THE HIDDEN COSTS OF ELECTRICITY: Externalities of Power Generation in Australia

A REPORT BY THE AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING (ATSE) 2009

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The key finding of this review conducted by the Australian Academy of Technological Sciences and Engineering is that a greater focus on externalities, preferably quantified in monetary terms, will help Australia to gain maximum social and environmental benefit from the portfolio of electricity generating technologies it will use for meeting emission reduction targets. Externalities are environmental and social costs that are not accounted for in the market price of electricity. Existing methods for valuing externalities do give an idea of their relative costs for different technologies in Australia but some major gaps and uncertainties need to be resolved through further work, preferably via collaboration with international centres of expertise.

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Photo: CSIRO

Executive Summary

This Academy study addresses the external social and environmental costs – the externalities – that accompany all electricity generating technologies. As reviewed here, these are costs not accounted for in the market price of electricity arising from impacts on, for example, climate, human health, crops, structures and biodiversity. Until identified, and then if possible quantified in monetary terms, they remain hidden, playing a limited role in technology selection.

The main rationale for this study is that the Australian Government, like others in the industrialised world, has adopted climate change policies such as the Carbon Pollution Reduction Scheme (CPRS) for constraining carbon dioxide (CO_2) and other emissions. Reduction targets call for a new portfolio of low-emission electricity generating technologies. The Academy believes that to meet these targets the focus must be on technology. Its recent study *Energy Technology for Climate Change: Accelerating the Technology Response* looked at technical, commercial and investment issues for various technology scenarios. Around $250 billion will be needed to bring the new technologies into production by 2050. There will also be heavy development costs.

While the power generation technologies of the future will inevitably have lower external impacts relating to CO_2 emissions, there will be other externalities. With adequate understanding of those externalities, policy and investment decisions relating to electricity generation can take into account all social costs and benefits. That is the ultimate purpose of this kind of review.

The best available studies of externalities of power generation are the European Union's (EU) ExternE Project and its successor NEEDS (New Energy Externalities Development for Sustainability). Drawing upon a huge body of research and analysis, ExternE has produced estimates of monetary costs of greenhouse, health and other environmental impacts of power station emissions, based on full life-cycle assessments. Ideally, expressing monetary valuations in metrics such as dollars per megawatt-hour ($/MWh) would allow objective, quantitative comparisons between the environmental credentials of different technologies. This is an ideal that in practice is difficult to attain.

ExternE work for Europe arrived at total external costs, in 2005 terms, of €41/MWh and €58/MWh for electricity generation from black and brown coal respectively. Renewable and nuclear energy had substantially lower external costs than all fossil fuels. For example, external costs were only €0.9/MWh for on-shore wind power and €4/MWh for nuclear power (light water reactor). The uncertainties and gaps in such estimates are acknowledged to be large but, even so, the processes for arriving at them and the indicative costs obtained are of great value in charting the way forward towards reduced external impacts.

A threshold question is whether these European methodologies can credibly be applied in Australia. This review concludes that they can, although the figures would need to be validated, affected as they are by exchange rates, taxes, healthcare costs, etc. With regard to the environmental cost of CO_2 emissions there is a wide range of estimates. This Academy study adopts a figure used in much of the ExternE calculations equivalent to $A31/tonne CO_2. On that basis greenhouse gas damage costs for currently deployed fossil fuel technologies in Australia range from $A18/MWh for natural gas to $A39/MWh for brown coal. An indicative figure for the average wholesale price of electricity in Australia is $A40/MWh, so these quantified external costs are very significant.

Other emissions from the combustion of fossil fuels, notably particulates or fine particles (PM_{10}), sulphur dioxide (SO_2) and nitrogen oxides (NO_X), can affect the local incidence of respiratory and cardiovascular disease. With its lower population density, Australian health damage costs per unit of emission are between seven and 20 per cent of costs in Europe if the same health impacts were to be assumed. On that basis, the total health damage cost of these three coal-fired power station emissions is about $13/MWh, equivalent to an aggregated national health burden of around $A2.6 billion per annum. These figures should be verified by Australian location-specific studies as health effects and costs may differ from Europe.

Combining greenhouse and health damage costs for Australia gives representative total external costs of $A19/MWh for natural gas, $A42/MWh for black coal and $A52/MWh for brown coal.

Carbon capture and storage (CCS) technology for coal and gas combustion is being developed as a key element of the CPRS strategy. CCS is predicted to remove 90 per cent of exhaust stack CO_2 emissions. Thus climate damage costs would be reduced significantly, though not by 90 per cent over a full life cycle due to the additional energy requirements of the process. As well, there will be externalities associated with the increased scale of fuel extraction, transport and generation, and with CO_2 pipelines. Deriving monetary valuations for these possible impacts of CCS needs further work.

External costs of renewable energy in Australia are likely to be low, as ExternE found for Europe. Typical figures are $A5/MWh for solar photovoltaic electricity and $A1.50/MWh for wind power. Greenhouse gas emissions are mainly attributable to the pre-generation (essentially manufacturing) stages of renewable technology life cycles. Other kinds of external impacts of renewable energy, such as wind farm impacts on amenity and biodiversity, are often important to the community but again hard to value.

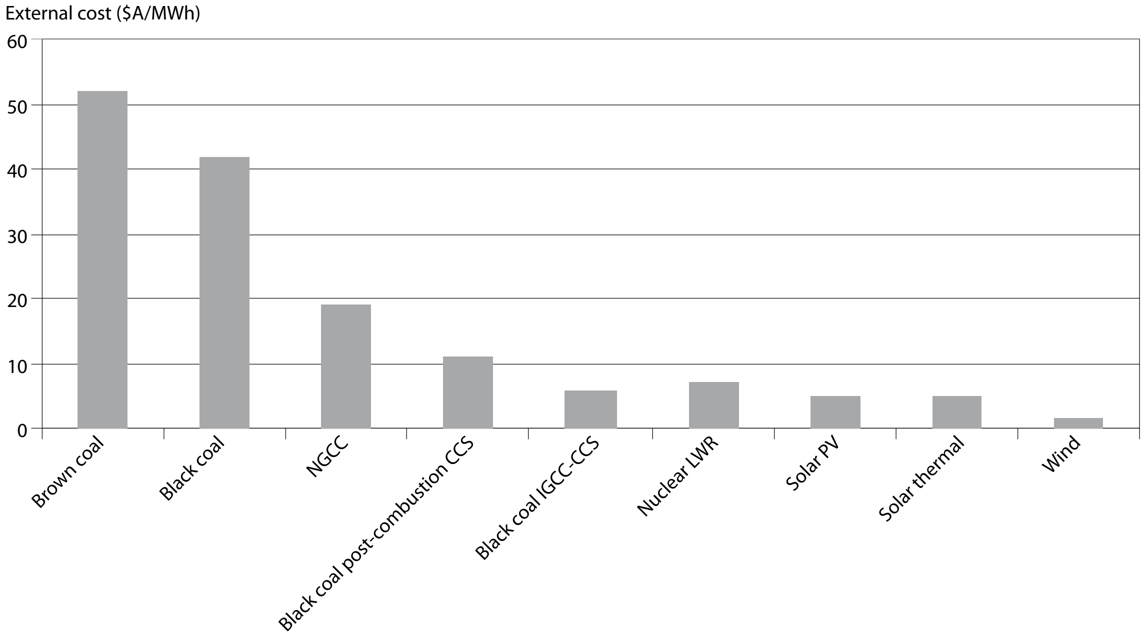
Solar energy, presently valuable in niche applications, will need to be deployed in very large installations to contribute materially to Australia's bulk energy needs. Resource inputs such as steel and concrete might be significant in relation to their current levels of production. Associated industrial expansion could have possible undesirable external impacts that merit further examination.

The potential environmental effects of geothermal energy recovery are thoroughly canvassed in the literature and their impacts are likely to be small. From a list that includes water and noise pollution, land and water usage, subsidence, induced seismicity and thermal pollution, only water usage might be of concern in Australia. Transmission costs favour geothermal plants being as close as possible to their markets but the most prospective geothermal areas can be far from Australian cities, so long transmission lines might create environmental costs.

Nuclear power stations emit no greenhouse gases. However when the life-cycle costs of the associated mining, construction and decommissioning processes are counted, the external costs of nuclear generation amount to around $A7/MWh. There is a further issue to do with perceptions about risk. Reactor accidents and nuclear proliferation are low frequency/high impact ('Damocles') risks that weigh heavily in public concerns about nuclear energy in Australia. As with such risks in other industrial processes their monetary valuation cannot be readily determined.

Even with the considerable uncertainties associated with credible valuation of externalities, the external costs derived in this Academy study and summarised in the diagram following provide a useful indicator of their relative magnitudes for some electricity generation technologies relevant to 2050. **The bars represent external costs only.** The present wholesale price of electricity in Australia, averaging around $40/MWh, gives a context for these monetary valuations of external costs. The picture is greatly simplified and gives no indication of the uncertainties, approximations and possible omissions involved. These still need to be addressed in reaching reliable investment-grade data.

External costs of some electricity generation technologies



Attaching monetary values to externalities is problematical and subjective but of increasing importance to an ever-more-watchful and well-informed society. With billion-dollar investments at stake, more work is needed to reduce the uncertainties and to explore the externalities of prospective technologies for reducing carbon emissions. Their evaluation, including open communication, discussion and understanding within the community, should not be left until too late.

Recommendations

RECOMMENDATION 1: INCREASE POLICY FOCUS ON EXTERNALITIES

Energy policies to reduce carbon emissions rely on introduction of a new portfolio of electricity generating technologies. The associated externalities need to be better understood and communicated in order that Australian energy policies maximise future social benefit. Enhancing knowledge and awareness of these externalities should be a priority for Federal and State government agencies with energy policy responsibilities. In particular an examination is required to verify that European-derived figures are applicable to Australian conditions. Ideally one Federal Government Department (possibly Resources, Energy and Tourism) should be charged with collection, analysis and dissemination of externalities data.

RECOMMENDATION 2: ENHANCE EXTERNALITIES DATABASE

The Australian Government's policy to reduce greenhouse gas emissions, part of international efforts to address climate change, has set emission targets. The Academy has shown (ATSE 2008, *Energy Technology for Climate Change: Accelerating the Technology Response*) that to meet these targets investment in lower-emission technologies must take place on a massive scale. Investment-grade data, preferably as monetary valuations, are needed for the associated externalities in order to inform policy development and optimise the future portfolio of generating technologies. The priorities are:

- increase the certainty of damage costings of greenhouse gas and other emissions from Australia's existing power stations;
- explore and quantify externalities associated with carbon capture and storage, a key strategy for reducing emissions;
- explore and quantify externalities of large scale renewable energy deployment, including solar, wind and geothermal;
- determine and quantify the externalities of nuclear power; and
- extend knowledge of externalities in areas not covered by this study, such as bioelectricity (energy from biomass), energy storage, energy security and multi-technology generating networks.

RECOMMENDATION 3: ENHANCE AUSTRALIAN CAPABILITY

Australian capability in externality assessment and valuation should be enhanced and expanded, especially through collaboration with relevant international agencies and centres of expertise.

RECOMMENDATION 4: ESTABLISH BROADLY BASED PUBLIC COMMUNICATION

The Australian community is entitled to reliable and factual information on the social and environmental externalities of its electricity generation technology options, especially in regard to climate change, health and safety. A comprehensive public communication plan should be developed and implemented.

Acknowledgements

The Academy is most grateful to the contributions made by the Chief Investigators, the author of this report and the Steering Committee established to oversee the conduct of the project. A brief background of the two Chief Investigators of the report is given below.

Dr Tom Biegler[1]

Dr Tom Biegler FTSE, an electrochemist with a PhD in Agricultural Science, spent most of his career in CSIRO, with some shorter periods at the Universities of Illinois, Kentucky and Bristol. His research fields included electrode kinetics, electrocatalysis in fuel cells, electrochemical reactions of sulphide minerals, and electrowinning and refining of metals. At CSIRO he led the Surface Chemistry and Hydrometallurgy sections before becoming Chief of the Division of Mineral Chemistry (later Mineral Products) in 1985 and then head of CSIRO's Corporate Business Department. After retiring from CSIRO in 1996, he consulted on fuel cell commercialisation. In more recent years he has written and spoken with the aim of improving public understanding of energy issues such as fuel cells and the hydrogen economy. He is also a Fellow of the Royal Australian Chemical Institute and the Australasian Institute of Mining and Metallurgy.

