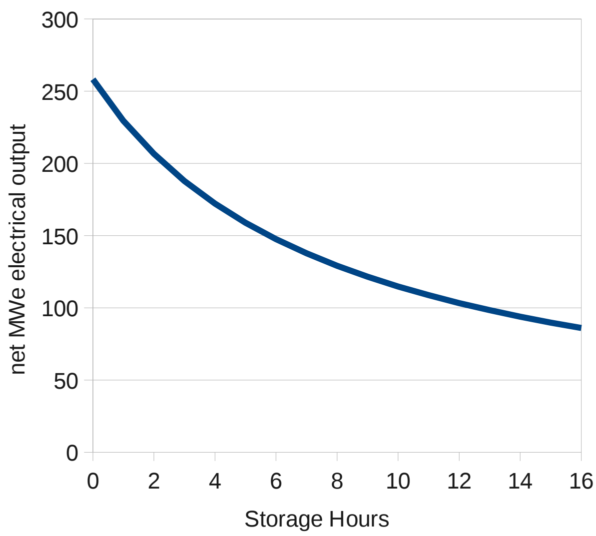
The amount of energy that a mirror field and receiver tower can collect ultimately determines the amount of electricity that can be generated, and is a more relevant comparison of solar thermal power plant size than the rated turbine capacity. For example—a Solar 100 heliostat field as specified by the U.S. Department of Energy's Sandia Laboratories/Sargent & Lundy can collect enough energy to provide 2,066 MWh of electricity per day. If the plant did not have storage, then a 258 MW turbine could be run for the average 8 hours a day that the sun is shining at full strength. However this electricity would not be available overnight, and the plant would have an average annual capacity factor of only 30%. Alternatively, if the plant has storage, it can deliver the electricity over a longer time period and into the night. The trade-off is a smaller turbine size, but it will still deliver the same total amount of electricity.

As an example, the different configurations to deliver the same total of 2,066 MWh per day are explored in Table A3.1 and Figure A3.2, using numbers from the Sargent & Lundy report discussed in section 3.1.

TABLE A3.1
Comparisons of plant capacity (turbine size) and storage for the same mirror field size.

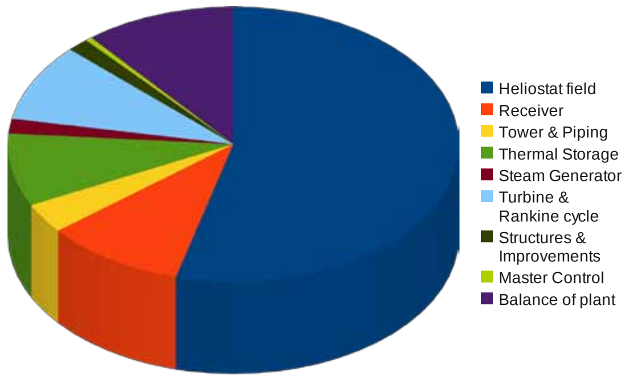
Mirror Field Size (m2)	Total Electricity Per Day (MWh)	Storage Hours	Turbine Size (MW)	Hours of Operation/ Day	Annual Capacity Factor
1,366,100	2,066	16	86	24	75-80%
1,366,100	2,066	8	130	16	50-60%
1,366,100	2,066	0	258	8	30%

FIGURE A3.2
Turbine size vs storage for same size mirror field (2,066 MWh/day)



A graphical comparison of plant capacity (turbine size) and storage for the same mirror field size.

FIGURE A3.3
Capital cost breakdown of S&L Solar 100 (75% capacity factor)

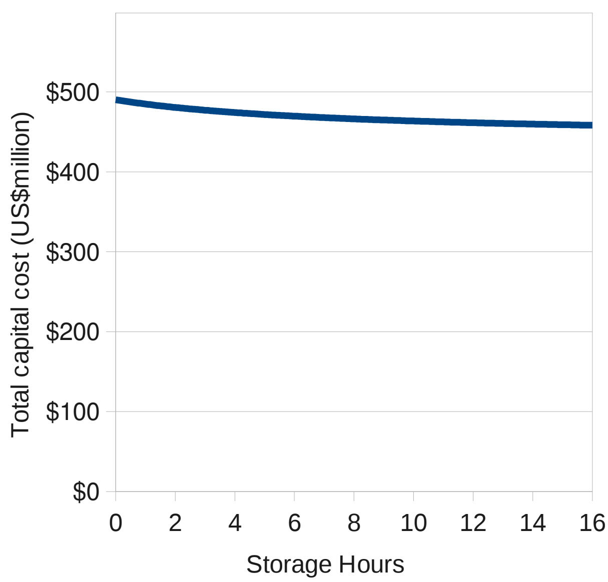


Sargent and Lundy's cost breakdown of a Solar 100 with 16 hours storage.

As shown in Figure A3.3, over half the capital cost of a solar thermal power tower plant is the heliostat field. Therefore, scaling up the storage size while downsizing the turbine for the same sized mirror field will not significantly impact the total capital cost of the plant, as the cost increase and decrease roughly cancel out.

In fact, as illustrated in Figure A3.4, storage is slightly cheaper than turbines, so a plant with 16 hours storage will be about 97% of the cost of a plant with no storage. Again they will both produce the same total amount of electricity from the same mirror field size, but the plant with storage can provide power reliably 24 hours a day.

FIGURE A3.4
Capital cost vs storage for Solar 100 plant (700 MWt tower/field)



In summary, the capital costs and total electricity generation (GWh/yr) are primarily dependent on the size of the mirror field. The turbine size and capacity factor is dependent upon the amount of thermal storage, but does not significantly affect the plant capital cost. This is important when comparing the published costs of today's solar thermal projects. Therefore a plant that produces electricity 24 hours a day can be built for roughly the same price as a plant with the same mirror field size that only operates on sun.

Economics of Solar Thermal Power

The economics and financing of solar thermal power projects are fundamentally different from that of fossil energy projects. Most of the cost of a solar thermal plant is in the capital expenditure, with fixed O&M costs very low, and there is no fuel cost. In fact, for an end-of-the-cost curve plant with a total levelised energy cost (LEC) of 5 AU c/kWh, the ongoing O&M cost component is only around 1c/kWh. As opposed to fossil energy, which has a lower upfront capital, but higher ongoing fuel costs which are subject to variability.

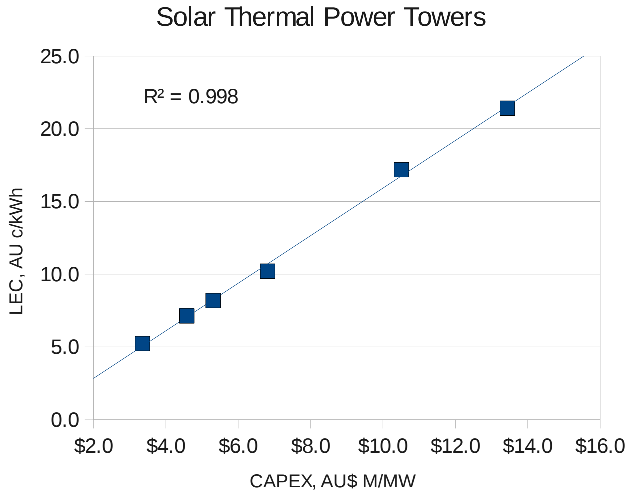
There are a variety of financial policies available for governments to assist the uptake of renewable energy. Two broadly different approaches are: An ongoing subsidy such as a Feed-in-Tariff, which pays the difference between the renewable LEC and the market LEC. An upfront subsidy, such as a direct investment, government loan, or Investment Tax Credit such as that implemented in the U.S., that lowers the debt associated with the capital cost of the plant.

Current cost of molten salt power towers

The cost of a molten salt power tower project today is referenced to the cost of SolarReserve's Tonopah project in Nevada. This will produce 480,000 GWh/year of electricity[7], and will cost over U.S.$700 million[8]. With enough storage (15 hrs) for full 24-hr dispatchable power and 75% capacity factor, a plant this size could have a turbine output of 75 MW. Adjusting for foreign exchange, it can be inferred that the cost of a First-Of-A-Kind plant of this size is $AU10.5 million per MW capacity. (Note that due to economies of scale, a plant producing less than 480,000 GWh per year would be expected to cost more per MW.) SolarReserve also has molten salt power tower projects announced in Rice, California and Alcazar, Spain.

Based on the equivalently priced projects from Sargent & Lundy's cost modelling, these SolarReserve plants should have a Levelised Electricity Cost of AU 20c/kWh, derived from Sargent & Lundy data[1] shown in .

FIGURE A3.5
Levelised Electricity Costs in relation to Capital Expenditure Costs (derived from Sargent & Lundy[1])



Achieving 10c/kWh baseload solar electricity

It is assumed that to be a financially viable renewable energy project in the current Australian market, solar thermal plants will at least need to be able to achieve a wholesale price (after any subsidies) equivalent to or less than wind power (10c/kWh). After achieving such a price, solar thermal could fit into a wider renewable energy incentive policy, for example an expanded version of the current Australian Mandatory Renewable Energy Target (would need to be much greater than 20%), an appropriately structured Feed-In-Tariff or similar.

From the same Sargent & Lundy cost modelling, a CST plant with a LEC of 10c/kWh needs to have a upfront capital of only $AU6-6.5 million/MW.

As shown in Figure A3.1, Sargent & Lundy predict that once 2,600 MW of towers (with ~15h storage) are installed globally, the levelised energy cost for tower plants will drop to US 5.5c/kWh, which equates to AU 8c/kWh today. Adjusting for Australian labour costs, we project that after 2,600 MW of 75% capacity factor solar power tower plants with molten salt storage are built, power towers will be cost-competitive with wind, conservatively estimated at 10c/kWh. This takes into account continued cost reductions in wind turbine technology.

The investment costs of these first plants have been modelled as such:

- First 1,000 MW priced at SolarReserve Tonopah equivalent, $10.5 million per MW—$10.5 Bn investment
- Next 1,600 MW priced at midway cost of $9 million per MW—$14.4 Bn investment

As seen in Spain, a true pipeline of projects is necessary within Australia to avoid stop-start of component factories, and achieve cost reductions and economies of scale.