Professor Dongke Zhang

Professor Dongke Zhang FTSE obtained his PhD in Chemical Engineering from the University of Newcastle in 1993. He then joined the Department of Chemical Engineering at Adelaide University as a lecturer, was promoted to Senior Lecturer in 1996 and Associate Professor in 1998, and served as Deputy Head of Department between 1997 and 1998. In 1999, he was appointed Professor of Chemical Engineering at Curtin University of Technology and named John Curtin Distinguished Professor in 2007. In 2008, he was appointed the Foundation Professor of Chemical Engineering and Director of newly established Centre for Petroleum, Fuels and Energy at the University of Western Australia (UWA).

This project was overseen on behalf of the Academy by a Steering Committee comprising:

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Dr David Brockway FTSE	CSIRO
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The development of this project was assisted by Professor Tony Owen, Professor of Energy Economics, Curtin University of Technology, who undertook critical review and provided detailed comments.

The project was established and managed by Dr Vaughan Beck FTSE, Technical Director, ATSE.

The production of this publication was overseen by Mr Bill Mackey, Communications Director, ATSE.

1 Dr T. Biegler is the author of this report
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1 Introduction

1.1 THE ATSE PROJECT – BACKGROUND, PURPOSE AND SCOPE

Energy is one of the four technology domains nominated by the Australian Academy of Technological Sciences and Engineering (ATSE) as forums for harnessing its Fellows' expertise for the benefit of Australia. Energy is vital to Australia's prosperity. The greatest energy challenge facing Australia is to ensure that its future energy needs are met sustainably and securely, given prevailing concerns about greenhouse-gas induced climate change and fossil fuel resource depletion. Of course Australia is not alone in facing this challenge, which is global in nature.

The Australian Government policy of setting targets for future greenhouse gas emissions will require major changes in the technologies used for generating electricity. Independent of climate change considerations, ATSE's view is that more attention needs to be given to making the economy more energy-efficient and sustainable through optimising the mix of energy supply technologies and fostering better energy use. Technology will have to be the focus for all such measures.

The technologies that can and will contribute to emission reductions might be aimed at improving the energy conversion efficiency of fossil fuels, they might involve reducing emissions through carbon capture and sequestration, or they might be based on a broad range of renewable and nuclear energy resources. There is a common view that by around 2050 Australia's electricity will come from a suite of energy conversion technologies very different from today's mix. ATSE has no particular policy on the preferred future energy make-up; to borrow from the terminology of the Energy Supply Association of Australia, ATSE is 'fuel and technology neutral'.

In progressing towards the desired goal of 'clean, low-emissions power', electricity generation businesses need to make energy source and technology choices and major capital investments. Innovative technologies may need to be progressed towards commercialisation, or be adapted to new circumstances, or even in some cases be developed from early-stage ideas. There is ongoing public and policy debate as to which sources and technologies are best positioned to meet future needs sustainably. There is also a vigorous debate about how best to achieve the targets set for reducing these emissions. ATSE has recently reported on the massive investment that the research, development, accelerated demonstration and installation of the necessary technologies will require (ATSE 2008A).

A recent study commissioned by the Energy Supply Association of Australia (ESAA 2007) expresses concern that the public and policy debates around the issues of energy technologies for the future are not sufficiently well informed:

> "The Chief Executives of the ESAA member businesses observed in early 2005 that many of the public statements being made by a wide variety of opinion shapers and decision makers were without the benefit of informed, expert and fact-based analysis of the outlook for greenhouse emissions from the stationary energy sector and the cost that was likely to be involved in reducing these emissions."

ATSE shares this concern and recommends that the public energy debate is informed by a proper understanding of energy technology issues through sound and rigorous analysis of their economic, social and environmental implications.

THE HIDDEN COSTS OF ELECTRICITY

KEY MESSAGE: The energy debate and the energy policies that emerge from it need to be based on sound information and analysis of technical as well as economic issues.

All technologies for generating electricity are accompanied by externalities. *Externality* is a term that comes from the discipline of economics. Externalities are generally unpriced costs, usually of side-effects of production processes, which impose costs on third parties through their impacts on climate, human health, crops, structures and biodiversity. The impact of greenhouse gas emissions on climate provides the prime, and most familiar, example of an externality. Climate impact however comprises only one of the many kinds of externalities treated in this report.

When the cost of an external impact like climate change is included in the price of a product such as electricity it is said to be *internalised*.

Sometimes an externality comprises a benefit. For example, the benefits of scientific research often flow to third parties who have not paid for the research work but get to know about and use research results through publication, reverse engineering and the like. These benefits are externalities.

It is accepted knowledge that externalities are important in determining how alternative electricity generating technologies are perceived by the community. The range of public attitudes to fossil fuels, wind, solar and nuclear energy provides examples. In some cases, externalities can dominate these perceptions. Nuclear energy is an example, where its long-term exclusion in Australia is due in part to the perceived high price the Australian community puts on the risk of nuclear accidents, spent fuel disposal and the threat of terrorism and proliferation that it associates with nuclear fuel and nuclear power generation.

Externalities arise at many points in the sequence of processes leading to the generation of electricity – in the exploration, mining and transport of the fuel; in the construction, manufacture and operation of the plant; and in the delivery and storage of the electricity produced. They may be associated with waste products or emissions from an operation. They may arise from consumption of a scarce resource such as water. They may result from transmission of electricity over long distances.

Identification of all such externalities therefore requires a full examination, a life cycle assessment, of all processes, inputs, outputs and ancillaries needed to generate and deliver the final product safely to the consumer.

Externalities take many different forms. Yet they ought to be considered and compared on some kind of common basis in order to determine rationally the relative merits and costs of competing electricity generation technologies. Thus economists try to express externality values in monetary terms. Ascribing monetary values to the externalities of electricity production is a relatively recent field of economic research, still concentrated in Europe and North America. While such values embody many uncertainties, the field is already having a significant impact on energy policy in Europe. However, little work has yet been directed to the Australian situation.

KEY MESSAGE: All power generation technologies are accompanied by social and environmental externalities, costs imposed on individuals or the community that are not paid for by the producer or consumer of electricity. Externalities however strongly influence public attitudes and thus impact on policy formation. Attaching monetary values to externalities is a tool that assists in rational assessment of the relative merits of alternative technologies.

ATSE, as the learned Academy for Australia's leading technological scientists and engineers, has a primary interest in the science, technology and engineering issues faced in making energy technology choices for the future. ATSE well recognises the influence on public policy of the specialised topic of energy externalities, most of which require technological analysis. This field has largely been the domain of resource and environmental economists. ATSE is keen to see greater input from engineers and technologists and is particularly determined to contribute objectively to:

- understanding the relevance to Australia of the existing body of knowledge, mainly European, concerning energy externalities;
- applying that knowledge where possible to estimating monetary valuations of power generation externalities relevant to Australia;
- ensuring that all potential external impacts of technologies that are in early stages of development are properly identified, understood and explained; and
- clarifying and disseminating the policy implications of the results of such work.

Accordingly, ATSE submitted a proposal to the Australian Research Council on the topic: *Externality Costs of Energy Production in Australia: A critical review*. The proposal was funded in 2007 under the Linkage Learned Academies Special Projects scheme. This Report, which concentrates on large scale stationary power generation, is the product of that funding. It was preceded by an Issues Paper released in April 2008 and circulated to interested parties.

KEY MESSAGE: ATSE seeks through this review to contribute authoritatively to the enhanced understanding of energy externalities attributable to electricity generation and their monetary evaluation relevant to Australia.

In relation to the broader question of how Australia will gain maximum net social and environmental benefit from its future electricity supply, the scope of this review of externalities covers but one element. Many other considerations will contribute to technology choices over the decades ahead. Capital and operating costs and the resulting market price of the electricity produced, technical feasibility, employment and beneficial by-products of emerging technologies are the most obvious.

This review covers some, but not all, of the technologies that could eventually contribute to Australia's stationary power needs. Brief descriptions of individual technologies are given in order to provide an immediate context for the discussion of their externalities. A more thorough treatment of the generating technologies expected to contribute to lowering emissions, their advantages and disadvantages, and their present and projected economic costs is presented in the recent Academy report *Energy Technology for Climate Change: Accelerating the Technology Response* (ATSE 2008A). Other comprehensive reviews of relevant technologies are referenced in this report to provide further information where needed.

The previous report (ATSE 2008A) arrived at the conclusion *"that it is unlikely that any single technology will achieve the CO_2 reduction outcome targets now being proposed. Rather, the response will require development and application of a portfolio of technologies."* Significantly, in assessing the technical and commercial issues associated with such technologies, the report notes *that "there are major issues related to public perception and government policy (e.g. nuclear energy), technical and environmental uncertainty regarding carbon dioxide storage sites (e.g. CCS), high investment cost to replace carbon (e.g. CCS, solar energy and geothermal generation) or other environmental issues (e.g. associated with extensive application of biomass, wind and wave generation)".* Many of these represent externalities. It is this mixture of technical/ commercial aspects and environmental issues that makes the objective comparison of external impacts of energy technologies through monetary valuation so important.

A section near the end of the present report (section 5, 'Some Suggested Future Externality Topics') includes some of the electricity generating technologies that could not be covered within the limited resources available here. They are all important, especially biomass (or bioelectricity), and should be treated in future work.

One thing is clear. Australia derives great economic and social benefit from its present supply of very reliable and relatively cheap electricity. It is most important to the economy and to individual Australians that this high quality supply is retained, and sustained, through the transition to any new portfolio of generating technologies. Ultimately all of the costs of these technologies will be weighed against all of the benefits arising from the choices made.

KEY MESSAGE: The scope of this report is restricted to the environmental and social externalities of large-scale electricity generation technologies. Many other factors contributing to future technology choices are not covered here. Some important electricity generating technologies could not be included in the scope and should be covered in future work.

This report contains many examples where dollar valuations of externalities are summarised as single numbers without any accompanying indication of the range of uncertainty. This should not be taken to mean that the values are known to the degree of precision implied – they are not. Indeed, externality valuation methodologies are acknowledged to involve large uncertainties that can range from reasonable approximations through to arbitrary assignments, unknowns and perhaps even unknowables. Some valuations in the literature cover an order of magnitude or more. However, for this report the statistical indicators of uncertainty were generally unknown and could not be developed within the scope of the work. The report does include numerous cautionary reminders of the indicative nature of its numerical estimates and of the uncertainties involved. This qualification is placed prominently here to help the reader appreciate the limitations of the methodologies applied.

1.2 ENERGY – AN AUSTRALIAN CONTEXT

This section is aimed at providing some facts on the subject of energy in Australia, especially electrical energy, to help with appreciating the central issues in energy externalities.

1.2.1 Energy, prosperity and economic growth

Energy, prosperity and economic growth are inextricably related. Energy drives industrial activities (production) as well as domestic consumption. As an economy grows, so does energy supply and use.

Australia's prosperity has benefited greatly through its access to low-cost, accessible primary energy sources in the form of black and brown coal (lignite), oil, natural gas and hydroelectric power. Coal and oil in particular have been favoured fuels because they are dense and concentrated stores of energy, easily extracted and converted to man's use. These are the properties that allowed coal, and later oil, to become the basis for the industrial revolution. All of the fossil fuels represent ancient organic matter of biological origin that has metamorphosed through the action of temperature and pressure over geological time, hundreds of millions of years. Their original energy source is the sun.

Australians are today being reminded of the historic role of fossil fuel energy in the rise of industrialised economies as they observe how Australian exports of primary energy and mineral resources have been contributing to the historically unprecedented rates of economic growth in China, India and other developing nations.

The Australian Bureau of Agricultural and Resource Economics (ABARE) routinely produces statistics and model-based projections for Australia's energy production and consumption (see for example ABARE 2008A). In absolute terms, energy consumption per person in Australia grew from around 175 GJ per annum in 1970 to 275 GJ in 2005. This reflects an average growth rate in energy consumption of around 1.3 per cent per annum. Total Australian primary energy consumption has also been increasing, but the growth rate has been trending downwards, from around five per cent per annum in the 1960s to a little more than two per cent per annum in more recent years.

ABARE's projections up until 2030 show Australia's total energy consumption continuing to grow at an average rate of 1.6 per cent per annum. By 2030 each Australian will be using on average 324 GJ per annum, representing a per capita growth rate of 0.66 per cent per annum.

The projected total energy growth rate for Australia is in the range made by other agencies over similar periods for various economies. For example, International Energy Outlook (IEO) figures (Energy Information Administration 2008) indicate 0.8 per cent and 2.6 per cent per annum energy growth rates for OECD (Organisation for Economic Co-operation and Development) and non-OECD nations respectively. For electricity consumption alone, the corresponding IEO projections are 1.3 per cent and 3.5 per cent per annum.

The rate of growth of national energy consumption in a country like Australia is the net outcome of various factors. Growth in population, in Gross Domestic Product (GDP) and in the energy-intensive production of goods such as aluminium drives energy usage upwards. Energy price increases and improvements in energy efficiency (which is stimulated by higher prices) drive it downwards.

KEY MESSAGE: Australia's energy needs are projected to grow at a rate in line with other developed economies.

1.2.2 Energy intensity and efficiency

Energy intensity of an economic activity is defined as the amount of energy consumed to produce one unit of output. For an economy as a whole, the energy intensity can be calculated as the energy consumed per unit of GDP. Energy intensity depends on many factors, including the structure or mix of activities in the economy and the relative values of different sectors, as well as the technical efficiency of energy use. Trends in energy intensity for a particular economy can give insights into the prospects that improvements in energy efficiency, as distinct from growth in energy consumption, can contribute to economic growth.

Several bodies (e.g. International Energy Agency, World Resources Institute, Energy Information Administration) publish energy intensity data, readily accessed online (e.g. EarthTrends 2008). Figures for individual countries, adjusted for purchasing parity, range over two orders of magnitude. But the combined data for large groupings such as continents show a simple and consistent picture (see Table 1). The structural factors that produce the differences in intensity for individual nations are smoothed out in the larger groupings and the resulting energy intensities are close to the global average.

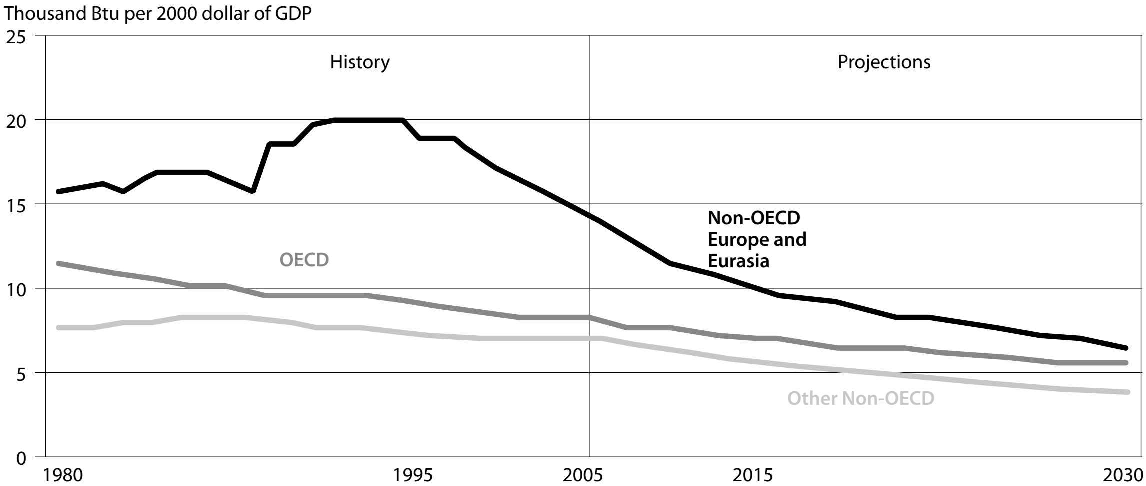
Table 1 Energy intensity for different regions. Data are for 2005, units are tonnes of oil-equivalent consumed per million dollars GDP, at constant 2000 international dollar value (EarthTrends 2008)

REGION	ENERGY INTENSITY
World	171.7
All developed nations	161.1
All developing nations	191.0
Europe	130.5
North America	194.1
Asia	173.2
Oceania	184.5
Australia	186.8

Table 1 shows that globally 171.7 tonnes of oil-equivalent were consumed in 2005 in order to create one million dollars ($US, year 2000) of GDP. For Australia, the corresponding figure was 186.8. Taking one tonne of oil-equivalent as 42 GJ and $US1 (2000) as $A1.36 (2008), the Australian figure (186.8) means that each dollar of Australian GDP on average represents consumption of 5.8 MJ of energy, or, in the equivalent electrical energy units, around 1.6 kWh of energy. [Note: This figure represents energy content of raw fuel, not electricity consumption.]

Energy intensity in most developed economies is currently improving. This has not always been so. In Australia (ABARE 2007) energy intensity remained broadly stable over the 1970s and 1980s and then fell on average 1.1 per cent per annum during the 1990s. ABARE (2007) forecast that decline to continue at around one per cent a year until 2030. Global regional patterns for energy intensity movements over time have historically been different (see Figure 1, reproduced from the Energy Information Administration report referred to in the caption). Present trends appear to be consistently downwards and the band of energy intensities projected out to 2030 seems to be converging.

Figure 1 Trends in energy intensity by region 1980-2030 (Energy Information Administration 2008)



The latest analysis from ABARE gives further insight into trends in energy intensity in Australia (ABARE 2008B). Using a factorisation technique, ABARE attributed the overall energy intensity trend to changes in three components:

1. the level of economic activity – activity effect;
2. the sectoral composition of the economy – structural effect; and
3. the energy intensity of sectors – real intensity effect.

These components are much the same as described above. Increase in economic activity is the main contributor to increased energy consumption. Trends in energy intensity differ for different sectors. Structural shifts account for a reduction in overall energy consumption. But the surprise finding in this ABARE study was that trends in the 'real intensity effect' had a negligible effect on energy consumption over the study period, 1989 to 1990 to 2005-06. This finding casts some doubt on expectations of economic growth arising from improvements in real energy intensities.

KEY MESSAGE: GDP and energy consumption follow similar trends. Each dollar of Australian GDP on average represents consumption of 5.8 MJ (equivalent to 1.6 kWh) of raw fuel energy content, a figure which decreases as energy intensity and efficiency improve.

1.2.3 Fuel sources

In common with most national economies, by far the greater part of Australia's energy is presently sourced from the fossil fuels coal, natural gas and oil.

For the last year for which figures are available, 2005-06, fossil fuels represented around 95 per cent of the energy consumed in Australia (ABARE 2007). The remainder came from renewable sources, primarily hydroelectricity. Of the fossil fuel sources, 41 per cent was coal (black and brown), 35 per cent oil and 19 per cent gas, by energy content.

ABARE projections show some change in the mix of fossil fuels being used by 2030 but hardly any change (94 per cent and six per cent) in the relative amounts of fossil energy and renewable energy. However, these projections are bound to change as new Government policies such as the recently announced Carbon Pollution Reduction Scheme (Department of Climate Change 2008A and 2008B) are introduced. ABARE will adjust its models when these new energy policies are in place and implementation measures are understood.

1.2.4 Energy sustainability

As already indicated, the current ABARE projections are that Australian energy usage will continue to increase in the foreseeable future, as an integral part of economic growth. The supply of energy, including electricity, will need to increase because efficiency improvements and increased efforts towards sustainable lifestyles are not expected to support projected growth rates in energy demand. This expectation is the basis, for example, of the conclusions of the recent Inquiry into Electricity Supply in NSW (Owen 2007), which found, *inter alia*, that major investment in base-load generating capacity will be required to meet that State's needs in 2013-14, even with projected improvements in energy efficiency and the introduction of some renewable technologies.

Similarly, CSIRO's Energy Futures Forum, in its report *The Heat is On: the Future of Energy in Australia* (CSIRO 2006), addressed a broad sample of energy scenarios that cover a range of policy and technology responses to climate change. The scenarios also cover various possible changes in community attitudes and behaviours. Energy demand increases in all of these scenarios, but to different extents.

Some commentators would like to see a reversal of these growth trends in production, domestic consumption and energy use. They advocate simpler lifestyles (see for example Hamilton and Denniss 2005) and often condemn economic growth as an undesirable form of consumerism that threatens environmental sustainability. The issue of climate change is a major plank in their arguments.

However, the view taken here is that the ABARE and other projections noted above are realistic. Most Australians will continue to see advances in their economic prosperity as a desirable goal consistent with advances in their personal prosperity and wellbeing. Such advances will require more energy in addition to increased efforts towards sustainability by way of efficiency gains in energy production and consumption.

KEY MESSAGE: The impact of energy efficiency improvements and other sustainability measures will not be sufficient to outweigh the community's desire for increased prosperity and hence more energy.

1.2.5 Role of Innovation

While it might seem obvious, especially to a technical audience, that technological innovation will be central to sustainable electricity supply and reduced greenhouse emissions, it is worth making the point here explicitly.

There is a wide range of measures available, or in prospect, for reducing greenhouse gas emissions from power generation. Power stations that burn fossil fuels can reduce such emissions by switching to fuels with inherently lower ratios of carbon/contained energy (especially natural gas), by implementing measures to improve the efficiency of energy conversion, or by capturing and disposing of the greenhouse emissions. Alternatively, energy sources other than fossil fuels can be harnessed in order to lower emissions. Many conversion technologies in use or under development can produce electricity from energy sources like nuclear, wind, solar, geothermal, biomass, tidal, wave and hydro.

Each emission reduction measure is associated with a change in technology or in the way that technologies are integrated and used. Sometimes the change is relatively small but more commonly it is major. Technologies such as carbon dioxide capture and disposal (by storage), conversion of solar thermal energy, or the harnessing of geothermal energy will all require major technical innovations. Innovation of this kind is a multi-stage and often drawn out process of invention, development, scale-up, improvement and ultimately (but not always) commercial implementation. The process always involves scientists, technologists and engineers.

The imperative to curb greenhouse emissions has in recent years generated many valuable studies of Australia's future energy scenarios (e.g. CSIRO 2006, Commonwealth of Australia, UMPNER (Uranium Mining Processing and Nuclear Energy Report) Report 2006, McLennan Magasanik Associates 2006, Connell Wagner 2007, ESAA 2005). These have in general looked at the current fuel and technology positions, projections for future energy requirements and sources, technology trends already established, and options available for reducing external impacts, primarily greenhouse gas emissions.

A question often asked is: When can a new energy technology be expected to become commercially available? It is natural for innovators to be optimistic about costs, performance and commercialisation timescales for their technologies. That optimism can often drive unrealistic public expectations. But investment needs certainty rather than optimism. When consulting engineers Connell Wagner were asked by the Owen Inquiry to recommend emission reduction technologies that would definitely be available in time to fill the electricity supply gap for NSW projected for 2014, their work (Connell Wagner 2007) led Owen to the conclusion that most of the extra NSW base-load would have to come from coal- and/or gas-fired generation *"as other technologies can only contribute on a relatively small scale or will not mature until 2020 at the earliest"*. Of the innovative coal-fired generation technologies considered, only ultra-critical pulverised fuel was considered capable of being operational by 2014. Integrated Gasification Combined Cycle and Ultra Clean Coal technologies were considered to be *"still at the demonstration stage"*.

The long time frame for commercial availability of innovative energy conversion technologies is one of the factors that will determine the mix of future technologies for generating electricity. As already mentioned, ATSE has recently published a report addressing the requirements for accelerating the development of such technologies (ATSE 2008A).

KEY MESSAGE: Technological innovation will be central to meeting the twin imperatives of increased electricity supply and reduced greenhouse gas emissions. Realistically, existing technologies based on fossil fuels will be required to meet base load requirements until at least 2020.

1.2.6 Government Energy Policy

Australia's energy policy is developing rapidly. A consistent theme is that the energy mix will move along a path towards reduced greenhouse emissions.

Soon after its election in 2007, the Australian government ratified the Kyoto Protocol, which essentially sets an emissions reduction figure to be met by 2012, and announced its intention to introduce by 2020 a national carbon emission target 20 per cent lower than 2000 levels. Following the July 2008 release of a draft, the final report of the Garnaut Climate Change Review was published in September 2008 (Garnaut 2008). It proposed, *inter alia*, an emissions trading scheme and suggested a large increase in Australian commitment to research, development and commercialisation of low-emission technologies, to more than$3 billion per annum.