TABLE A3.2
Cost Trajectory for Solar Thermal

Phase		Phase 1	Phase 2	Phase 3	Phase 4	
Price reference		Solar Reserve	SunLab First-of a-kind	Solar 100	Solar 200	TOTAL
Incremental installation	MW	1,000	1,600	2,400	3,700	
Cumulative installed capacity	MW	1,000	2,600	5,000	8,700	
Capacity Factor	%	72%	72%	72%	72%	
Produced Electricity	GWh /yr	6,300	16,400	31,535	54,870	
Unit Capital cost	$M/MW	$10.5	$9.0	$6.5	$5.3	
Total Phase Capital Cost	$Bn	$10.5	$14.4	$15.6	$19.6	$60
LEC	c/kWh	20	16	10	8	5

Cost parity with conventional fossil energy

Again, as shown in Figure A3.1, further expansion to a total of 8,700 MW of global installed tower capacity would allow CST tower plants with storage to hit cost parity with conventional new coal & gas plants: AU 5c/kWh (US 3.5c/kWh).

Once parity with wind is achieved, the price will continue to drop. The stage of installments has been costed as:

- 2,400 MW at wind price parity, $6.5 million per MW—$15.6 Bn investment
- 3,700 MW at Solar 200 price, $5.3 million per MW—$19.6 Bn investment

Note on conservatism: These costs and required subsidies are very conservative. In reality, it is likely that the initial costs of tower plants will come down much more rapidly from the current $AU10.2million/MW, due to continuous industry improvement elsewhere in the world. In addition, the requirements of building 2,600 MW and 8,700 MW to bring costs down should take into account total global installed capacity, the projects being built in the U.S.A. & Spain. However, we have assumed that this is the maximum industry size that will need to be developed in Australia to achieve the Sargent & Lundy cost reductions.

Therefore, the required phases of installation given here represent the upper bounds of the initial higher-cost investment that will be necessary to introduce cheap baseload solar electricity to Australia.

Conclusion

From this trajectory, it is projected that building the first 8,700 MWe of solar thermal power towers with >15hrs molten salt storage will cost a total of $AU60 billion. Initial plants in the range of 50-200 MW will be scaled up in size until 220 MW modules are built which will achieve a levelised electricity cost of 5c/kWh when run at 70-75% capacity factor.

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Appendix 3B
Projected Wind Energy Capital Costs

Current costs of wind power

Table A3.3 gives the average capital costs from 7 large current wind farm projects in Australia. This gives the total capital costs of $2.5 Million/MW. This figure has been confirmed by Australian wind developers Pacific Hydro and turbine manufacturer Suzlon. The large variation between each wind project is due to differences between each wind farm project, such as grid connection, planning requirements, and terrain (which will alter the construction costs).

While turbine costs have historically reduced over the past decade with increases in turbine sizes and improvement in technology, in recent years prices have gone up.

This price increase was caused by a slower than expected expansion of the wind industry in 2001-2004, followed by a sharp increase in the global market for wind turbines (30-40% annually) until around mid 2008. This was combined with an increase in raw material prices and later the Global Financial Crisis.[6]

In addition to this the current capital cost of wind farms in Australia is much higher than it is in Europe. This is because Australia has seen a much slower growth in wind power than in other countries such as Europe and America. There are currently no turbine manufacturers located in Australia, with most turbine components needing to be shipped from overseas, which increases the costs.

Short Term Wind Turbine Costs

A 2009 report by the EWEA on the Economics of Wind Energy, incorporated the effect of current demand and supply on the changing costs of wind turbines to obtain a long term estimate of wind capital costs.[6] This study assumes the wind industry will grow to 180 GW internationally by 2020 and that half of all new investments in 2020 will be for offshore wind farms.

This work took into account the recent increases in wind turbine costs due to market constraints to extend the work of the European commission to produce a forecast cost reduction for wind turbines.

Based on this study the 2010 forecast capital costs of onshore wind is approximately €1,200/kW (2006 prices) or $AU2,200/kW (current prices). By 2015 the European capital costs of onshore wind is estimated at around €900/kW (2006 prices, $AU1,650 in current prices) and forecast to drop to €826/kW (2006 prices, $AU1500) by 2020.

The report also gathered information from a number of wind farms in Europe to show the relative costs of each component in the installation of a wind turbine. This is presented in Table 2. The report found that the turbine accounted for 68-84% of the total share of capital costs, with a typical amount for an average turbine installation in Europe of 75.6%. The second largest figure was Grid Connection.

The ZCA2020 Plan has calculated the transmissions costs separately to the capital costs of the wind farm projects, but given the large range possible for this figure, we have not excluded this cost from the total average capital cost of a wind farm. Therefore it is expected that wind farm capital costs used in the Plan are conservative and the final cost may be slightly lower than quoted.

Long Term Capital Costs – the influence of China

The European Wind Energy Association research however has not taken into account the impact that China's wind turbines will have on the global market in the near future.

TABLE A3.3
Capital Costs of Major Wind Farms in Australia

Developer	Location	Operating Date	Capacity (MW)	Capital Costs ($Million)	$M/MW	Reference
Origin	Stockyard Hill	2011	484	1400	2.89	1
Acciona	Waubra	2009	192	450	2.34	2
AGL	MacArthur	2011	365	800	2.19	3
Silverton Wind Farm Developments	Silverton	2011	1000	2200	2.20	4
AGL & Windlab Systems	Coopers Gap	2011	440	1200	2.73	4
AGL	Hallet 5	2011	52	120	2.31	5
Roaring 40s	Waterloo	2010	111	300	2.70	4
				Average	**2.48**	

TABLE A3.4
Cost Breakdown for a Medium Sized Turbine - Based on Data from Germany, Denmark, Spain and UK[6]

	Share of Total Cost (%)	Typical Share of Other Cost (%)
Turbine (ex works)	68-84	-
Grid Connection	2-10	35-45
Foundation	1-9	20-25
Electric Installation	1-9	10-15
Land	1-5	5-10
Financial Costs	1-5	5-10
Road Construction	1-5	5-10
Consultancy	1-3	5-10

Current industry estimates suggest that wind turbines manufactured in China are 20-25% of Australian wind turbine prices.

In 2005 the Chinese Government passed the Renewable Energy Law. This law mandated that new wind farms must have at least 70% of all wind power equipment manufactured in China. The Chinese National Energy Administration has indicated that it plans to remove this requirement in the near future, although no date has been set.[7]

Nonetheless this law has created an incredible boom in Chinese manufactured turbines, with total domestic installations from Chinese manufacturers growing from only 18% in 2004 to 62% in 2008.[7]

Companies such as Goldwind, which is one of the largest and most reliable wind turbine manufacturers in China, are planning to start selling a 3 MW wind turbine on the global market from 2011 onwards.[8]

The Chinese government has recently announced plans to build seven wind power bases, each with a minimum capacity of 10,000 MW, by 2020. The planned combined capacity of these wind bases will be 120GW.[9]

The first of these wind bases, dubbed the "Three Gorges Wind" project, is the 20,000 MW wind farm to be constructed in Jiuquan city in the Gansu Province. Construction of the wind farm is now under way at an estimated capital cost of $US 17.6 Billion (120 Billion Yuan).[9] This equates to roughly $AU 1 million/MW, more than half the current capital cost for wind farms in Australia.

Estimated costs for ZCA 2020 Plan

Due to the planned nature of the ZCA2020 program, turbine suppliers would be given significant forward notice of orders for the Australian market. This significantly reduces the risk of capacity constraints, as the turbine suppliers are able to address their supply chain, and ensure that components and materials are available to meet the significant upswing in demand. Implementation of the plan would involve forward contracting for the supply of turbines in order to guarantee this.

Alternatively government investment could help set up a local wind turbine manufacturing industry to supply some or all of the necessary components.

For the first 6 years of the Stationary Energy plan, the capital costs of wind turbines are expected to transition from the current Australian capital costs – $2.5 million/MW to the forecast 2015 European amount - $1.65 million/MW. This is because it will require some time before manufacturers can ramp up production and for orders to be fulfilled in Australia.

It is expected that the final 5 years of the plan will make the most of the influence of Chinese manufacturers on the market, either indirectly or directly (by purchasing from a Chinese wind manufacturer).

Given that the Three Gorges of Wind project will take a number of years to construct, it is expected that the Chinese capital cost estimate will remain relatively stable at $1 million/MW. Accounting for differing labour costs and adopting the 25% rule of thumb, we can reliable expect the capital costs to drop to approximately $1.25 million/MW in Australia.

Table 3.9 in Section 3.2 gives the yearly expected costs of turbine installations.

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Appendix 4
Water Use at CST sites

This appendix outlines in more detail, the availability of water for consumption as well as current water use in each of the concentrating solar tower (CST) plants proposed in the Plan. The total water consumption of the proposed CST plants combined is far less than the amount of water consumed through Australia's power generation currently. However, it is important to demonstrate that there is sufficient water availability at the proposed CST plant sites which each consume 6.3 GL/yr.

This investigation focuses on the availability and use of surface water (water from above-ground rivers and lakes) although in some instances ground water and desalinated sea-water are also considered. The **average total surface water availability** is the mean annual outflow of water. This is generally measured at the points of maximum available flow within a region or surface water management authority (SWMA)[1]. SWMAs are regions of water management, which are generally defined by the catchment of a river system.

Not all surface water is available for use however, as some must be allocated to the environment. Hence, the "sustainable yield" of water is a more useful figure. The **sustainable yield** of water is defined in the Australian Natural Resource Atlas as "the limit on potentially divertible water that will be allowed to be diverted from a resource after taking account of environmental values and making provision for environmental water needs"[2].

In some regions either the total surface water availability or the sustainable yield is unknown, hence the average water use is also noted to indicate the potential availability of water. This figure must be considered cautiously, however, as current water use is not necessarily at a sustainable level. These figures are summarised in Table A4.1.

Carnarvon

Surface Water Management Authority: Gascoyne River

Although the sustainable yield in this catchment is 196 GL/yr with 98% reliability in 95% of years[3], the current maximum allocation limit is 18 GL/yr[4]. Of this 18 GL/yr, 80% is allocated to irrigation and new industries in the region[4]. Current water use is below this allocation limit, hence there is potentially sufficient water in this region to supply a CST plant.