Around the same time the Australian Government issued its Green Paper on a Carbon Pollution Reduction Scheme (Department of Climate Change 2008A), which explored a range of options for a 'cap and trade' scheme aimed at reducing Australian carbon emissions by 60 per cent by 2050. The White Paper containing the Government's policy decisions was released in December 2008 (Department of Climate Change 2008B). It confirmed the 60 per cent carbon emissions reduction target by 2050 and set the short and medium term trajectory for reaching that target. By 2020, the target is a 15 per cent reduction below 2000 levels if there is strong international action to reduce carbon emissions and, if not, a five per cent reduction irrespective of the actions of other countries.

The White Paper also defined certain other complementary measures that together with the CPRS comprise the Government's emissions reduction strategy. They are:

- an expanded Renewable Energy Target (RET);
- investment in carbon capture and storage demonstration; and
- action on energy efficiency.

The RET is aimed at ensuring that 20 per cent of Australia's electricity is generated from renewable sources by 2020. The RET is intended to work together with the market-based CPRS to stimulate deployment of renewable electricity during its early years. The RET is to be phased out between 2020 and 2030.

In summary, Australia's present energy policy (as at date of publication) in relation to carbon emissions relies on:

- the success of a market-based emissions trading scheme in driving emissions down;
- the effectiveness of a mandated national target for the use of renewable forms of electricity; and
- the commercial introduction of carbon capture and storage technology that will allow emission reduction targets to be met while coal continues to be a major source of energy.

Further development of energy policy is expected to occur, with an Australian Government Energy White Paper due for release at the end of 2009.

ATSE continues to develop its views on energy policy and has, for example, put a position in its response to the UMPNER Draft Report (ATSE 2006). ATSE believes that Australia does need a soundly based national energy policy, that a portfolio approach is needed in relation to the choices to be made from renewable and non-renewable energy sources, and that, in the light of the many areas of contention concerning energy, there should be rational well-informed community debate based on scientific analysis and commercial realities. This report and the recent reports on accelerating the technology response to emission targets (ATSE 2008A) and on biofuels for transport (ATSE 2008B) are intended to contribute to that debate.

1.3 ENERGY EXTERNALITIES AND LIFE CYCLE ASSESSMENTS

Before looking at the specifics of externalities associated with various electricity generation technologies, a few introductory remarks on energy externalities and the role of life cycle assessment or analysis are needed.

1.3.1 Significance of externalities

As noted above, all power generation technologies are accompanied by externalities, costs imposed on individuals or the community that are not paid for by the producer or consumer of electricity.

The European ExternE project (www.externe.info) stands out in any review of the subject of energy externalities. It was launched in 1991 by the European Commission and the US Department of Energy. The USA withdrew in 1994 but the European Union (EU) is still funding the energy externalities research. In recent years the European Commission has been supporting the research through the NEEDS Project (New Energy Externalities Development for Sustainability, www.needs-project.org/). NEEDS is a consortium of 66 partners in 26 countries (mainly EU) that is evaluating the costs and benefits of energy policies and future energy systems, as well as addressing the question of energy security in Europe.

The Foreword to the ExternE 2005 update (ExterneE 2005) captures the essence of the European view on energy externalities:

> "Externalities are related to social welfare and to the economy. The idea is firstly to measure the damages to society which are not paid for by its main actors; secondly, to translate these damages into a monetary value; and thirdly, to explore how these external costs could be charged to the producers and consumers. Indeed, if the market takes into consideration the private costs, policy-makers should try to take account of the external costs.
>
> The ExternE methodology is widely accepted by the scientific community and is considered as the world reference in the field. With ExternE, and this new "green accounting framework", a ranking of technologies can be made according to their social and environmental impacts. Internalising external costs, by taxing the most damaging technologies or by subsidising the cleanest and healthiest ones, can give an impetus to new technologies and could help to achieve a more sustainable world."

In summary, the ExternE view is that externalities are costs that need to be exposed and valued in monetary terms in order that the full social cost of a commodity such as electricity is properly known. Economic policy should then exploit that knowledge.

ExternE represents the major contribution (more than5000 pages of published reports) to the body of work on energy externalities. The work has involved to date a direct EU investment of around €15 million (di Valdalbero 2006), although this probably does not reflect the full cost of the work. Research teams include economists, environmental scientists, epidemiologists and other health specialists, engineers and energy technologists, atmospheric chemists, etc, located throughout the EU. The impacts covered include climate change, human health, crops, biodiversity and structures. The main costs relate to climate change and health impacts.

Table 2 Range of impacts, pollutants and effects covered by the ExternE Project (from European Commission 2003)

Impact Category	Pollutant / Burden	Effects
Human Health – mortality	PM_{10}*, SO_2, NO_X, O_3	Reduction in life expectancy
	As, Cd, Cr, Ni Benzene, Benzo-[a]-pyrene 1,3-butadiene Diesel particles	Cancers
	Accident risk	Fatality risk from traffic and workplace accidents
Human Health – morbidity	PM_{10}, O_3, SO_2	Respiratory hospital admissions
	PM_{10}, O_3	Restricted activity days
	PM_{10}, CO	Congestive heart failure
	Benzene, Benzo-[a]-pyrene 1,3-butadiene Diesel particles	Cancer risk (non-fatal)
	PM_{10}	Cerebro-vascular hospital admissions Cases of chronic bronchitis Cases of chronic cough in children Cough in asthmatics Lower respiratory symptoms
	Pb	Neurotoxicity (decrease IQ)
	O_3	Asthma attacks Symptom days
	Noise	Myocardial infarction Angina pectoris Hypertension Sleep disturbance
	Accident risk	Risk of injuries from traffic and workplace accidents
Building Material	SO_2 Acid deposition	Ageing of galvanised steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	NO_X, SO_2	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O_3	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
Global Warming	CO_2, CH_4, N_2O, N, S	World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	Acid deposition, nitrogen deposition	Acidity and eutrophication (avoidance costs for reducing areas where critical loads are exceeded)

*PM_{10} refers to particles (ie in particulate emissions) with diameters less than 10 µm (micrometres)

Table 2, reproduced from European Commission (2003), contains a comprehensive list of impacts considered in the ExternE project.

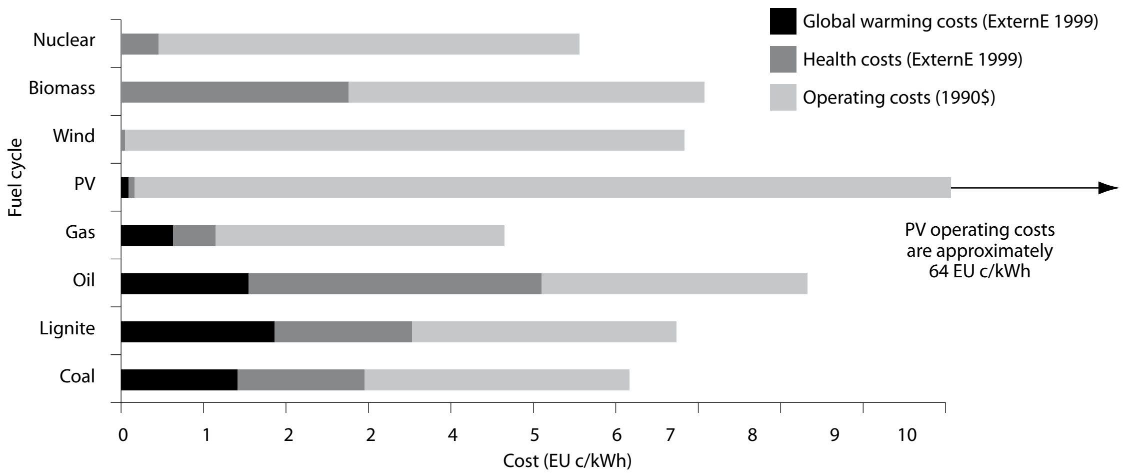
Of the extensive set of impact categories, pollutants and effects covered in the ExternE project and listed n Table 2, only those few emissions that make the greatest contribution to external costs will be considered here in any detail - in relation to externalities of Australian power generation. They include particulate material (PM_{10}) and the gaseous combustion products carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_X). The terms 'particulate material' or 'particulates' refer to the very small (or 'fine') solid particles that emerge from the combustion of coal and other fossil fuels. They are classified according to size, which is of the order of micrometres or millionths of a metre (µm). PM_{10} means particles smaller than 10 µm.

KEY MESSAGE: The European ExternE project and its successor NEEDS (New Energy Externalities Development for Sustainability) provide the major contributions to methodology and results for valuing energy externalities in monetary terms.

The monetary valuations of these externalities would hardly be relevant if they turned out to be insignificant compared with the other costs of electricity production. A clear illustration of their significance is shown in Figure 2, a bar chart taken directly from an Australian report on externalities (Maddox *et al* 2004). The original data came from ExternE work. While it is not strictly correct to represent externalities and operating costs as being additive, the lengths of the different bars do give an indication of relative magnitudes.

It can be seen that externality costs evaluated for human health and global warming for all of the fossil fuel based generation technologies are significant in comparison with the normal operating costs of the generators. If these external costs were to be internalised, a noticeable effect on power prices can be expected. The price impact of external costs for nuclear and renewable sources would be much less, based on the data in Figure 2.

Figure 2 Comparison of external and operating costs of generating electricity under German conditions (from Maddox et al 2004)



Proper valuation of monetary costs of an externality can provide guidance as to what should be spent on control measures for environmental and health damage. The costs of implementing such measures – the control or abatement costs – will become part of the full cost of the electricity produced by that technology. Relative costs of producing power by different technologies would then change and the above kind of diagram gives some idea of what those relative changes might be. For example, the above German data suggest that power produced from wind and coal would have similar costs if control costs were to be included in the price of electricity from coal-fired generators.

KEY MESSAGE: For most electricity generation technologies based on fossil fuels, the main external costs relate to climate change and human health. These costs can be significant compared with conventional operating costs.

1.3.2 Externalities and energy policy

Professor David Pearce, a pioneer in the field of environmental economics, has listed how externality valuations might be used in economic policy and the benefits so obtained (Pearce 2001):

- for making investment decisions in ways that ensure that the full social cost of electricity from different sources is taken into account in planning future capacity;
- for estimating environmental taxes, such as the UK landfill tax;
- for incorporation into national accounts. In principle, externality adders could be used to calculate a net national product that allows for resource depreciation and environmental damage;

- for raising awareness. The exercise of identifying and evaluating externalities in itself draws attention to the fact that all energy systems have externalities that can create economic inefficiencies; and
- for setting environmental policy priorities, that is, using externality valuations in cost-benefit analyses in order to determine where the best returns can be secured from new environmental policies.

Ascribing monetary values to external impacts on climate, health, biodiversity and other environmental qualities is acknowledged to be a complex, imprecise, and subjective exercise. Pearce (2001), Rabl and Spadaro (1999), ExternE (2005) and Sundqvist (2004) are among the many works that have discussed the intrinsic limitations to deriving agreed values for externalities. Assigning values to ill health, a life lost or a period of shortening of life is in itself a controversial topic. Valuations of future costs depend greatly on the discount rate chosen, adding another source of uncertainty.

There are those who claim that the degree of uncertainty inherent in valuing externalities means that efforts at their quantification are not worthwhile. Pearce (2001) has argued that uncertainty is not a reason for neglecting economic valuation, that any policy decisions in response to global warming (the most prominent area of uncertainty) will contain implied economic values anyway, and that therefore it is better to be as explicit as possible about the numbers *"rather than masking them by procedures that allegedly do not use them"*.

Richard Tol (2005), another widely quoted energy economist, says:

> "Actively working in the area of external costs of energy in general and climate change in particular, I am often confronted with people who argue that climate change is too uncertain to say anything about the marginal costs of carbon dioxide emissions. The uncertainties are indeed substantial, but not as large as these people think."