Kalgoorlie

Surface Water Management Authority: Salt Lake

The nominal estimate of the sustainable yield of surface water in this catchment is 1.03 GL/yr[5]. The actual water use is much higher however (approximately 11.4 GL/yr), which consists almost completely (>99%) of imported surface water from nearby catchments and is allocated

TABLE A4.1
Water Use at Solar sites (with Sustainable Yield for some sites)

Proposed Site	Surface Water Management Authority	Current Available Surface Water (GL/yr)	Sustainable Yield (GL/yr)	Current Water Usage (GL/yr)
Carnarvon	Gascoyne River	646 [3]	196 [3]	< 18.0 [4]
Kalgoorlie	Salt Lake	No data	1.03 [5]	> 11.41 [5]
Port Augusta	Mambray Coast	38 [6]	6 [6]	3.96 [6]
Broken Hill	Darling River	2,944 [1]	No data	299 [7]
Mildura	Mid-Murray River	11,162 [8]	No data	4,045 [8]
Bourke	Barwon-Darling Rivers	3,515 [9]	No data	230 [9]
Dubbo	Macquarie-Castlereagh	1,567 [10]	No data	371 [10]
Moree	Gwydir River	782 [11]	No data	321 [11]
Roma	Condamine-Balonne	1,363 [12]	No data	722 [12]
Charleville	Warrego River	423 [13]	No data	11 [13]
Longreach	Cooper Creek	1,126 [14]	No data	6.9 [14]
Prairie	Flinders River and Belyando/Suttor	6,718 [15,16]	No data	86.3 [15,16]

mostly to urban and industrial use[5]. In addition to surface water, large volumes of hyper saline groundwater (which is unfit for domestic use) are used by the local mines for mineral processing and dewatering[17]. For example, KCGM, a local gold mine, uses approximately 12 GL/yr, of which 83% comes from ground water and recycled water[18]. Whether or not such saline water could be used directly on the mirrors without treatment, the water demand by CST plants in this region will not need to compete with local domestic or irrigation demands.

Port Augusta

Surface Water Management Authority: Mambray Coast

The sustainable yield of surface water in this region is 6 GL/yr, although the highly variable runoff means that the supply is fairly unreliable[6]. Water use is 3.96 GL/yr of which approximately 40% is imported surface water[6].

Clearly, meeting the demand for a CST plant in this area will be a challenge. Further investigation is necessary to ascertain whether or not water can be imported from nearby catchments or from groundwater in order to supply the CST plant proposed in the Plan at this site. If this proves to be unfeasible, it may be worth considering desalination plants in order to meet the CST plant's as well as local domestic demand for water.

Broken Hill

Surface Water Management Authority: Darling River

Broken Hill falls into the Darling River SWMA. Much of the water supplied to the region is stored in the Menindee Lakes, which are located about 70 km south-east of Broken Hill. The lakes have a combined capacity of 1,794 GL and the average surface water availability, as measured at Menindee is 2,944 GL/yr[1]. Of this approximately 299 GL/yr are allocated to meet the local industrial, domestic and agricultural demand for water along 690 km of the Darling River[7]. There has been some concern about the declining water levels in the lakes, in particular due to the amount of water lost through evaporation from their large surface areas[19]. However data acquisition is underway to research the potential for storing water in naturally occurring underground aquifers (which will eliminate losses due to evaporation) which so far, has been promising.

Mildura

Surface Water Management Authority: Mid-Murray River

Mildura is located on the banks of the Murray River, which, as Australia's largest river means that this site is one of the Plan's more secure sites with regard to water supply. The mid-Murray region spans several major centres along the river's banks from Albury-Wodonga to Goolwa and therefore there is high demand for water for domestic and agricultural use[8]. The average surface water availability for this region is 11,162 GL/yr of which 4,045 GL/yr is used[8]. This level of consumption is quite high (36%) and although a reliable figure for the sustainable yield in the region was not found, it would almost certainly be less than current levels of consumption. Hence, although the demand of 6.7 GL/yr by one CST site in this region could easily be met by current surface water availability, care would need to be taken to ensure that this was balanced with allocations to other water consumers as well as meeting environmental flow requirements.

Bourke

Surface Water Management Authority: Barwon-Darling Rivers

Bourke is located in the Barwon-Darling region of the Murray-Darling basin in north-west New South Wales and shares the region's water resources with several other town centres. The average surface water availability for the entire Darling Basin assessed at Bourke is 3515 GL/yr, however as this is not the sustainable yield, it is not indicative of what can realistically be consumed[9]. Current surface water use for the region is 230 GL/yr and groundwater use is about 10 GL/yr which is thought to be underdeveloped[9]. Hence, meeting the water resource requirements for the proposed CST plant site in this region is feasible.

Dubbo

Surface Water Management Authority: Macquarie-Castlereagh

Dubbo is located in the Macquarie-Castlereagh region, which is also part of the greater Murray-Darling basin. This region includes the Macquarie, Castlereagh and Bogan Rivers which supply water to the centres of Wellington, Mudgee, Orange, Bathurst as well as Dubbo for domestic use, but mostly irrigation[10]. The current average surface water availability is 1,567 GL/yr of which 371 GL/yr are used[10]. Again, meeting the water resource requirements for the proposed CST plant site in this region should not be a challenge, however care will need to be taken to ensure that environmental flows are met together with meeting the demands of other water users.

Moree

Surface Water Management Authority: Gwydir

The Gwydir region, also part of the Murray-Darling basin, is based around the Gwydir River and supplies the town of Moree as well as local agriculture. The current average surface water availability is 782 GL/yr of which 321 GL/yr is used[11].

Roma

Surface Water Management Authority: Condamine Balonne

This region, located mostly in the Queensland share of the Murray-Darling basin, services several centres including Roma. Average surface water availability is 1,363 GL/yr and current use is 722 GL/yr[12]. Groundwater is an additional source of water, with current use at 160 GL/yr[12].

Charleville

Surface Water Management Authority: Warrego

The Warrego region, which is mostly located in Queensland is one of the northern regions of the Murray-Darling Basin. Water availability here is less reliable than in other parts of the Murray-Darling Basin, although the average total water availability is still 423 GL/yr[13]. In the lowest one-year period on record, diversions from this region were 11.3 GL/yr[13].

Longreach

Surface Water Management Authority: Cooper Creek

Longreach is located within the part of the Cooper Creek catchment that lies in Queensland. There is no data for the sustainable yield of water from this catchment however the average total available surface water is 1126 GL/yr[14]. Diversions of water for use are 6.9 GL/yr[14]. As a fraction of the total available surface water, this level of diversion is fairly low. Whilst this might usually be explained by there being a high demand for environmental flows in the region, in this case, it could also be due to the low level of development in the region. That is, there are no major storages or other types of development within the catchment[14] which may be why current diversions of water are significantly less than the total available surface water. More investigation into the actual sustainable yield of this SWMA will be necessary to ascertain whether or not it can supply the CST plant proposed in the Plan for this site without competing with other water users. If sufficient water is available within a sustainable yield, further developments might be necessary to facilitate the extra diversion to the CST plants.

Prairie

Surface Water Management Authority: Flinders River and Belyando/Suttor

Prairie is located in Queensland, on the border of the Flinders River and Belyando/Suttor catchments. There is no data for the sustainable yield of water from these catchments, however their total available surface water is 3,857 GL/yr and 2,861 GL/yr respectively[15,16]. The current water use in these catchments is 7.7 GL/yr and 78.6 GL/yr respectively[15,16].

Further investigation will be necessary to determine the exact location of the proposed CST plant in this region and hence whether it will be more feasible to draw water from the Flinders River or the Belyando/Suttor catchment. Both regions have quite a low level of development meaning that with new or expanded infrastructure, there is potential for diversions to be increased beyond current use as long as environmental flows can be met.

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Appendix 5
Industrial Case Study

Alumina Refinery Cogeneration Case Study

This details and analyses how a series of solar thermal power plants, based on the Solar 220 design, can be adapted to meet the combined heat and power requirements of the Gladstone Alumina Refinery. Combined heat and power, or co-generation, is a commonly used industrial process whereby the excess heat from an electrical generating system is used directly for heating requirements. Solar thermal, like other power stations, also produce excess heat, which can be used for this purpose.

Basis

The information provided in the United Company Rusal's recent public submission[1] to the Australian Government's energy white paper provided the basis for this case study. The annual energy requirements for the Alumina plant, outlined in the submission, can be found in Table A5.1.

TABLE A5.1
Annual Energy Requirements for Alumina Plant[1]

Energy Required	Quantity
Electricity	777000 MWh
Gas	13.5 PJ
Coal	1.42 Mt

The coal is used to generate steam; the required quality of this steam is a significant factor. High pressure steam 5,000 kPa at 270°C is required to operate the digester[1], and must be available from any proposed modified system.

An Australian Exchange Rate of 0.9136[2] was used in the economic basis of the case study.

Modified Design

The energy requirements of the plant were altered to reflect the change in energy use in the modified plant. In the proposed modification, the gas fired kiln is to be replaced by an electrically fired kiln. The electrical requirement was based on an energy grade function of 1 (even though a value of 0.913[3] would be acceptable). The energy content of coal is 30 GJ/tonne and the steam requirement was calculated on 90%[4] conversion rate from coal energy to steam. These numbers are conservative values. The plant's modified energy requirements are shown in Table A5.2:

TABLE A5.2
Annual Energy Requirements for the Modified Plant Design

Energy Required	Quantity
Electrical	4527 GWh
Steam	10650 GWh

The modified system is based on the Solar 220 design. A Co-generation Heat and Power (CHP) system was design to meet the various energy requirements of the plant. Given the steam conditions required in the process, a backpressure turbine with an efficiency of 15% is necessary. The outputs from the Solar 220 systems are shown in Table A5.3 and Table A5.4.

TABLE A5.3
Solar 220 Output

	Efficiency	Output (MW)	Gwh per year
Electrical	0.463	245	2146.2

TABLE A5.4
Cogen Solar 220 Output

	Efficiency	Output (MW)	Gwh per year
Electrical	0.15	79.37	695.31
Steam	0.6	317.49	2781.25

Using this modified design, it was determined that 4 of these modified 220 plants would be required to meet the total steam requirement of the plant. A single unmodified Solar 220 is required to ensure the remaining electrical demand is met. A slight excess of electricity is produced, perhaps suitable for export to the grid.

Capital Cost

The capital costs of the project were based on the results reported in the Sargent and Lundy report[5] for the Solar 220 design. It was assumed that the capital costs for the modified Solar 220 with cogeneration were the same as that for the Solar 220 outlined in the report. The receiver and heliostats represent the largest proportion of the capital cost (74%) and are unmodified in the co-generation design. The inclusion of a backpressure turbine in the power block (the remaining 26% of the cost) is more likely to decrease the cost of this component (backpressure turbines are typically less expensive than their high efficiency counterparts[4]). A break down of the costs can be found in Table A5.5.

TABLE A5.5
Cost Breakdown

	CAPEX (Million $US)
Heliostat	198.8 [5]
Power block	83.6 [5]
Receiver	34.4 [5]
Total	316.8
Total ($AU)	**346.76**
No. Solar 220 modules	5
TOTAL CAPEX ($AU)	**1733.8**

Revenue

The revenue delivered by this project is realised by the reduction in utility expenditure. To determine this reduction, utility prices are required; the prices used were taken from treasury estimates and can be found in Table A5.6.