The NEEDS Project has looked specifically at the factors promoting or hindering the use of monetary valuation methods and associated cost benefit analyses in energy policy-making processes (NEEDS 2006). In the three countries examined, the rate of diffusion of monetary valuations of environmental externalities into public policy was greatest in the USA and least in France, with the UK in an intermediate position. Bureaucratic structures and the relationships between economists and policy officials were claimed to be behind this ranking. The study suggested that the enthusiasm of economists for using willingness-to-pay concepts in making efficient public decisions was not widely shared except within agencies, such as environmental offices, where the profession was well represented. In contrast, it says that *"lobby groups (industrialists, environmentalists) are far less interested in using or producing such studies"* (that is monetary valuations). The report develops a novel political economy approach to the issue, to which the reader is referred for further detail.

There are some useful comments on the application of externality valuations in a World Energy Council (WEC) study on life cycle assessment (WEC 2004). It points out the uncertainty as to whether aesthetic and other qualitative externalities can properly be valued. Willingness-to-pay to avoid adverse impacts is to some extent incorporated into some LCAs (Life Cycle Assessments) but biodiversity impacts are acknowledged as being much harder to define and to measure.

Economists use methodologies such as the contingent valuation method (eliciting willingness-to-pay or willingness-to-accept by direct questionnaire) and the hedonic price method (assessing value through willingness-to-pay in an associated market, for example, via a reduction in property value due to increase in noise). For the present purposes it is enough to know that such methods exist and there is an extensive literature on these valuation methods alone.

A key point for this ATSE study is to recognise that there are intrinsic uncertainties in externality valuations, which means that the processes of attaching numbers to environmental externalities might not be able to resolve arguments about contentious external impacts.

KEY MESSAGE: Externality valuations have several potential applications to economic policy such as investment decisions, environmental taxes and setting policy priorities. Actual usage varies between countries. There are intrinsic limitations to valuation methodologies. The associated uncertainties affect the level of enthusiasm for such use.

1.3.3 Externalities or external impacts?

The term externality has become part of the jargon of the energy field. As such it tends to be used loosely to refer to all external impacts of economic consequence, not just the externalities (unpriced costs). Should the present study embrace all such impacts? There are several points to make on this matter.

Firstly, there are some impacts known to have a profound effect on energy policy, and on shaping public opinion, even though their costs have actually been priced into the product (that is. internalised). For example, the costs of disposal of nuclear wastes and decommissioning of nuclear power plants are included in the price of nuclear power (that is, internalised) in OECD countries, and producers of nuclear power take into account 'virtually all life cycle costs' (UMPNER Report, 2006, Chapter 4). Nevertheless, opponents of nuclear power are generally not persuaded by the argument that such potential impacts have been appropriately valued and paid for. Pearce describes the problem as one of properly valuing 'disaster aversion' (Pearce 2001). Occupational health and accident risks are in a similar category. Riskier jobs attract higher wages, meaning that the associated additional costs have been internalised.

Secondly, it may not always be clear when a particular cost has been or will be internalised. One focus of the present study is to identify external impacts of novel energy technologies, the development of which may be at anywhere from a conceptual to a late pre-commercialisation stage. In those circumstances it can be difficult to predict whether or not the associated cost is destined to be internalised.

Finally, there are some environmental impacts that influence policy and public opinion for which there seems no reasonable prospect of reaching an agreed monetary value for the damage. Risks to rare or endangered species are an example of an impact that can perhaps be described qualitatively but seems unlikely to be amenable to monetary evaluation, at least with any acceptable degree of precision.

Therefore, any discussion of externalities should be prepared to cover all contentious areas of environmental impacts rather than be restricted to the 'technical economic' definition of an externality.

KEY MESSAGE: A comprehensive treatment of externalities of electricity technologies should include all external impacts, even though some external costs may in practice be, or turn out to be, internalised.

1.3.4 Life cycle assessment

The concept of life cycle assessment is best introduced with simple examples. Battery-powered electric vehicles, with no tailpipe emissions, are sometimes unquestioningly regarded as pollution-free and environmentally friendly. While the vehicle itself generates no emissions, the 'pollution-free' claim is wrong because it ignores, *inter alia*, the emissions at the power station where the electricity needed to charge the car's batteries is generated, and the cost of disposal of battery waste. Again, the promotion of hydrogen as a 'clean abundant fuel' and an 'inexhaustible source of energy' overlooks the external impacts of processes needed to produce hydrogen.

In general, in order to paint an accurate picture of the externalities, complete life cycles and production systems need be analysed. With electricity generation, external impacts can arise at many stages: in the exploration, mining and transport of the fuel; during the construction or manufacture phase of the generation plant and its components; in the operation of the generator; in the course of delivering or storing the electricity; or in later recycling or disposal stages.

Life cycle assessment, or analysis, (LCA) is a well established specialised field of engineering. Sometimes life cycle assessments are described in terms like "from the cradle to the grave" or in the case of transportation systems "from well to wheel". In Australia there is an Australian Life Cycle Assessment Society (http://www.alcas.asn.au/) and an associated project on creating an Australian Life Cycle Inventory Database (www.auslci.com). LCA, as the Australian website says, "*is an internationally recognised method for evaluating environmental impacts of products and services and the implications of production and consumption*".

LCA can be a complex and difficult process with a large number of inputs. Performance of detailed life cycle assessments is outside the scope of the present work, which draws on the many reputable studies available in order to draw its conclusions.

The LCA process must deal with the fact that some aspects of a lifecycle can seem benign today yet damaging tomorrow. Carbon dioxide emissions are the prime example. It is interesting to recall that not so long ago electricity was sponsored by governments as the cleanest fuel, as was the all-electric home. Only within the past two or three decades have CO_2 emissions emerged as a major environmental issue, after re-evaluation of their effects. Historically, the basic science of the greenhouse effect is old, dating from the early 1800s. Recognition of a possible additional effect of man-made emissions from the burning of fossil fuels also has a long history (see for example Arrhenius 1896). However, it took until the 1950s for developments in climate science and the unprecedented growth in fossil fuel usage to raise concerns once again about climate change.

KEY MESSAGE: External impacts of an energy technology need to be assessed over its complete life cycle. Ignoring this will lead to wrong assessments and to misconceptions about the environmental credentials of a fuel, a technology or a product.

Much of what follows relates to externalities specific to a particular technology. There is a further stage to which the consideration of externalities should be taken in future, particularly where a generating technology is intermittent in nature. For example, wind and solar power will usually require either electrical storage or some form of back-up from a base load generator, or both. In those cases estimation of the externalities of the final product (electricity) needs to consider the whole generation/storage/back-up system. Those externalities will be specific to the site and characteristics of the particular integrated system, so a single technology-dependent external cost figure cannot be expected.

1.4 EXTERNALITIES – EXISTING KNOWLEDGE BASE

1.4.1 The ExternE Project

The central importance of the European ExternE Project (www.externe.info) in the field of energy externalities was pointed out above. ExternE is widely acknowledged as the 'gold standard' of energy externality research and the scientific quality of its work is recognised internationally (Krewitt 2002). ExternE work covers externalities of stationary power generation as well as transport and other activities such as incineration.

ExternE provides a major part of the knowledge base on externalities. An important aim of the present work is therefore to establish how relevant are the ExternE methods, and in particular the results for electricity generation, to externalities of energy production in Australia.

Health impacts and climate change contribute the largest costs in the ExternE work. The following gives a brief summary of ExternE methodology and findings, especially as they concern power generation. A fuller account can be found in the extensive update of ExternE methodology published in 2005 (ExternE 2005).

KEY MESSAGE: The ExternE Project is the key source of information about costing climate and health impacts of power generation technologies.

1.4.2 ExternE methodology: Climate change costs

The cost of climate impacts of greenhouse emissions is central to evaluation of energy externalities. The field of economic modelling of climate change costs is large and complex as indicated by the following long list of factors that have been taken into account (Watkiss *et al* 2005):

- impacts of sea level rise, erosion, loss of land/coastal wetlands, and need for coastal protection;
- effects on agriculture;
- effects on energy use (including heating and cooling);
- effects to human health from changes in cold related and heat related effects;
- effects to human health from the disease burden (and other secondary effects);
- effects on water resources, water supply and water quality;
- changes to tourism potential and destinations;
- effects on ecosystems (loss of productivity and bio-diversity);
- impacts from drought;
- impacts from flooding;
- impacts from storm damage and extreme weather (including costs to infrastructure);
- socially contingent effects (arising from multiple stresses and leading to migration, famine, etc); and
- impacts from major events (e.g. loss of thermo-haline circulation (ocean circulation driven by density gradients), collapse of West-Antarctic ice sheet, methane hydrates).

ExternE uses two general methodologies for putting values on these various climate impacts. First, models are used to estimate the costs attributable to the damage caused by climate change – the **damage cost**. Second, the costs of abating or avoiding damage, such as through reducing emissions to some target value, are calculated – the **abatement, control or avoidance cost**. In both cases the relevant figure is the marginal cost, that is the cost associated with an increment (or decrement) of damage or abatement.

The ExternE damage cost model is known as the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). The model has been developed over several years and now covers 16 world regions (one of which comprises Australia and New Zealand). The model contains a set of 'exogenous scenarios' and 'endogenous perturbations'. 'Scenarios' include the rate of population growth, economic growth, autonomous energy efficiency improvements, the rate of decarbonisation of energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. 'Perturbations' include deaths and disease due to heat stress, cold stress, malaria, and tropical cyclones. The model runs from 1950 to 2300.

Tol offers some general comments that are useful in understanding the problems of evaluating climate change impacts (Tol 2005). He points out the difficulties in reducing the complex pattern of local and individual climate impacts to a single parameter representing a global damage cost per tonne of emissions. Research into the economic impacts of climate change, he says, is still at an early stage. The influence of 'adaptation' is not properly assessed in valuations of climate change damage.

The Stern Review (Stern 2007) is one of the most influential works on the matter of evaluating the impact of climate change. That review is notable for its unequivocal statements about the high costs and risks of man-made climate change. Its conclusion, that the costs of doing nothing about greenhouse gas emissions are much greater than the costs of reducing them, has often been quoted as the fundamental basis for emission reduction policies in Australia. According to Stern, those *"costs and risks of climate change will be equivalent to losing at least five per cent of global GDP each year, now and forever"* and could rise *"to 20 per cent of GDP or more"*.

The Stern Review has come under some criticism. Tol (2006) singles out the lack of attention to adaptation in the Stern Review: "*Stern … assumes that society will never get used to higher temperatures, changed rainfall patterns, or higher sea levels. This is a rather dim view of human ingenuity"*. Nordhaus (2007) focuses on the discount rate used by Stern. Deciding the appropriate discount rate by which to value the present cost of future damage is a philosophical issue much discussed by economists. Pointing out the major discrepancy between the conclusions reached by Stern and earlier economic models, Nordhaus concludes that:

> "The Review's radical revision of the economics of climate change does not arise from any new economics, science, or modelling. Rather, it depends decisively on the assumption of a near-zero time discount rate combined with a specific utility function. The Review's unambiguous conclusions about the need for extreme immediate action will not survive the substitution of assumptions that are more consistent with today's marketplace real interest rates and savings rates. Hence, the central questions about global-warming policy – how much, how fast, and how costly – remain open."

KEY MESSAGE: Estimating the damage costs of climate change is a complex as well as controversial matter. Discount rate is a critical parameter in arriving at valuations.

The abatement, or control, cost is the marginal cost of reducing CO_2 emissions to some target level. From an economic point of view, there is an 'optimal' level of CO_2 or other emission at the point where the marginal control cost equals the marginal damage cost. Away from that point, the cost of removing a unit of emission is either greater or less than the additional damage that unit causes. If less, then there is a case for spending more to reduce the emission further. If greater, then the control measures are costing more than the damage produced and there is a case for relaxing the measure. In order to assess the optimal point, complete marginal damage and control cost curves would need to be known. Whether this will ever be feasible is debatable, but the underlying principles remain important and ought to form the basis of any taxation or tradable permit system for reducing carbon emissions.

Given the range of methods, inputs and associated economic models referred to above, and in particular the influence of choice of discount rate, it is not surprising that much uncertainty still surrounds the valuation of external costs of climate change.

Tol (2005) has reviewed 88 estimates of the marginal costs of CO_2 emissions reported in 22 published studies and has constructed a probability density function from those results. The mode for that distribution is $US5 per tonne carbon, which Tol suggests represents a 'best guess' for arriving at the marginal cost of CO_2 emissions. Because the distribution function is strongly right-skewed, the mode is far removed from the mean and 95 percentile figures, $US104 and $US446 per tonne carbon respectively. Tol argues that there are good reasons to discriminate between the studies and to give less weight to the outlying data. His conclusion is that the marginal costs are *"unlikely to exceed $50/tC, and probably much smaller"*.