TABLE A5.6
Utility Prices

Commodity	Price	Unit
Electricity (wholesale)	42.4 [6]	$/MWh
Gas	5.0 [6]	$/MJ
Coal	125 [6]	$/Tonne

Using the prices in Table A5.6, and the current energy usage, the potential savings (via reduction in expenditure on utility costs) were determined. Table A5.7 outlines a breakdown of the realised revenue.

TABLE A5.7
Realised Revenue Breakdown

	Amount	Unit	Realised Revenue (Million $AU)
Electricity	777000	MWh	32.94
Gas	13.5	PJ	67.5
Coal	1.42	Mt	177.5

Operation and Maintenance

The operating costs were based on the results reported in the Sargent and Lundy report[5] for a Solar 220 design. It was assumed that the operating cost for the modified Solar 220 with cogeneration would be the same as that for the Solar 220 outlined in the report. The modified designs would not significantly alter the operational and maintenance cost, due to the similarity in the designs. A breakdown of the costs can be found in Table A5.8.

TABLE A5.8
Breakdown of Operation and Maintenance Costs

	OPEX (Million $US)
Burdened labour rate	0.04 [5]
Staff Cost	2.81 [5]
Material and Service Cost	34.4 [5]
Total	4.71
Total ($AU)	5.16
Total # Solar 220's	5
TOTAL OPEX	25.8

Cashflow Analysis

A cashflow analysis of the project was performed to allow various economic measures (including return on investment, payback period and net present value) to be determined. In the evaluation of the cashflow sheet, several standard assumptions were utilised. The assumptions used in this analysis are as follows:

- Fixed Capital Investment expenditure spread over two years[5] (70% first year, 30% second year[7]
- Flat line depreciation of capital over 10 years[7]).
- Corporate tax rate of 30% [8]
- Operating life of 30 years [5]
- Discount rate of 8%
- Operating Capital equivalent to 10% of the Fixed Capital Investment[7], and redeemable in the final year of operation.

Units: Million AUD

Summary

The above cashflow analysis was used to determine some basic economic measures. These measures provide an indication of the feasibility and economic viability of a project.

Payback Period	9 years
ROI	25.2%
IRR	10.5%
NPV	436 Million $AU

TABLE 5.9
Results of discount cashflow analysis for Alumina Refinery Cogeneration

Year	CAPEX	O and M	REVENUE	DEPRECIATION	TAXABLE INCOME	TAX	PROFIT	CASHFLOW	CUMULATIVE CASHFLOW	DCCF	NPV
-2	-1213.66	0	0	0	0	0	0	-1213.66	-1213.66	-1213.66	-1213.66
-1	-520.14	0	0	0	0	0	0	-520.14	-1733.8	-481.61	-1695.27
0	-86.69	-25.8	277.94	-173.38	78.77	-23.63	228.52	141.83	-1591.97	121.59	-1573.68
1	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	-1363.46	181.4	-1392.28
2	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	-1134.94	167.97	-1224.31
3	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	-906.43	155.52	-1068.78
4	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	-677.91	144	-924.78
5	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	-449.39	133.34	-791.44
6	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	-220.88	123.46	-667.98
7	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	7.64	114.31	-553.67
8	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	236.15	105.85	-447.82
9	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	464.67	98.01	-349.82
10	0	-25.8	277.94	-173.38	78.77	-23.63	228.52	228.52	693.19	90.75	-259.07
11	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	869.69	64.9	-194.17
12	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	1046.19	60.09	-134.08
13	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	1222.69	55.64	-78.44
14	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	1399.19	51.52	-26.92
15	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	1575.7	47.7	20.79
16	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	1752.2	44.17	64.96
17	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	1928.7	40.9	105.85
18	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	2105.2	37.87	143.72
19	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	2281.7	35.06	178.78
20	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	2458.21	32.47	211.25
21	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	2634.71	30.06	241.31
22	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	2811.21	27.83	269.15
23	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	2987.71	25.77	294.92
24	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	3164.21	23.86	318.78
25	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	3340.72	22.1	340.88
26	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	3517.22	20.46	361.34
27	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	3693.72	18.94	380.28
28	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	3870.22	17.54	397.82
29	0	-25.8	277.94	0	252.15	-75.64	176.5	176.5	4046.72	16.24	414.06
30	86.69	-25.8	277.94	0	252.15	-75.64	176.5	263.19	4309.92	22.42	436.49

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Appendix 6
Transmission Upgrades

Costs for transmission have been derived from published industry data.

Distances of transmission lines have been mapped out using highly accurate Google Earth software. These are detailed in Table A6.2.

Costs of HVDC & HVAC cabling, and HVAC reactive compensation stations have been sourced from ABB, a leading power engineering company and pioneers of the HVDC technology.

The cost of the HVDC converter station has been derived from the existing published cost of Siemen's HVDC project from UK to the Netherlands. This is considered a more real-world indicative cost, as recommended by SKM's review. However, as the cabling for this project is underwater, it would be more expensive and is not considered representative compared to ZCA2020's land-based HVDC links.

All costs have been converted to Australian dollars at an exchange rate of 1AUD = 0.85USD, and 1AUD = 0.6EURO.

TABLE A6.1
Converted costs of HVDC substations[2]

	Original Project	Scaled (ZCA2020)
MW	1000	4000
kV	450	500
EUR per substation pair	EUR 220,000,000	EUR 978,000,000
AUD/EUR		0.6
Cost for ZCA2020 pair		$1,630,000,000

FIGURE A6.1
Costs of HVAC and HVDC[1]

table 1. Comparative costs of HVDC and EHV AC transmission alternatives.

Alternative	DC Alternatives: + 500 Kv Bipole	DC Alternatives: 2 x + 500 kV 2 bipoles	DC Alternatives: + 600 kV Bipole	DC Alternatives: +800 kV Bipole	AC Alternatives: 500 kV 2 Single Ckt	AC Alternatives: 500 kV Double Ckt	AC Alternatives: 765 kV 2 Singl Ckt	Hybrid AC/DC Alternative: + 500 kV Bipole	Hybrid AC/DC Alternative: 500 kV Single Ckt	Hybrid AC/DC Alternative: Total AC + DC
Capital Cost										
Rated Power (MW)	3000	4000	3000	3000	3000	3000	3000	3000	1500	4500
Station costs including reactive compensation (M$)	$420	$680	$465	$510	$542	$542	$630	$420	$302	$722
Transmission line cost (M$/mile)	$1.60	$1.60	$1.80	$1.95	$2.00	$3.20	$2.80	$1.60	$2.00	
Distance in miles	750	1,500	750	750	1,500	750	1,500	750	750	1,500
Transmission Line Cost (M$)	$1,200	$2,400	$1,350	$1,463	$3,000	$2,400	$4,200	$1,200	$1,500	$2,700
Total Cost (M$)	**$1,620**	**$3,080**	**$1,815**	**$1,973**	**$3,542**	**$2,942**	**$4,830**	**$1,620**	**$1,802**	**$3,422**
Annual Payment, 30 years @ 10%	$172	$327	$193	$209	$376	$312	$512	$172	$191	$363
Cost per kW-Yr	$57.28	$81.68	$64.18	$69.75	$125.24	$104.03	$170.77	$57.28	$127.40	$80.66
Cost per MWh @ 85% Utilization Factor	$7.69	$10.97	$8.62	$9.37	$16.82	$13.97	$22.93	$7.69	$17.11	$10.83
Losses @ full load	193	134	148	103	208	208	139	106	48	154
Losses at full load in %	6.44%	3.35%	4.93%	3.43%	6.93%	6.93%	4.62%	5.29%	4.79%	5.12%
Capitalized cost of losses @ $1500 kW (M$)	$246	$171	$188	$131	$265	$265	$177	$135	$61	$196
Parameters:										
Interest rate %	10%									
Capitalized cost of losses $/kW	$1,500									

Note:
AC current assumes 94% pf
Full load converter station losses = 9.75% per station
Total substation losses (transformers, reactors) assumed = 0.5% of rated power

TABLE A6.2
Technical details and costings of ZCA2020 proposed high-voltage transmission upgrades

Site	Power Station Size	Purpose	Line name	Type	Length	Rating
	MW				km	MW
Carnarvon	4000	Solar Plug-in	Carnarvon to Geraldton	HVAC	499	6000
Kalgoorlie	4000	Solar Plug-in	Kalgoorlie to Perth	HVAC	560	6000
Broken Hill	4000	Solar Plug-in	Broken Hill to Mildura	HVDC	262	4000
Bourke	4000	Solar Plug-in	Bourke to Mount Piper	HVDC	567	4000
Dubbo	4000	Solar Plug-in	Dubbo to Mt Piper Direct	HVAC	249	3000
Moree	4000	Solar Plug-in	Moree to Armidale	HVAC	364	6000
Prairie	4000	Solar Plug-in	Prairie Plug-in	HVAC	296	6000
Longreach	4000	Solar Plug-in	Longreach Plug-in (direct)	HVDC	654	4000
Charleville	4000	Solar Plug-in	Charleville to Roma	HVDC	311	4000
Albany	2000	Wind plug-in	Albany Plug-in	HVAC	430	3000
Esperance	2000	Wind plug-in	Esperance Plug-in	HVAC	363	3000
Geraldton	2000	Wind plug-in	Geraldton to Perth	HVDC	440	4000
Bunbury	2000	Wind plug-in	Bunbury Plug-in	HVAC	10	3000
(Great Aust. Bight)		Wind plug-in	Cleve to Port Augusta	HVDC	201	8000
Ceduna	3000	Wind plug-in	Ceduna Plug-in	HVAC	327	3000
Yongala	2000	Wind plug-in	Yongala Plug-in	HVAC	125	3000
Port Lincoln	2000	Wind plug-in	Port Lincoln Plug-in	HVAC	121	3000
Cape Jaffa	2000	Wind plug-in	Cape Jaffa Plug-in	HVAC	54	3000
Streaky Bay	3000	Wind plug-in	Streaky Bay Plug-in	HVAC	269	3000
Port Fairy	2000	Wind plug-in	Port Fairy Plug-in	HVAC	61	3000
Ballarat	2000	Wind plug-in	Ballarat Plug-in	HVAC	79	3000
Mt Gellibrand	2000	Wind plug-in	Mt Gellibrand Plug-in	HVAC	56	3000
Wonthaggi	2000	Wind plug-in	Wonthaggi Plug-in	HVAC	96	3000
Crookwell	2000	Wind plug-in	Crookwell Plug-in	HVAC	86	3000
Orange	2000	Wind plug-in	Dubbo-Orange-Mt Piper	HVAC	93	3000
Walcha	2000	Wind plug-in	Walcha Plug-in	HVAC	35	3000
Cooma	2000	Wind plug-in	Cooma Plug-in	HVAC	122	3000
Silverton	2000	Wind plug-in	Silverton to Mildura	HVAC	287	3000
Stanthorpe	2000	Wind plug-in	Stanthorpe Plug-in	HVAC	98	3000
Atherton	2000	Wind plug-in	Atherton Plug-in	HVAC	62	3000
Collinsville	2000	Wind plug-in	Collinsville Plug-in	HVAC	18	3000
Georgetown	2000	Wind plug-in	Georgetown Plug-in	HVAC	272	3000
Interstate QLD-NSW		Grid Upgrade	Roma to Moree	HVDC	417	4000
Interstate SA-NSW		Grid Upgrade	Port Augusta to Mount Piper	HVDC	1169	8000
Interstate VIC-NSW		Grid Upgrade	Mildura to Mount Piper	HVDC	708	4000
Intrastate		Grid Upgrade	Mildura to Melbourne	HVDC	544	8000
Interstate SA-VIC		Grid Upgrade	Port Augusta to Mildura	HVDC	461	4000
Interstate SA-VIC		Grid Upgrade	Port Augusta to Melbourne	HVDC	886	4000
Interstate SA-VIC		Grid Upgrade	Port Augusta to Naracoorte	HVDC	560	4000
Interstate SA-VIC		Grid Upgrade	Naracoorte to Portland	HVAC	216	6000
Interstate QLD-NSW		Grid Upgrade	Roma to Armidale	HVAC	662	6000
NEM-Mt Isa		Grid Connection	Mt Isa upgrade	HVDC	847	4000
SWIS-NEM		Grid Connection	Perth to Port Augusta	HVDC	2146	4000
SWIS-NEM		Grid Connection	Kalgoorlie to Port Augusta	HVDC	1586	4000
SWIS-NWIS		Grid Connection	SWIS-NWIS Connection	HVAC	561	6000