ExternE (2005) gives an update on the methodology of climate impact valuation, best summarised by quoting from it directly:

> "The derived damage cost estimate is around $33/tC = ca. €9/t$CO_2$ for a medium discount rate. However, this figure is conservative in the sense that only damage that can be estimated with a reasonable certainty is included; for instance impacts such as extended floods and more frequent hurricanes with higher energy density are not taken into account, as there is not enough information about the possible relationship between global warming and these impacts."
>
> Thus, to account for the precautionary principle, we propose to use an avoidance costs approach for the central value. As discussed, the avoidance costs for reaching the broadly accepted Kyoto aim is roughly between €5 and €20 per t of CO_2. In addition it is now possible to look at the prices of the tradeable CO_2 permits, which increased from end of July 2005 to the beginning of October 2005 from about €18/tCO_2 to about €24/tCO_2. The large decrease in the beginning of September 2005 showed that the price still varies. This confirms the use of €19/t CO_2 as a central value. The lower bound is determined by the damage cost approach to about €9/t CO_2."

(Conversion between the above costs per unit carbon and per unit carbon dioxide derives from the carbon content of carbon dioxide, 27.3 per cent. Many references to carbon costs, carbon taxes etc in public documents and the media are actually referring to carbon dioxide.)

So, the ExternE position in 2005 was to use an avoidance cost rather than damage cost approach. The figure it settled on as a 'central value' for the cost of greenhouse emissions was €19/t CO_2.

In reviewing ExternE and other data, Watkiss *et al* (2005) arrive at rather different values from the above. They conclude from additional analysis of existing climate change valuation models that a lower central bound might result in a value of €15/t CO_2, a central illustrative estimate of €20-25/t CO_2, and an upper central estimate of €80/t CO_2. However they concede that not all impacts are included in these figures.

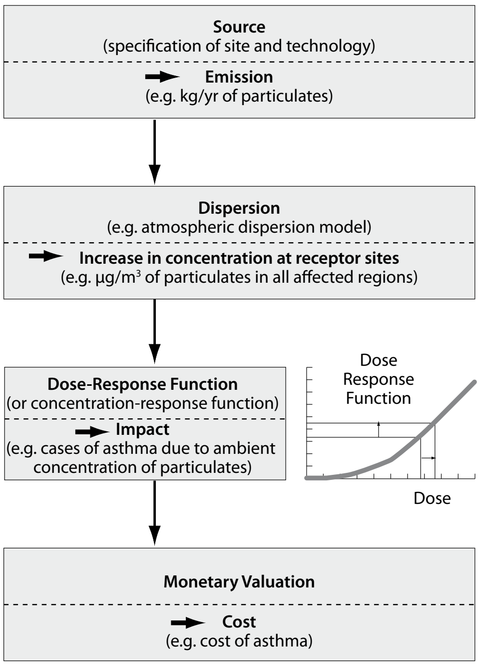
The rest of this report uses ExternE's 'central value' of €19/t CO_2 for the external cost of greenhouse emissions from power stations. It is a somewhat arbitrary choice. The uncertainties in this number have been discussed above and the need for improving its degree of certainty should be clear.

1.4.3 ExternE methodology: Health damage costs of power station emissions

As already noted, there are three main contributors to health effects arising from power station emissions: PM_{10}, fine particulate material, 10 μm or less in diameter; sulphur dioxide SO_2; and the various nitrogen oxides grouped together under the symbol NO_X. There are many other emissions that can have adverse impacts on health, as listed in Table 2 taken from ExternE, but these three are the major ones.

For determining the health impact costs of these and other emissions, ExternE developed the 'Impact Pathway' methodology, illustrated in Figure 3 (see for example ExternE 2005). In this methodology, the source, quantity and dispersion of an emission are specified; the health impact on the population is

Figure 3 The ExternE impact pathway approach (ExternE 2005)



measured via a dose-response function; and a monetary cost is attached to that impact. The Impact Pathway method has been applied to a variety of emissions from electricity generators, as well as other emission sources such as incinerators, situated throughout Europe and employing a range of fuels and technologies.

These atmospheric emissions increase the incidence of respiratory and cardiovascular disease, with accompanying increases in sickness (morbidity) and premature deaths (mortality). The largest contribution to the health damage cost is claimed to arise from mortality, often from a chronic illness, due to particulate matter. Chronic bronchitis due to particles is also important. There may also be significant direct health impacts of sulphur dioxide, but the evidence for direct effects of nitrogen oxides NO_X is less clear.

In a typical conventional power plant, stack emissions are transported by wind and diluted by atmospheric turbulence. The nature of the emissions (which depend amongst other factors on the technology used and the composition of the fuel), the height of the stack and the prevailing atmospheric conditions all mean that each power station will behave somewhat differently with respect to its emissions.

From the point source at the top of the stack, the fate of the emissions depends on their chemical nature. The principal greenhouse gases carbon dioxide, methane and nitrous oxide are taken to be stable enough eventually to mix more or less uniformly throughout the Earth's atmosphere, though homogeneous mixing will take a long time.

Other primary pollutants may take part in chemical reactions in the atmosphere and form secondary pollutants, such as sulphuric acid or ozone. The original or modified emissions will reach ground level by a turbulent diffusion mechanism or by precipitation with rain or snow. Wind and turbulence act to disperse these emissions over hundreds to thousands of kilometres, that is their effects can be regarded as both local and regional.

ExternE uses a combination of local and regional models to calculate these effects. For example, the Gaussian plume model ISC calculates local plume distributions. The Windrose Trajectory Model is used to estimate the concentration and deposition of acid species formed by chemical reactions during dispersion. Modelling of ozone is based on the EMEP MSC-W oxidant model. More recent ExternE work (ExternE 2005) has developed new and/or composite models to account for the differing dispersion characteristics of longer-lived emission components, such as potentially toxic metals (As, Cd, Cr, Hg, Ni and Pb), as well as certain organic pollutants, in particular dioxins. Other models account for movement of components through the soil, water and the food chain, up to the point where they are ingested or inhaled by humans. Further details, and references to the original works on these models, are contained in the ExternE 2005 update.

Once the dispersion of emission components has been quantified, the next step is to incorporate the appropriate dose-response functions. These are in principle determined from epidemiological or laboratory studies. However, to be useful in practice for determining the health impacts of emissions, they need to be transposed into forms that can show health impact as a function of atmospheric concentration at the point of interaction with the population. Hence the results are often expressed as concentration-response or exposure-response functions.

These exposure-health impact relationships are acknowledged in reports such as the ExternE 2005 update as a major source of uncertainty in the ExternE health impact methodology. Often they are simply unknown or are very uncertain. And often the only properly established parameter is the threshold levels for zero or lowest observable health impacts. In the absence of more reliable data, most of the dose-response functions used in ExternE are assumed to be linear, even though many examples are known where non-linear responses have been observed.

The final step in the Impact Pathway process is monetary valuation. The aim in such valuation is to account for all costs, both 'market' and 'non-market'. This means, for example, that the valuation attributed to an asthma attack should include both the cost of treating the patient (market) and that patient's willingness to pay to avoid the attack and associated suffering (non-market). ExternE finds that the damage costs of air pollution are dominated by non-market costs, especially in the case of deaths.

Economic methodology for establishing these non-market costs is a field in itself that can only be touched on here. The cost of mortality is determined via concepts such as the value of a prevented fatality (VPF), often called the value of statistical life (VSL or VOSL). VPF, according to the ExternE 2005 update is "*an unfortunate term that often evokes hostile reactions among non-economists. In reality VPF is merely a shorthand for 'willingness-to-pay (WTP) to avoid the risk of an anonymous premature death'.*" The hostile reactions arise because of the common view, and experience, that no means are or should be spared to save the life of an individual who is known to be in immediate danger. Rescues from the sea or mine disasters are typical examples. Any public policy that invokes the concept of value of a statistical life is likely to arouse hostility, even when the greatest care is taken to explain its nature.

The subject of valuing loss of health and of life has been reviewed, for example, by Pearce (2001), and recently by Abelson (2007) who puts an emphasis on Australia. There are many uncertainties, particularly in the methodology for WTP figures. Pearce notes that, since atmospheric pollution like power station emissions tends to kill more elderly people than, say, traffic accidents, the question arises of whether WTP should be considered to vary with age. Inconsistencies between willingness to pay and ability to pay also arise. These uncertainties need to be kept in mind in relation to the arbitrary use of single figures for the costs of health impacts.

Abelson reviewed the key concepts and valuation principles behind the quantitative assessment of the value of life and health. He also reviewed numerous studies of VSL, only two of which were for Australia. His compilation of their results shows a wide range, covering \$US0.5 million to \$US19.1 million. From his review, Abelson proposed the following values for adoption by public agencies in Australia:

- a VSL of \$3.5 million for avoiding an immediate death of a healthy individual aged about 50 or younger.
- a constant value of a life year (VOLY) of \$151,000, independent of age.
- age-specific VSLs for older persons equal to the present value of future VOLYs of \$151,000 discounted by three per cent per annum.

VSL figures used for policy decisions in Europe and North America have ranged from €1 million to €5 million, though the more recent ExternE work has lowered the value to the bottom end of this range. However, there is an argument that VSL is not the appropriate quantity for costing air pollution mortality, firstly because the associated loss of life expectancy is much shorter than for accidents and secondly because air pollution is mainly a contributor to and not a cause of most of the premature deaths with which it will be associated. There are other more complex considerations, but the main conclusion is that the loss of life expectancy is the meaningful statistic for valuing the health impacts of energy emissions.

In order to value losses of life expectancy, one needs the figure known as the 'value of a life year' (VOLY). ExternE points out the relative lack of studies on quantifying the VOLY concept and reviews the work done in France, Italy and the UK. Based on these results, ExternE is now using a VOLY of €50,000.

All of the components outlined above are brought together in the ExternE integrated software package EcoSense for calculating for calculating damage costs (ExternE 2005). This uses a combination of atmospheric dispersion models, together with databases for dose-response functions, 'receptor' subjects (that is, humans, buildings, crops etc) and monetary values ascribed to a unit of damage.

Health impact valuations estimated by ExternE are summarised in Table 3.

Table 3 ExternE valuations for a range of health impacts (di Valdalbero 2006)

Health end-point	Recommended central unit values in € price year 2000
Value of a prevented fatality	1,000,000
Year of life lost	50,000/year lost
Hospital admissions	2,000/admission
Emergency room visit for respiratory illness	670/visit
General practitioner visits	
Asthma	53/consultation
Lower respiratory symptoms	75/consultation
Respiratory symptoms in asthmatics	
Adults	130/event
Children	280/event
Respiratory medication use – adults and children	1/day
Restricted activity days	130/day
Cough day	38/day
Symtom day	38/day
Work loss day	82/day
Minor restricted activity day	38/day
Chronic bronchitis	190,000/case

KEY MESSAGE: The principal method for determining health damage costs from power station emissions is the ExternE impact pathway approach. This uses models to calculate costs from the quantity of an emission, its dispersion pattern, its effect on health as a function of dose, and monetary valuations of those effects. All of these inputs are subject to uncertainty.

1.4.4 ExternE Results: Climate and health damage costs of power station emissions

This section presents in summary form the more significant results for electricity externalities that have emerged from ExternE work.

For the main emissions considered to cause health damage, the most recent ExternE damage costs are given in Table 4.

Table 4 Health damage costs of power station emissions (di Valdalbero 2006)

NO_x	€4,200 – €11,000 per tonne
SO_2	€5,400 – €16,000 per tonne
NH_3	€10,000 – €30,000 per tonne
Volatile organics	€920 - €2,700 per tonne
Particulate material	€25,000 – €72,000 per tonne

With regard to particulate material, ExternE publications refer at different points to two size fractions, those 10µm and smaller and those 2.5µm and smaller. The health effects of these fractions are likely to be different but it is not clear from the published ExternE work as to whether those differences have been measured and/or related to quantities of their emissions. In what follows, the different size fractions are not distinguished and particulates are designated simply as PM_{10}. Future work might allow differentiation between the external costs associated with these fractions.