Multiple lines – single or double	HVDC station costs ($AU M) – 4 GW Capacity	HVAC station costs ($AU M) - 3 GW Capacity	HVDC Transmission line cost ($AU M/km) – 4 GW Capacity	HVAC Transmission line cost ($AU M/km) – 3 GW Capacity	Total Cost ($AU M) (cable + station)
	$1,630	**$638**	**$1.17**	**$2.34**	
2		$1,275		$2,335	**$3,610**
2		$1,275		$2,620	**$3,895**
1	$1,630		$306		**$1,936**
1	$1,630		$663		**$2,293**
1		$638		$582	**$1,220**
2		$1,275		$1,705	**$2,980**
2		$1,275		$1,385	**$2,660**
1	$1,630		$765		**$2,395**
1	$1,630		$363		**$1,993**
1		$638		$1,005	**$1,643**
1		$638		$849	**$1,487**
1	$1,630		$515		**$2,144**
1		$638		$24	**$662**
2	$3,259		$470		**$3,729**
1		$638		$765	**$1,403**
1		$638		$293	**$930**
1		$638		$283	**$921**
1		$638		$127	**$765**
1		$638		$630	**$1,267**
1		$638		$143	**$780**
1		$638		$186	**$823**
1		$638		$131	**$769**
1		$638		$224	**$862**
1		$638		$202	**$839**
1		$638		$217	**$854**
1		$638		$81	**$719**
1		$638		$285	**$923**
1		$638		$672	**$1,310**
1		$638		$230	**$867**
1		$638		$145	**$783**
1		$638		$43	**$680**
1		$638		$636	**$1,274**
1	$1,630		$488		**$2,117**
2	$3,259		$2,735		**$5,994**
1	$1,630		$828		**$2,458**
2	$3,259		$1,273		**$4,533**
1	$1,630		$539		**$2,169**
1	$1,630		$1,036		**$2,666**
1	$1,630		$655		**$2,285**
2		$1,275		$1,011	**$2,286**
2		$1,275		$3,096	**$4,372**
1	$1,630		$991		**$2,620**
1	$1,630		$2,510		**$4,140**
1	$1,630		$1,855		**$3,485**
2		$1,275		$2,625	**$3,900**
				TOTAL:	**$92,440**

Sinclair Knight Merz (SKM) Review of ZCA2020 Stationary Energy Plan

Keith Frearson, 20 May 2010

Background

SKM has reviewed the ZCA2020 Stationary Energy plan prepared by Beyond Zero Emissions and the Climate Emergency Network in terms of the connection of the proposed Zero Carbon generation and its connection to the transmission network.

The review finds that the transmission scenario proposed is technically feasible in terms of capacity and reliability. In addition, the proposed transmission uses mature technology with proven capability around the world.

Key Review Findings

General Arrangements

The transmission connection arrangements have been designed based on using large centralised generation centres for both solar thermal installations and wind farms – typically 3500 MW and 2000 MW respectively. As a consequence, the transmission arrangements are sized to accommodate these power levels.

Due to the magnitude of the generation and the distances involved, the transmission connection for the solar thermal plant has been assumed to be HVDC at +/-500 kV and 4000 MW capability. This makes sense in terms of Node-Node transfer capability of large amounts of energy.

For wind farms, the connection has been assumed to be HVAC at 500 kV with 3000 MW capability (per circuit) to allow for easier connection of dispersed sites. For example, the south western coastline of South Australia has been identified as a major wind-resource area. As there are a number of wind generation centres proposed for that area, it is preferable to use HVAC as distributed connection points can be more easily arranged.

Overall Generation/Load Balance

The plan provides a reasonable balance between generation and load in each state as shown in the following table:

Important points to note from the table are:

- The total installed Solar thermal generation is 42,500 MW; note – Numbers in table have been rounded, each CST solar thermal site is in fact 3,537 MW
- The total load is 58,200 MW;
- Wind and existing Hydro provide a further 53,000 MW;
- The major source for Hydro generation is the Snowy Mountains scheme;
- Victoria and New South Wales have a slight deficit in terms of Solar Thermal generation and peak demand but this is compensated for by wind generation, hydro generation and enhanced transmission interconnections to other regions. Furthermore, additional Solar Thermal stations could be installed in both Victoria and New South Wales should the need arise.

Transmission Concept

The transmission concept is to use the existing network wherever possible and to develop major HVDC hubs in South Australia, Victoria and New South Wales (at Port Augusta, Mildura and Mt Piper respectively). The HVDC transmission will provide full access to the Solar Thermal generation located across a number of time zones. HVDC at voltage levels in excess of +/-500 kV is used extensively throughout the world and is considered a "mature" technology. The major technical drawback with HVDC is the difficulty in creating connections between the terminating hubs. In this study, it has been assumed that all HVDC links are Hub-Hub and no off-takes are provided.

The location of the hubs has not been optimised but they are viable locations, given the sources of generation (Solar and Wind) and the underlying transmission network.

Where HVDC is not practical (for example where a significant number of connections are required), 500 kV HVAC transmission has been used (eg for wind farms across South Australia). 500 kV HVAC is currently employed in both Victoria and New South Wales and is being proposed for Queensland.

TABLE A6.3
Power Generation Supply and Demand Analysis by State

State *	Solar (MW)	Wind (MW)	Hydro (MW)	Total Generation (MW)	Peak Demand (MW in 2020)
Western Australia	7,000	8,000	-	15,000	7,500
South Australia	3,500	14,000	-	17,500	4,300
Victoria	7,000	8,000	500	15,000	12,800
NSW	10,500	10,000	3,750	24,250	19,600
Queensland	14,000	8,000	700	22,000	14,000

*Tasmania has been neglected from this analysis as the possible use of solar thermal generation is limited

In addition, AEMO has recently published reports entitled "Network Extensions to Remote Areas: Parts 1 and 2". In these reports, the concepts of major enhancements to the 500 kV grid are examined, as well as using long-distance HVDC to connect remote renewable generation and upgrading interstate transmission capability. To some extent, these reports validate the transmission concepts proposed for the various renewable energy sources.

Generation Sources

Solar Thermal stations have been sited across Australia in a number of different time zones. This feature, together with using locations having high solar incidence, will act to ensure high availability of output from the solar thermal generators.

The proposed centres for wind farms are located along over 6,000 km of coastline from Albany to Cairns. This diversity should ensure that there will be a significant wind resource available at one or more locations.

The hydro generation can be used to provide a buffer to the variability of the wind generation. Alternatively, the wind generation can be thought of as preserving the hydro resources for periods when it can most usefully be used. This also applies to solar thermal power – in periods of high wind output, excess heat can be stored in the molten salt tanks for later use.

System Demand

The system demand for 2020 has been estimated based on load forecasts in the various annual planning reports publicly available. Where necessary, the data has been extrapolated to 2020 using the growth rate assumed in these forecasts.

Network Development

The transmission network as proposed will not appear overnight – it will be staged over many years. As a consequence, there will be a need to consider the staging options to provide the most efficient and practical outcome over time. For example, it may well be the case that the Western Australian connections to South Australia would be the last connections to be made – if found to be of value.

The development of a 500 kV network to capture the wind potential of South Australia could well be the first project requiring major capital investment but would provide access for proven wind farm technology.

A number of the CST plants and wind farms could be completed without the requirement for major transmission upgrades, at least in the initial phases of development. Three examples demonstrate this:

- Moree Solar Thermal plant is situated within 200 km to Armidale in NSW and Bulli in Queensland. These two stations form part of the Queensland-NSW Interconnector (QNI). If the QNI is to be upgraded to 500 kV then taking the 500 kV QNI via Moree would represent an efficient solution.
- Dubbo Solar Thermal plant is 180 km from Mt Piper while Orange Wind Farm is approximately 80 km from Mt Piper and almost in a direct line to Dubbo. Mt Piper is already a major transmission hub in NSW so connection costs can be kept to a minimum. The possibility of using one Double Circuit 500 kV line to service both Dubbo CST and Orange Wind Farm, at least in the initial development stages, creates opportunities for significant savings.
- Port Augusta Solar Thermal plant is close to the Davenport 275 kV substation. Assuming the proposed Olympic Dam load eventuates, Davenport 275 kV substation could accommodate significant injection from the CST (say 500 MW) without the need for major inter-regional transmission development. Thus, initial development could proceed in a staged manner at minimal initial cost.

Hydro

No new hydro power stations have been proposed but the presence of existing hydro generation will provide a reliable and easily controlled generation source should it be required.

Transmission Costs

The costing of the proposed transmission connections has been carried out using figures derived from past projects but no formal evaluation has been made in this regard. It is recognised that the costs presented are very high – but not unrealistic if the development timeframe is considered. The costs could amount to $10 B/year over a 10 year development horizon with much of the cost "back-ended".

Disclaimer

The review has considered connection feasibility in terms of capacity and security. The network examined has not been optimised and constraints on the underlying (existing) transmission system have not been specifically addressed. The costing of the proposed transmission connections has been carried out using figures derived from past projects but no formal evaluation has been made in this regard.

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Appendix 7
Implementation – Timeline and Jobs

Implementation Timeline Modelling

The ten-year timeline for implementing the ZCA2020 Plan has been modelled from January 2011 to December 2020. The plan takes into account a ramp-up of the renewables industry over a number of years. This analysis is intended to demonstrate the scale of installation that would be required to achieve the transition. It is recognised that there are social and political constraints that would need to be overcome to allow this timeline to occur, along with fast-track planning approval for projects.

The installation of the various components of the renewable energy system (wind, CST, transmission etc) have been modelled in six monthly time intervals, to approximate a steady stream of projects. Construction timelines vary with each particular technology.

Jobs calculation methodology

The methodology for calculating the jobs requirements is based on similar work completed by Rutovitz and Atherton analysing the rollout of renewable energy on a global scale[1].

Construction jobs are calculated on the basis of the required job-years per MW of capacity, using referenced industry data. One job-year is the equivalent of one person employed for one year, and is considered the most relevant measure of the labour task required for construction projects. For example, a project that requires 50 job-years to construct, could be completed in one year with 50 workers, or two years with 25 workers.

Operations and Maintenance (O&M) jobs are calculated on the basis of jobs per MW of commissioned capacity. These job numbers progressively increase during the project period, in line with the progressive increase in commissioned capacity.

'Decline factors' are used to describe the way employment intensity (job-years per MW) reduces gradually over time, as skills and technology efficiency improve. This factor accounts for the projected reduction in employment per MW of renewable and fossil fuel technologies over time, as the technologies and companies become more efficient, and as economies of scale are realised. The decline factors are applied to all categories of jobs (manufacture, installation, and operation and maintenance).

Annual Decline Factors for Various Technologies

Technology Type	Annual Decline in Job Factors
Coal	1.00%
Gas	0.40%
Solar thermal	1.60%
Wind (on-shore)	1.40%
Biomass	1.00%
Solar PV	7.72%
Hydro	-0.60%

* These decline factors are based on Greenpeace's Energy [R]evolution scenario which has a global (if more limited) roll-out of renewable energy technologies. There are considerable uncertainties in deciding how much these factors would change under the ZCA2020 scenario, but they give a reasonable indication of the employment pattern over time.

Manufacturing Industry employment

It is assumed that as domestic demand declines towards the end of the construction period, we are able to continue manufacturing renewable equipment, and export it into the emerging international markets.

CST parameters

As of 2010, there is not yet a CST industry in Australia. It is therefore expected that it will take a number of years to grow.

SolarReserve currently expects a 2-2.5 year construction timeline for its first CST tower plants in the USA[2]. The Rice Solar Energy Project is a tower plant that will produce over 450,000 MWh/yr of electricity in California. As outlined in more detail in Appendices 3A and 3B, this is equivalent to a 75 MW plant running at 70-75% capacity factor, as with the configurations specified for ZCA2020. Official project documentation gives the labour requirements as an average of 280 construction jobs over a 2.5-year construction period, equivalent to 700 job-years – 9.33 job-years/MW, or an average of 3.73 jobs per year per MW. For later stages of the ZCA2020 Plan, employment for the shorter construction timelines has been modelled as still requiring the same total labour (job-years/MW), but with a larger number of jobs over the period, to complete the task in a shorter timeframe.

Parameter	Value	Reference
Construction time (2011 projects)	2.5 years	SolarReserve Rice[2]
Construction time (2012-2013 projects)	2 years	Mid-term estimate
Construction time (2014 onward)	1.5 years	Andasol[3]
Installation Job-years/MW	9.33	SolarReserve Rice[2]
O&M Jobs/MW	0.7	SolarReserve Rice[2]

Construction period years	Construction Jobs/yr/MW
2.5	3.73
2	4.67
1.5	6.22

CST Heliostat manufacturing

Sandia National Laboratories[4] have completed studies and costing regarding labour requirements (person-hours) for manufacturing assembly of heliostats of various sizes. This has been used as the basis for estimating direct manufacturing labour requirements for heliostat production. A 148 m^2 heliostat requires 46 person-hours of shop assembly. Based on 223 production days per year, and single 8-hour shifts per day, job requirements have been calculated at 25.8 jobs per 1000 heliostats per year. However it has also been assumed that only 50% of the manufacturing task is carried out in Australia. This could reflect an arrangement such as shipping individual mirror panels for assembly in Australia.

Wind parameters

Wind power is already a fast growing industry in Australia, with a current operational wind power of 1,700 MW[5], and another 11,000 MW of projects at various stages of planning and development[6].

With fast tracking of existing wind power projects and continued growth, it is expected that by 2014, wind power installation can reach a constant rate of construction of 6,000 MW per year.

It is also assumed that 50% of manufacturing is done onshore. As of mid-2010 there is no domestic wind manufacturing in Australia.

The following parameters were used in the modelling of ZCA2020 wind installation:

Parameter	Value	Reference
Construction time	1 year	Industry standard
Installation Job-years/MW	1.2	EWEA[7]
Manufacturing Job-years/MW	7.5	EWEA[7]
O&M Jobs/MW	0.33	EWEA[7]

Biomass parameters

Biomass plant construction requires adding biomass firing facilities to selected CST plants. The biomass construction timeline begins in January 2015 and continues through to the end of 2020. Construction activity for each plant is assumed to take 1 year.

Biomass jobs are considered in two components - those associated with co-firing the CST plants (biomass backup), and those associated with supplying the biomass fuel. Two modifiers are used:

Construction — Since the biomass here will use most of the same facilities as the CST plant, the jobs factor for biomass construction is reduced to 0.5 of the normal factor. The factor used is based on the analysis of thermal plants from Atherton et al[8].

O&M — The O&M jobs specifically for biomass backup are considered negligible compared with CST because the normal jobs factor used for biomass electricity generation is quite high, reflecting the relatively small size of plant usually involved. Since the biomass here is associated with relatively large CST plants, and the biomass will only be brought online occasionally (when the sun is not shining, the salt storage is exhausted and the wind cannot cover the demand), so that the O&M staff at the CST plants will be able to manage the O&M requirements for the biomass.

For jobs in the supply of biomass fuel, the normal jobs factor is applied.

The following parameters were used in the modelling of ZCA2020 biomass system:

Parameter	Value	Reference
Construction time	1 year	
Installation Job-years/MW	4.3 x 0.5 = 2.15	Atherton et al[8]
O&M Jobs/MW	0	Discussion in text
Jobs collecting biomass fuel Jobs/GWh	0.22	Atherton et al[8]

Results of detailed timeline modelling. 'Under construction' is the amount of capacity under construction at the beginning of each 6-month time period. 'Operational (Cumulative) is the total amount of operational capacity at the beginning of the time period.

Construction Task		Jan 2011	Jul 2011	Jan 2012	Jul 2012	Jan 2013	Jul 2013	Jan 2014	Jul 2014	Jan 2015
CST (On-grid)	Under Construction	250	1,000	2,000	3,500	5,000	5,750	6,700	8,060	9,860
(MW)	Operational (Cumulative)	0	0	0	0	0	250	2,000	3,500	5,000
CST (Off-grid)	Under Construction	0	0	0	0	0	0	0	0	0
(MW)	Operational (Cumulative)	0	0	0	0	0	0	0	0	0
Wind	Under Construction	500	1,250	2,000	3,250	4,500	5,500	6,000	6,000	6,000
(MW)	Operational (Cumulative)	2,000	2,000	2,500	3,250	4,500	6,500	9,000	12,000	15,000
Biomass	Under Construction	0	0	0	0	0	0	0	0	500
(MW)	Operational (Cumulative)	0	0	0	0	0	0	0	0	0
Transmission	Under Construction	500	1,500	3,000	4,000	4,500	4,500	4,500	4,500	4,500
(km)	Operational (Cumulative)	0	0	0	500	1,500	3,000	4,500	6,000	7,500
Jobs										
CST (On-grid)	Construction	933	3,703	8,266	15,032	21,689	25,101	33,791	43,723	56,060
Jobs	O&M	0	0	0	0	0	168	1,334	2,316	3,281
	Heliostat Manufacturing	0	0	172	1,366	2,371	3,191	4,465	5,329	6,466
CST (Off-grid)	Construction	0	0	0	0	0	0	0	0	0
Jobs	O&M	0	0	0	0	0	0	0	0	0
Wind	Construction	600	1,490	2,367	3,819	5,250	6,372	6,903	6,855	6,807
Jobs	O&M	800	794	986	1,273	1,750	2,510	3,451	4,570	5,672
	Manufacturing	0	0	7,395	11,933	16,407	19,913	21,571	21,742	21,913
Biomass	Construction	0	0	0	0	0	0	0	0	1,033
Jobs	O&M	0	0	0	0	0	0	0	0	0
	Collecting Biomass	0	0	0	0	0	0	0	0	0
Transmission	Construction	700	2,100	4,200	5,600	6,300	6,300	6,300	6,300	6,300
Jobs										
Total Jobs	Construction	2,233	7,293	14,832	24,451	33,239	37,773	46,994	56,877	70,199
Total Jobs	O&M	800	794	986	1,273	1,750	2,678	4,785	6,885	8,953
Total Jobs	Manufacturing	0	0	7,567	13,299	18,778	23,105	26,037	27,070	28,380