The early ExternE data on external costs of power generation are summarised in Table 5. They represent the full range of results obtained for all of the participating countries in the ExternE project. The greenhouse damage cost used in arriving at these results is €19/t CO_2.

Table 5 External Costs* for electricity production in various countries of the European Union, expressed in Euro ¢/kWh, from www.externe.info

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AUT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5**			0.2
FI	2-4	2-5				1			
FR	7–10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.07		
UK	4-7		3-5	1-2	0.25	1			0.15

* Sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)
** Biomass co-fired with lignites

The next two diagrams, figures 4 and 5, contain summaries in graphical form of a large amount of more recent data from the ExternE project. They are both reproduced directly from ExternE-Pol (2005). The first shows the magnitude of external costs for several technologies of interest, averaged over several European plants in each case. The second shows how the various emissions contribute to the total external costs. All results represent full life cycle assessments of these emissions.

Figure 4 External costs of several electricity generating systems, divided between power plant operation and rest of the energy chain (ExternE- Pol 2005)

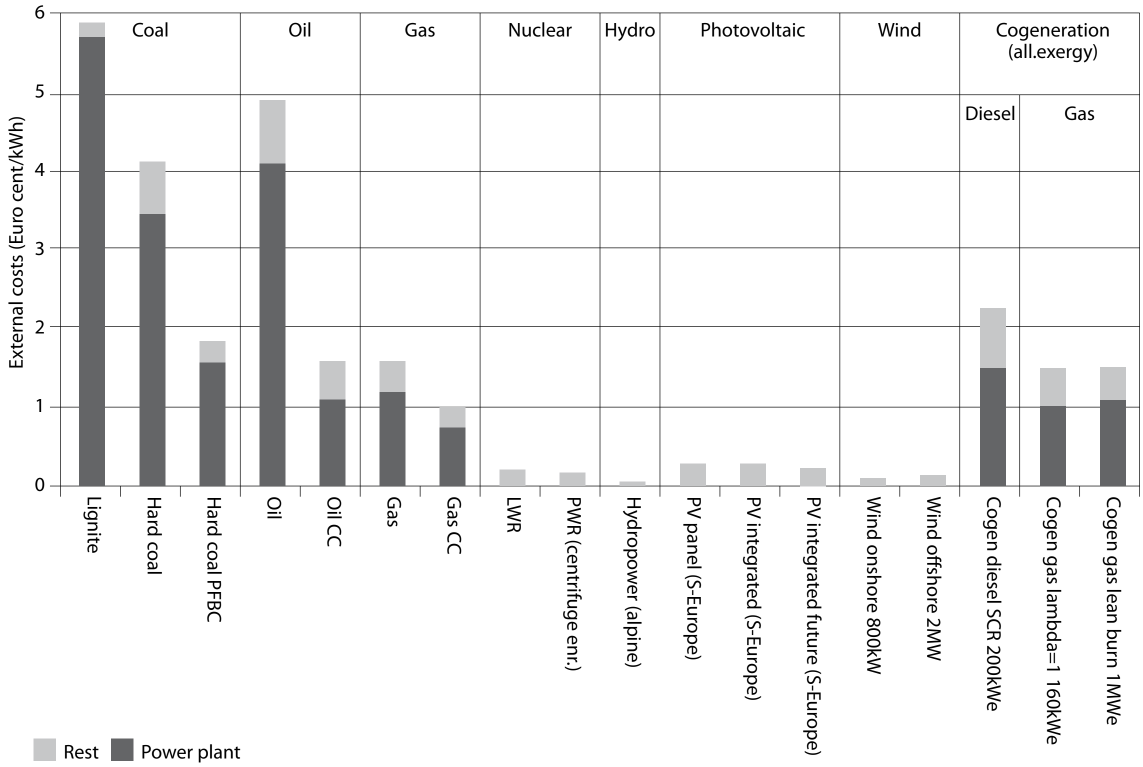
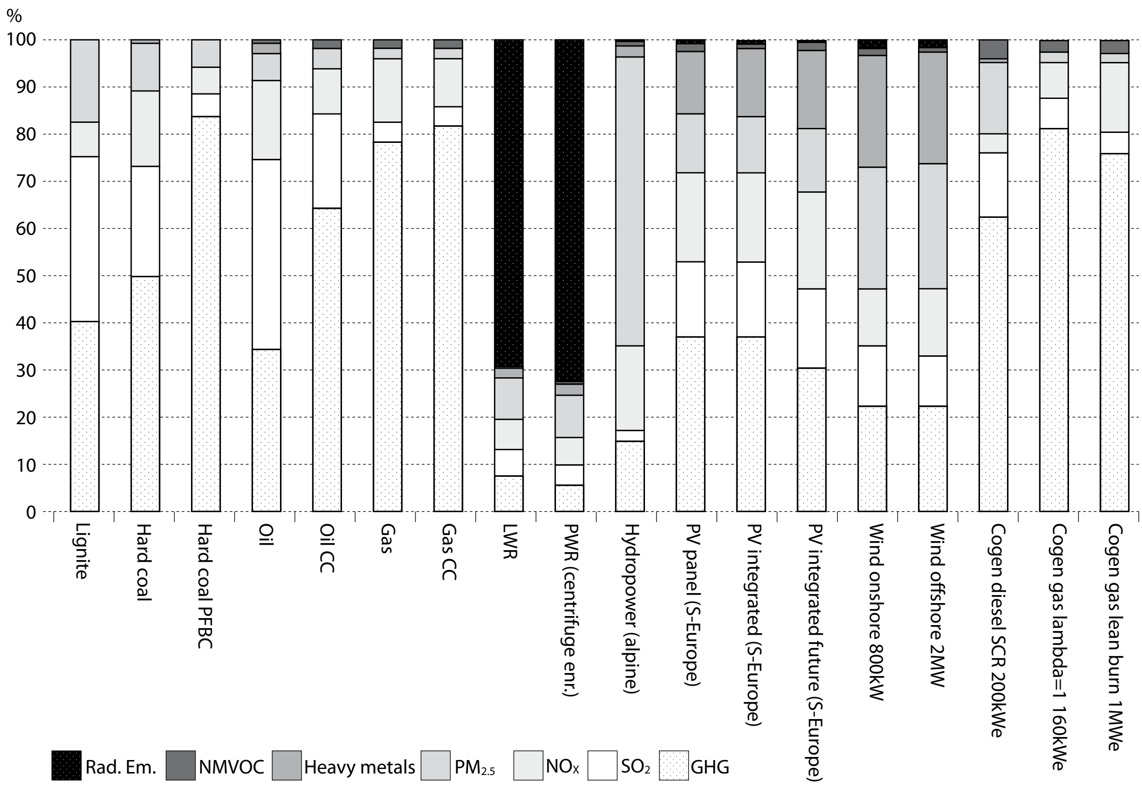


Figure 5 Per cent contribution to external costs of several electricity generating systems, by species (ExternE-Pol 2005)



The somewhat earlier ExternE cost estimates in Table 5 cover quite wide ranges. This is at least in part due to the fact that ExternE work deliberately included state-of-art generation plants as well as older plants equipped with fewer emission controls. New plants would be expected to have external costs towards the lower ends of those ranges. In Australia, coal used for power generation is usually lower in sulphur and nitrogen than European coal and Australian power stations do not include additional stages for controlling emissions of their oxides. The net effect of these opposing factors will be addressed later in this report.

Another point to note is that atmospheric dispersion modelling of emissions generally calls for a radial distribution of receptor measurements at various distances from the central power station. In the ExternE work, for countries at the perimeter of the studies, or with borders adjoining the former Soviet Union, such as Finland and Sweden, these receptor data are absent and the calculated costs are accordingly lower than for other countries. Where particular power stations are located in more populous areas, the costs are higher.

These factors contribute to the rather wide range of reported external cost data. The cautions given earlier regarding inherent uncertainty in externality valuations also needs to be kept in mind.

KEY MESSAGE: ExternE methodology has produced valuations of externalities associated with power generation using fossil fuels, nuclear and renewable energy sources. Nuclear and renewable energies have significantly lower external costs than other technologies, mainly because of lower greenhouse gas impacts and life cycle emissions of PM_{10}, SO_2 and NO_X

Some of the important conclusions drawn by the ExternE project team (di Valdalbero 2006) are:

- when all of the health impacts of air pollution arising from the electricity and transport sectors in Europe are considered, the aggregated health cost for Europe is €80 billion per annum;
- air pollution from electricity generation reduces average European life expectancy by about five months;
- electricity from coal would cost significantly more if associated externalities were internalised;
- understanding and internalising external costs can lead to a more sustainable energy system;
- ignoring externalities will distort the market and favour non-sustainable technologies; and
- internalising external costs can make alternative energy technologies competitive.

In addition to arriving at the above conclusions, the ExternE participants believe that much more research is still required in the field of energy externalities. In the associated important area of emission reduction technologies, European research priorities include the following (see di Valdalbero 2006 for a more complete list):

- fuel cells and hydrogen;
- renewables for electricity, fuels, heating and cooling;
- energy savings and efficiency;
- carbon capture and sequestration; and
- clean coal technologies

1.5 AUSTRALIAN STUDIES OF ELECTRICITY GENERATION EXTERNALITIES

Four Australian studies on the subject of externalities of electricity generation have been identified in the literature. They are (with short titles for easy reference):

1. ***'WA study'*** – a study conducted in 1990 for the Western Australian Government (Stocker *et al* 1990).
2. ***'Victorian study'*** – a 1992 energy externalities project commissioned by the Victorian Department of Manufacturing and Industry Development (Philpot 1992).
3. ***'DEST study'*** – a report (DEST 1996) *Subsidies to the Use of Natural Resources*, commissioned by the then Commonwealth Department of the Environment, Sport and Territories (DEST). The consultant was the National Institute of Economic and Industry Research (NIEIR).
4. ***'CCSD study'*** – a report (Maddox *et al* 2004) from the Co-operative Research Centre for Coal in Sustainable Development (CCSD) that reviewed ExternE work and the above Victorian study, as well as performing its own estimates of externality costs of power generation in NSW, using methods derived from ExternE.

Neither of the documents 1 or 2 above was directly accessible for the present work. However, both of the reports for 3 and 4 draw extensively on those prior studies and include sufficient information about them for the present purposes.

Note that these reports and others interchangeably use damage cost units of either cents/kWh or $/MWh. The conversion is 1 cent/kWh = $10/MWh.

The DEST study considers externalities in the context of subsidies:

> "Governments may also subsidise production by not enforcing payment for costs imposed on other parties by producing entities. In economic terms these costs are termed external costs and where they impact on the environment are known as environmental externalities. In this paper such subsidies are termed 'environmental subsidies' since they are costs which are not reflected in prices."

In relation to energy production, the DEST study notes the various environmental impacts, including greenhouse effects, of coal in the full cycle of extraction and use for electricity production, including damage to natural habitats, runoff from mine wastes, fugitive emissions of methane, and the various atmospheric gaseous and solid emissions, as well as solid residues, from the combustion process. It points out that Australian coal is relatively low in sulphur content and this property, together with the characteristics of Australian soils, mean that acid rain pollution is not the problem it is in Europe and North America. However, it quotes a National Health and Medical Research Council study in claiming that particulate and SO_2 emissions in coal combustion intensive regions such as Newcastle and Wollongong are of some concern.

As well as drawing on the above two prior studies on external costs of electricity production, the DEST report notes that quantitative data on externalities are hard to find, that market valuations are often lacking, and that the available valuations are contentious because of the different estimation approaches used. These views are consistent with what has been said here earlier regarding ExternE work.