Jul 2015	Jan 2016	Jul 2016	Jan 2017	Jul 2017	Jan 2018	Jul 2018	Jan 2019	Jul 2019	Jan 2020	Jul 2020	Jan 2021
9,680	10,120	10,120	9,900	9,680	9,460	9,240	9,020	8,580	5,500	2,640	0
8,700	11,560	14,860	18,380	21,680	24,980	28,280	31,360	34,440	37,520	40,380	43,020
400	850	1,350	1,475	1,550	1,575	1,575	1,575	1,550	1,025	500	0
0	0	0	400	850	1,350	1,875	2,400	2,925	3,450	3,975	4,475
6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	5,000	2,000	0
18,000	21,000	24,000	27,000	30,000	33,000	36,000	39,000	42,000	45,000	48,000	50,000
1,000	1,500	2,000	3,000	4,000	4,000	4,000	4,000	3,000	2,000	1,000	0
0	500	1,000	2,000	3,000	5,000	7,000	9,000	11,000	13,000	14,000	15,000
4,500	4,500	4,500	4,500	4,500	4,250	3,750	3,250	2,750	1,750	750	0
9,000	10,500	12,000	13,500	15,000	16,500	18,000	19,500	20,750	21,750	22,750	23,500
56,014	58,090	57,623	55,918	54,236	52,578	50,943	49,330	46,547	29,598	14,093	0
5,664	7,465	9,519	11,679	13,665	15,619	17,540	19,295	21,019	22,715	24,250	25,628
6,558	7,079	7,342	7,223	7,237	7,250	7,264	7,278	7,292	7,305	7,319	7,333
2,315	4,879	7,687	8,331	8,685	8,754	8,683	8,614	8,409	5,516	2,669	0
0	0	0	254	536	844	1,163	1,477	1,785	2,089	2,387	2,666
6,759	6,712	6,665	6,618	6,572	6,526	6,480	6,435	6,390	5,287	2,100	0
6,759	7,830	8,886	9,927	10,953	11,964	12,960	13,942	14,909	15,862	16,801	17,379
22,086	22,261	22,436	22,614	22,792	22,972	23,153	23,336	23,520	23,706	23,893	24,082
2,055	3,067	4,069	6,073	8,057	8,017	7,977	7,937	5,923	3,929	1,955	0
0	0	0	0	0	0	0	0	0	0	0	0
0	38	76	152	227	376	524	670	815	958	1,027	1,095
6,300	6,300	6,300	6,300	6,300	5,950	5,250	4,550	3,850	2,450	1,050	0
73,443	79,048	82,344	83,241	83,850	81,824	79,333	76,866	71,118	46,780	21,867	0
12,423	15,295	18,405	21,860	25,154	28,427	31,663	34,713	37,713	40,666	43,439	45,673
28,644	29,340	29,779	29,837	30,029	30,222	30,418	30,614	30,812	31,011	31,212	31,415

Transmission parameters

New transmission line capacity is required early in the project, to connect new generating plant into the grid. The transmission installation timeline begins in 2011, and continues steadily throughout the project. The parameters for construction rate and employment are derived from National Environmental Policy Act (NEPA) documents on 500kV transmission lines projects in the USA. Construction jobs are based on an employment level of 2.1 job-yrs/km at an installation rate of 1.5 years/km of line. This is equivalent to 1.4 jobs/yr/km.

The following parameters were used for installation of new transmission lines:

Parameter	Value	Reference
Construction time	1.5 years	NEPA[9,10]
Installation Job-years/ km	2.1	See text and NEPA[9,10]
Jobs/yr/MW	1.4	

Direct Displacement of Fossil Fuel Employment

The assessment of fossil fuel jobs displaced by the ZCA2020 Stationary Energy System is based on the following:

- Jobs created by coal and gas exports are not counted in this study.
  The most recent employment data that details coal mining and gas extraction jobs as opposed to overall mining industry employment is 2007. This has been scaled up at a factor of 2% growth per year to 2010. This is considered reasonable for domestic fossil fuel production, which has not seen the fast rate of growth that the export fossil fuel industry has in the years to 2010.
- The proportion of coal mined in Australia that is used in domestic electricity production is 28%[12]. As at June 2007, a total of 26,491 Australians were employed in coal mining[11], leading to an estimated 28,100 for 2010 and so approximately 7,900 of these are counted as directly employed in the generation of electricity from coal.
- The proportion of gas and LPG extracted (or refined) in Australia that is used in domestic electricity production and end-use heat is 55%[12]. As at June 2007, a total of 10,240 Australians were employed in Oil and Gas Extraction[11], with an estimated 11,100 in 2010, and so approximately 6,100 of these are counted as directly employed in the generation of electricity and end-use heat.
- There were 5,914 existing (2006) direct jobs in electricity production from fossil fuels (excluding extraction of fuels as above)[13]. Scaled up to 2010, this is approximately 6,300 electricity generation jobs.

Replacement of coal and gas as fuel sources in the domestic market, and conversion of existing fossil fuel electricity generation to renewable energy would therefore directly affect approximately 20,300 jobs.

This displacement of 20,300 jobs over 10 years can be compared with the monthly average fluctuations in national employment of 19,480 for January 2010[14], or the 77,000 ongoing jobs created in O&M and manufacturing by the ZCA2020 Plan.

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Appendix 8
Resource Requirements

Resource requirements calculated for major components of CST, Wind and transmission systems.

CST

There are six main types of resources required for a CST Tower system as proposed in the ZCA2020 project. The resources are steel, concrete, glass, silver, aluminium and nitrate salt (or fertiliser).

Steel, Glass and Concrete

TABLE A8.1
Summary of ATS-148 resource requirements, calculated using data from Sandia Labs' heliostat study[1]. Steel and glass from Table 3-4, pg 44; Concrete from Table 3-10, pg 49, and concrete data[6].

ATS-148 Heliostat Requirements				
Material Breakdown	**lb**	**kg**		
Structural Steel	8709	3950		
Gear Drives (steel and cast iron)	1500	675		
Steel Fasteners and Misc.	104	47		
Motors & Controls (Steel, Copper, etc.)	120	54		
Glass Mirrors	3300	1485		
Adhesives	160	72		
	13893	6283		
			148	m^2 heliostat
Total Steel		4726	31.9	kg/m^2
Total Glass		1485	10.0	kg/m^2
Total Adhesive		72		

ATS Concrete Requirements			
Concrete Foundation	2.5		yards (cubic) per heliostat
	0.914		yards/metre
m3 per heliostat	1.91		m^3 per heliostat
kg/m3 concrete	2400		
kg per heliostat	4587		
		31.0	kg/m^2

For the CST component of the ZCA2020 project the requirements of steel, glass and concrete is as follows.

This calculation is based on data from eSolar and the ATS-148 heliostat.

TABLE A8.2
Summary of eSolar resource requirements, calculated from information from eSolar product information[2] and communication from eSolar CEO Bill Gross[4]. Additional concrete information from [5].

	eSolar Steel
46	MWe on-sun power tower module [1]
16	towers and receivers [1]
192000	heliostats [1]
1.14	m^2/mirror [3]
218880	m^2 mirrors
4758	m^2 mirror/MWe
4.76	m^2/kWe
75	kg steel/kWe [3]
15.8	kg/m^2 mirror field
	eSolar concrete
60	lbs/mirror [3]
27.2	kg/mirror
23.9	kg concrete/m^2 mirror
	eSolar glass
3	mm thick glass [3]
0.0030	m^3 glass/m^2 mirror
2600	kg/m^3 glass density [4]
7.8	kg glass/m^2 mirror

Mirrors and Heliostats

Mirrors are constructed of a substrate, a reflective material and a protective coating for the reflective material. Typically mirrors has glass as the substrate and silver as the reflective material, with copper and paint applied as protection. In the ZCA2020 project, standard mirrors are used for the CST systems. There are other alternatives such as polymer based mirrors or polished steel or aluminum mirrors. But standard mirrors are ideal due to their availability, cost effectiveness and efficiency.

The total mirror required for heliostats in the ZCA2020 project. This is based on Solar 220 requirements of 2,650,000 m^2 of mirrors per 217 MWe (spread out over 13.9 km^2 of land) [7].

Summary of silver requirements for ZCA2020 and Australian silver production.[9]

TABLE A8.3
Total Mirror Field Requirements

Value	Units
217	MWe – Solar 220
2.65	km2 – mirror aperture area for Solar 2207
0.012	km2 mirror/MWe
47000	MWe Total CST capacity for Australia
572	km2 mirror surface

TABLE A8.4
Mirror Silver Requirements (both mirror types)

Silver film backing on high peformance glass	
75	mg per ft^2, source [8]
0.09	m^2 per ft^2
833	mg per m^2
0.83	g per m^2
572	km^2 mirror surface for ZCA2020
572,098,864	m^2 mirror surface
ZCA2020 Requirements	
476,749	kg of silver needed
0.48	thousand tonnes of silver total
Australian silver production	
61.9	millions of ounces per year (2008)[9]
28.35	grams per ounce
2	thousand tonnes/yr of silver
Australian 10 year silver production	
18	thousand tonnes of silver

TABLE A8.5
Nitrate Salt Requirements for thermocline vs two-tank

Component	Two-Tank Molten Salt	Thermocline with Quartzite
Nitrate Solar Salt $	11,800,000	3,800,000
Filler Material	0	2,200,000
Tanks(s)	3,800,000	2,400,000
Salt-to-Oil Heat Exchanger	5,500,000	5,500,000
Total	21,100,000	13,900,000
Specific Cost,$/kWh	31	20
MWh storage	688	
per tonne salt	$450.00	
per tonne quartzite filler	$72.00	
	Two tank	Thermocline
	$11,800,000	$3,800,000
tonnes salt	26222	8444
tonnes/MWh	38	12
	difference:	32%
Filler		$2,200,000
tonnes filler		30556
Power Tower system		
(uses less salt than trough due to higher operating temperature)		
tonnes salt per MWh	14.3	
tonnes if thermocline used	4.61	
MWe installed	46,878	
hours storage each	17	
MWh storage	796,919	
	Two-tank	Thermocline
tonnes salt	11,395,936	3,669,878
MT salt	11.40	3.67

CST Energy Storage

The ZCA2020 proposes a molten salt storage systems to be integrated to provide energy storage for the CST system. Molten salt utilises common nitrate salts, such as fertiliser, to store energy as heat in a insulated environment. Table A8.5 and Table A8.6 compare salt requirements for various systems, based on data from Sandia studies[10,11].

TABLE A8.6
Comparison of amount of salt required for higher temperature (650˚C) storage and lower temperature storage.[11]

Molten salt storage		Binary salt	Binary salt	Binary salt with oxygen blanket	Ternary salt with oxygen blanket	Quaternary salt with oxygen blanket
	MWh	1	1	1	1	1
Specific heat capacity (c) of molten salt	kJ/kg.K	1.52	1.52	1.52	1.35	1.35
Hot tank temperature	°C	500	565	650	650	650
Cold tank temperature	°C	290	290	290	190	170
Rankine (steam) cycle efficiency - supercritical double reheat	%	46	46	46	46	46
Electrical energy required	kJ	3,600,000	3,600,000	3,600,000	3,600,000	3,600,000
Thermal energy storage requirement	kJ	7,826,087	7,826,087	7,826,087	7,826,087	7,826,087
Q= mc(T2-T1)						
m = Q/(c(T2-T1)) mass of salt	kg	24,518	18,723	14,302	12,602	12,077
	m^3	14	10	8	7	7
Mass of salt with 2/3 quartzite filler	kg	8,173	6,241	4,767	4,201	4,026
Density	kg/m^3	1800	1800	1800	1800	1800

TABLE A8.7
Resources Required for ZCA2020 Electrical Transmission

HVDC **Equivalent to single circuit HVAC (single tower)**	**Resources Required**
Length of 500kV HVDC line	13,673 km
Steel	379,210 tonnes
Aluminium	73,823 tonnes
Concrete	1,063,604 tonnes
HVAC **Equivalent of two single circuit HVAC (double circuit, single tower)**	**Resources Required**
Length of 500kV HVAC line	9,631 km
Steel	290,631 tonnes
Aluminium	103,999 tonnes
Concrete	749,181 tonnes

Total Resources Required	
Steel	669,841 tonnes
Aluminium	177,822 tonnes
Concrete	1,812,785 tonnes

Transmission

The ZCA2020 project will require a total of 23,304 km of transmission lines, 13,673 km of HVDC and 9,613 km of HVAC of transmission lines. A total of 39067 transmission towers are required at 350 m intervals. The HVDC transmission lines are estimated to be equivalant to a single circuit HVAC requirements. The HVAC transmission lines are estimated to be equivalant to two single circuit HVAC requirements.

The estimation of transmission system resources is based on the summaries for outlined in the tables in this section. This includes both resources requirements per transmission tower and resources requirement per unit length of transmission lines. The 500 kV transmission lines requirements are based two Orange/Zebra 1 conducter per unit length, and 2 OPGW Earth wire per unit length. Data from [12,13,14].

TABLE A8.8
Conductor Resource Requirements

Conductor	Material	Ton/km
Orange / Zebra x1	Steel	0.44
	Aluminium	1.19
Earth Wire (OPGW)	Steel	0.35
	Aluminium	0.33

TABLE A8.9
Tower and Conductor Totals

Individual Tower Weights (kg)				
Voltage (kV)	Steel	Aluminium	Concrete	Circuits
500	8,851.86	0	27,225.13	1
Conductor (kg/km)				
Voltage (kV)	Steel	Aluminium	Rating Amps	MVA
500	2,442.4	5,399.2	3,484	3,017.23

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Appendix 9
Economic Comparison Assumptions and References

This appendix provides the basis for "Business-As-Usual" (BAU) Stationary and Transport energy supply and demand, the resulting greenhouse gas emissions, and the discounted present-value costs, for the period 2010 to 2040. In addition, it provide back-up information regarding comparisons of the Plan to other economic activity.

ZCA2020 Plan vs Business As Usual

The assumptions on which the BAU scenario was modelled include the following:

The BAU scenario models how much conventional fossil fuel generation will be required to meet a projected electricity demand of 325TWh/yr by 2020. Capital expenditure is made until 2020 to meet growing demand, and in the same fashion as the ZCA2020 case, any new capacity required beyond 2020 is not in the scope of this analysis. This 325 TWh/yr would be enough to meet BAU demand growth if no efficiency measures are implemented, or the full heating & transport load if efficiency and fuel swtiching occurs. Capital and operating costs are based on data from ACIL Tasman[2] and other industry sources.

Capital expenditure

New black coal power stations are built to replace old coal generation as it is retired, the equivalent of 1/30th of total MW capacity per year amortised over the time period. This is priced at $1,900/kW.

New capacity which is added to meet growing peak and average demand is a mixture of open-cycle (OCGT) and combined-cycle gas turbines (CCGT), at $850/kW. Based on industry sources, BAU peak electricity demand is assumed to continue to grow faster than GDP at 3.15%/yr[3].

New transmission expenditure is $2 billion/yr[4].

Operating expenditures

Electricity generation grows to supply 325TWh/yr in 2020. Mix continues to be 25% brown coal, 55% black coal and 20% gas[5].

Brown coal fuel cost is $5/MWh (electrical), based on current industry prices, and is assumed to remain constant.

Black coal is $85/tonne in 2011, $100/tonne in 2012 and rises in line with GDP growth (2.1%/yr) thereafter, reflecting parity with international markets. Average black coal fleet efficiency is 35% sent-out, reflecting a mix of older, low-efficiency plants and newer, higher-efficiency plants.

Natural gas is priced based on ACIL Tasman forecasts. $3.9/GJ in 2010, to $4.5/GJ in 2020, $5.2 in 2030 and $6.1 in 2040. Thermal efficiency is 40%, reflecting the mix of OCGT and CCGT.

For fossil fuels, variable O&M Costs are $1.50/MWh. Fixed O&M costs are $40,000/MW/yr (coal) and $10,500/MW/yr (gas). Solar fixed O&M is $60,000/MW/yr[21], wind is $40,000/MW/yr[22].

Non-electrical fuels

BAU oil and gas demand for transport and heating, respectively, are also modelled. This is the 'bill' that would occur if no efforts are made (under either BAU or ZCA2020) to fuel-switch to supply these service with electricity, and the extra electricity supply is used to meet a growing demand for current services with no efficiency measures. It is recognised that extra capital investment would be needed to supply the electrified transport and heating infrastructure to make this change. However, the fossil fuel 'bill' that will otherwise be incurred can be considered a fund from which the fuel switch and efficiency expenditure can be sourced, to avoid future fossil fuel costs.

It is assumed that without efficiency or fuel switching, demand for oil and gas continue to rise from current rates of consumption in line with GDP growth of 2.1%/yr[1].

Gas price is the same as above.

Crude Oil Price: The present crude oil price is used as a 2010 starting point (US$80/bbl). Given that the world is now broadly at the peak of oil production, an escalation rate of 5% on top of normal CPI is assumed, but capped at $US 130 / barrel (2010 real dollar terms). This cap represents a view that under Business As Usual, alternative (and environmentally damaging) oil sources such as tar sands and shale oil will set a limit to which the price of oil can rise in real dollar terms. This price projection is informed by CSIRO research[8].

Other modelling assumptions

Foreign Exchange Rate: An exchange rate of 0.85 $US/$A is assumed as representing a long term historical average.

Carbon Price: Another possible scenario is that a carbon price is established in Australia. A 2011 starting price of $A10/tonne is assumed, rising within two years to $A20/tonne, and then escalating at 5% per year on top of normal CPI. This reflects the view that there is already too much carbon in the atmosphere and that the world will move to stabilise and then reduce carbon in the atmosphere over the period 2010—2040. The BAU case therefore represents the situation where Australia is exposed to an initially moderate carbon cost but nevertheless chooses not to take action to reduce carbon emissions.

Discount Rate: A discount rate of 1.4% is assumed. This is the same as used by the Stern Review[6,7]. It is made up of two components: a pure time preference rate of 0.1% and an allowance for the marginal utility of consumption of 1.3%.

The pure time preference rate is an allowance only for extinction and reflects the utilitarian view that a unit of consumption to someone now should be valued equally to a unit of consumption by someone else in the future.

1.3% is the assumed rate of real income growth. Discounting with this implements an assumption that the marginal utility of consumption is constant as a proportion of total consumption. That is, a marginal dollar of consumption when total consumption is $100 has the same utility as two marginal dollars of consumption when total consumption is $200.

They key results of the model are shown in Table A9.1.

For comparison, the model has also been run at discount rates of 6% (Table A9.2) and 8% (Table A9.3).

TABLE A9.1
Summary of Economic Model results

	BAU	ZCA2020	BAU-ZCA
Capital Investments	$135	$337	-$203
BAU electricity ramp down - operating & fuel costs (2011 - 2020, ZCA case only)		$77	
Coal and Gas for electricity	$300		
Operations and Maintenance Costs	$55	$90	
Emissions (Stationary Energy)	$424	$42	
Oil – BAU or ZCA2020 ramp-down	$1,297	$236	
Heating Gas – BAU or ZCA2020 ramp-down	$143	$24	
Summary Results			
Sum	$2,354	$806	$1,548
Sum Excl Oil & Gas	$914	$546	$368
Sum Excl Emissions	$1,930	$765	$1,165
Sum Excl Oil, Gas & Emissions	$490	$504	-$15

TABLE A9.2
Summary of results using 6% discount rate

	BAU	ZCA	Diff
Sum	$1,153	$598	$554
Sum Excl Oil & Gas	$436	$388	$49
Sum Excl Emissions	$974	$565	$409
Sum Excl Oil, Gas & Emissions	$257	$354	-$97

TABLE A9.3
Summary of results using 8% discount rate

	BAU	ZCA	Diff
Sum	$881	$530	$351
Sum Excl Fuel	$331	$337	-$7
Sum Excl Emissions	$752	$500	$253
Sum Excl Fuel and Emissions	$202	$307	-$105

Parameters for electricity price modelling

TABLE A9.4
Parameters used for AER Electricity Model[9]

Modelling Parameters	
Nominal Risk Free Rate	5.65%
Expected Inflation rate	2.57%
Debt Risk Premium	3.25%
Market Risk Premium	6.5%
Utilisation of Imputation (Franking) Credits	60%
Gearing (Debt/Equity)	60%
Equity Beta	0.8
Debt raising cost benchmark	0.08%
Nominal Vanilla WACC	9.68%
Economic lifetime	30 years

Comparable Expenditures Elsewhere in the Economy

Comparison Figures Item	$A Billion	Reference
Nation Building Program	6.0	10
Alcohol 2003—04	9.3	11
Gross Value Added (GVA) 2009—Arts & Recreation	10.1	12
Gambling 2005-06	17.0	13
Domestic Appliances 2009	18.4	14
Federal Defence 2008—09	19.2	15
Federal Education 2008—09	22.6	15
Banking & Mining Industry Tax 2009	29.0	16
GVA 2009—IT & Telecoms	34.2	12
GVA 2009—Rental/ Hiring/ Real Estate	36.0	12
Gas, Coal & Uranium investments per year until 2016	36.5	17
ZCA Plan	37.0	
Insurance 2009	37.8	18
Recreation 2003-2004	45.0	11
GVA 2009—Education	48.7	12
Federal Health 2008—09	49.1	15
Car Retailing 2009	54.7	19
GVA 2009—Transport, Postal & Warehousing	59.5	12
GVA 2009—Healthcare & Social Assistance	66.6	12
GVA 2009—Mining	80.8	12
GVA 2009—Construction	81.6	12
GVA 2009—Manufacturing	103.1	12
GVA 2009—Finance & Insurance	118.0	12
Federal Social Security & Welfare 2008—09	124.6	15
Federal Expenditure 2009	324.6	15
Australia Gross Domestic Product (GDP)	1,197.0	20

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