According to the DEST report, the prior 'Victorian study' considered greenhouse gas emissions as well as impacts on water resources, air quality, land and crops, and structures (e.g. corrosion due to acid rain), but did not include components for mining and some other environmental effects. The quantitative results related to the Loy Yang brown coal power station (Latrobe Valley, Victoria). They are given in Table 6 (taken directly from the DEST report):

Table 6 Costing of Loy Yang power station externalities (from DEST 1996)

Externality category (units)	Annual emissions	Low ($/kWh)	Central ($/kWh)	High ($/kWh)
PM_{10} — Human health (tonnes PM_{10})	383	1.3x10 -5	1.8x10 -5	2.3x10 -5
PM_{10} —Visibility (tonnes PM_{10})	383	1.3x10 -6	n/a	1.7x10 -6
NO_X — Human health (tonnes NO_X)	24 332	0	0	0
SO_2 — Human health (tonnes SO_2)	46 862	0	0	0
Ozone — Human health (tonnes NO_X)	24 332	1.2x10 -6	1.9x10 -6	3.3x10 -6
Air toxics — Cancer (tonnes As)	0.206	n/a	1.6x10 -6	n/a
Air toxics — Cancer (tonnes Be)	0.0013	n/a	3.5x10 -10	n/a
Air toxics — Cancer (tonnes Cd)	0.0118	n/a	2.0x10 -8	n/a
Air toxics — Cancer (tonnes Cr)	1.38	n/a	6.2x10 -7	n/a
Air toxics — Cancer (tonnes Ni)	0.0502	n/a	4.0x10 -9	n/a
Waste water discharge — (ML/year)	18 250	0	0	5.3x10 -6
Land use/solid waste (hectares/year)	17.8	9.7x10 -7	1.9x10 -6	2.9x10 -6
Greenhouse gas (GHG) (tonnes CO_2)	17 441	0	0	0.03
Total ($/kWh)		**0.000017**	**0.000025**	**00.03004**

There are obvious major discrepancies between the three totals for the low, central and high cases in Table 6 but they need to be interpreted carefully. For reasons that are not clear, there are several missing values in the body of the Table. There is also an obvious error; the annual GHG emissions figure for Loy Yang should be in units of kilo tonnes, not tonnes. Most importantly, only the 'high' column contains the greenhouse (climate impact) estimate of three cents/kWh. If that figure is included in all columns the differences in totals between the 'high' and 'low' cases become insignificant, simply because the greenhouse impact is orders of magnitude greater than the others.

Regarding that greenhouse cost estimate, the DEST report notes that its figure of three cents/kWh was developed using both damage and control cost considerations but gives no further details of methodology.

The non-greenhouse components for the low, central and high cases total 0.0017, 0.0025 and 0.004 cents/kWh respectively. So, the Victorian study found that greenhouse costs, three cents/kWh, far outweighed the health and other costs of non-greenhouse emissions, by a factor of around 1000. This relativity is orders of magnitude greater than the corresponding results from ExternE.

The DEST report discussed this discrepancy and pointed out that at the time of the Victorian study Loy Yang had already installed extensive pollution control equipment and had the most advanced environmental design of an Australian power station. However the report still commented that the non-greenhouse costs probably understated the true cost. It also gave the view that other coal-fired power stations would have higher non-greenhouse externality costs, perhaps in the range of one cent/kWh.

To reconcile the 'Victorian study' with ExternE data, one would have to attribute exceptionally low health impacts to Loy Yang emissions or simply agree with the DEST consultants that the 'Victorian study' externality estimates were wrong.

Table 7 Application of damage/avoided damage costs to black coal based electricity generation in Western Australia (from DEST 1996)

Source of damage (costing basis)	Cost (¢/kWh, 1990 $s)
Mining (land rehabilitation)	0.2
CO_2 (sequestration)	1.8–10.0
NO_x and SO_2 (control costs)	0.5–4.0
Resource depletion (sustainability)	1.3–13.8
Total	**3.8–28.0**

The other work analysed for DEST by NIEIR was the 'WA study' performed in relation to Western Australian electricity generation. That study was based on an avoidance cost methodology. Its results are given in Table 7.

Only two components of Table 7 are directly comparable with the Victorian work – greenhouse costs and NO_X and SO_2 impacts. The greenhouse estimate, 1.8-10.0 cents/KWh, includes within its range the single figure derived in the Victorian study. But the costs associated with NO_X and SO_2 emissions, which would largely be health costs, are considerably higher. The DEST report view was that the Victorian costing was probably too low.

In addition to the above electricity externality studies, the DEST consultant (NIEIR) referred to their own earlier (1988) and current (that is 1996) estimates of greenhouse externalities based on the abatement costs through sequestering CO_2 using reforestation. Those estimates were 2.3 and 4.0 cents/kWh respectively, with a range of 1 to 8 cents/kWh.

Integrating the Victorian, WA and NIEIR's own figures, the DEST report arrived at the conclusion that externalities associated with electricity production from coal in Australia were in the range of about 1 to 9 cents/kWh. Of that total, the non-greenhouse components would amount to 0.5 to 4 cents/kWh, that is, greenhouse costs represented about 50 per cent of the total. The report noted that total externalities of the magnitude estimated were significant compared with quoted production costs of 4.5 to 6.0 cents/kWh. It also quoted North American and German studies as supporting the orders of magnitude of the cost estimates for Australian coal-fired electricity generators. All of these conclusions are consistent with ExternE results presented above in this report.

The CCSD study, as noted earlier, reviewed both the 'Victorian study' and ExternE, as well as calculating its own estimates of externality costs of power generation in NSW, using methods derived from ExternE.

With regard to the Victorian study, the CCSD report concluded, on the basis of the 'high' case value discussed above, that the total external costs of around $32/MWh were of the same order as the then current (2004) generation cost of $25-30/MWh. [Note: It is not clear why the CCSD used $32/MWh rather than the slightly lower actual Victorian result of $30/MWh.] This is the same conclusion reached in the DEST report. Remember that almost all of these external costs relate to climate change.

With regard to their estimation of externalities for electricity generation in NSW, the CCSD workers took the following approach:

- damage costs for particulates (PM_{10}), SO_2, NO_X and CO_2 as published by ExternE in units of €/kg were converted to Australian dollars at the prevailing exchange rate;
- a lifecycle analysis for all NSW generators (coal-fired) was carried out to determine total emissions. The results were expressed in terms of kg of each emission per MWh, for the NSW grid as a whole;

- a scaling factor for transferring ExternE results to NSW conditions was calculated, based on the relative population densities within 1000 km of the generators included in the ExternE and NSW studies; and
- the external cost for each emission was calculated by multiplying the emission quantity by the scaled cost.

The ExternE damage cost data on which the CCSD based its calculations are given in Table 8. Some of them fall outside the range of the ExternE data quoted by di Valdalbero (2006) and shown in an earlier table. The figures used by the CCSD probably represent older ExternE estimates. The conversion rate to Australian dollars is the one used by the CCSD at the time ($A1=€0.55).

Table 8 Damage costs used by the CCSD in costing externalities of the NSW grid

Pollutant	Impact on	Cost €/kg	Cost $A/kg
PM_{10}	Health	15.4	28
SO_2	Health, crops, materials	10.55	19.2
NO_x	Health, crops	16.0	29.1
CO_2	Climate	0.029	0.053

The CCSD's lifecycle analysis for emissions from the NSW grid gave the results in Table 9.

Table 9 Total power station emissions for the NSW grid

Pollutant	Amount
PM_{10}	0.19 kg/MWh
SO_2	4.14 kg/MWh
NO_x	2.92 kg/MWh
CO_2	974 kg/MWh

The required scaling for population density used for the next stage of the calculations was done as follows. The average population density within 1000 km of the European power stations included in the ExternE estimates was taken to be 80 persons/km^2. The analogous population density for NSW power stations was estimated by the CCSD at 2.6 persons/km^2. ExternE damage costs (other than climate impacts) were then multiplied by the factor 2.6/80, or 0.0325. For reasons explained earlier, the climate impact of CO_2 is not subject to a scaling factor as it represents a uniform global figure.

Proceeding through these calculation steps gives the results in Table 10 for the NSW damage costs of each emission in terms of generated power.

It can be seen in Table 10 that the climate costs (that is CO_2) comprise some 90 per cent of this total, with the remainder, mainly health damage costs, being $5.51/MWh. Particulates account for only three per cent of these health damage costs.

Table 10 Damage costs for atmospheric emissions from the NSW grid

Pollutant	Cost $A/MWh
PM_{10}	0.173
SO_2	2.58
NO_x	2.76
CO_2	51.6
TOTAL	**57.1**

The results of the four studies are summarised in Table 11. The figures have all been expressed in the same units, Australian dollars per megawatt-hour. The original data shown in various tables above for the WA and Victorian studies were in cents per kilowatt-hour. The currency values for the different base years have not been harmonised here but in the context of the large ranges and differences such minor corrections would make no appreciable difference. The last column uses mid-range values where the original data covered a range.

Table 11 Summary of findings of four Australian electricity externality studies

Study	Total externality costs $A/MWh	Fraction due to climate change
WA study 1990	38-280	37%
Victorian study 1992	30	99.9%
DEST study 1996	10-90	45%
CCSD study 2004	57	90%

On the whole, given the different methodologies employed the total externality costs reached are in reasonable agreement and within the range expected from ExternE work. However there is a striking difference in the proportion of climate to total externality costs. ExternE data in Figure 5 show that greenhouse gas emissions contribute 40 per cent of the total external costs for lignite-fuelled power stations and 50 per cent for hard coal, with most of the balance attributable to health costs. Two of the above Australian results (90 per cent and 99.9 per cent due to climate change) are clearly inconsistent with the ExternE data. Some of the difference might be due to differences in population densities (see below) but full resolution of the inconsistency must await further information.

KEY MESSAGE: While there have been at least four studies of externality costings for Australian electricity generators, they use different methodologies and arrive at different conclusions. Further information and analysis are needed to place Australian externalities properly into the context of the more authoritative ExternE work.

There is some additional information contained in Australian work on transport emission impacts that could be relevant to electricity externalities:

- according to the Victorian EPA (Environmental Protection Authority) (Denison *et al* 2001), Melbourne air pollution due to ozone, nitrogen dioxide, carbon monoxide and fine particles arises mainly from motor vehicles, some industrial processes and domestic wood burning. For these emissions, the contribution from power generation in the Latrobe Valley is seen as insignificant;
- Amoako *et al* (2003) of the Bureau of Transport and Regional Economics concluded that European health risk data, such as the risk ratios (the incremental increase in mortality or morbidity for a given increase in PM_{10}) published by Künzli *et al* (2000), are applicable to Australian conditions and can be used to calculate, for example, monetary values of transport emission health impacts in Australian capital cities for emissions such as PM_{10};
- in deriving monetary valuations of transport externalities, Amoako *et al* used $A1.3 million for the value of a statistical life (VSL or VOSL) and $50,000 for the value of a healthy year of life lost due to disability (YLD); and
- aggregating their calculations for all capital cities, Amoako *et al* arrived at a 'gross economic burden' resulting from traffic pollution in Australian capital cities of about $A3.3 billion (range $A2.7 billion to $A3.9 billion). They also concluded that the number of traffic pollution-induced deaths in Australian cities was higher, though only slightly, than the number of traffic fatalities.

2 Externalities of Electiricty Generation Techologies in Australia

2.1 INTRODUCTION

The remainder of this report is devoted to expanding the understanding of externalities associated with power generation in Australia at the present time, and exploring the external impacts of some of the candidate energy conversion technologies for meeting emission reduction targets.

This section and the next look separately at:

- greenhouse impacts (that is climate change) of fossil-fuelled power stations using existing or near-commercial combustion technologies;
- non-greenhouse, essentially health, impacts of existing Australian power stations, estimated with the help of relevant ExternE findings; and
- externalities of some of some energy conversion and related technologies being put forward for their potential to have a major influence on reducing Australian greenhouse gas emissions.

The first category comprises impacts of a global kind to which Australian generators contribute. These contributions can be derived from readily available information on emissions and energy efficiency. From such data, CO_2 emissions per unit generation (such as MWh) can be derived and the results converted into damage costs using results from work such as the ExternE project. Selection of appropriate figures for damage costs is discussed further below.

The second category relies on published compilations of data for certain non-greenhouse emissions from Australian power stations. A methodology based on the ExternE impact pathway approach is then used for estimating damage costs. The results give an insight into the general applicability of ExternE work to the Australian situation.

The third category includes renewable energy, nuclear and clean coal technologies. Much has already been written on their externalities but the applicability to Australian conditions needs further assessment and some of the technologies that are in early stage of development need closer attention.

2.2 GREENHOUSE IMPACTS OF AUSTRALIAN POWER STATIONS

This section covers one aspect, climate impact, of the externalities of the main technologies and fuels that are presently in use in Australia for generating grid power. It also extends the analysis to related fossil fuel technologies that are already available for future adoption or are at the demonstration stage. Even though they might not be in present use in Australia, there are adequate CO_2 emission data available for these newer technologies.

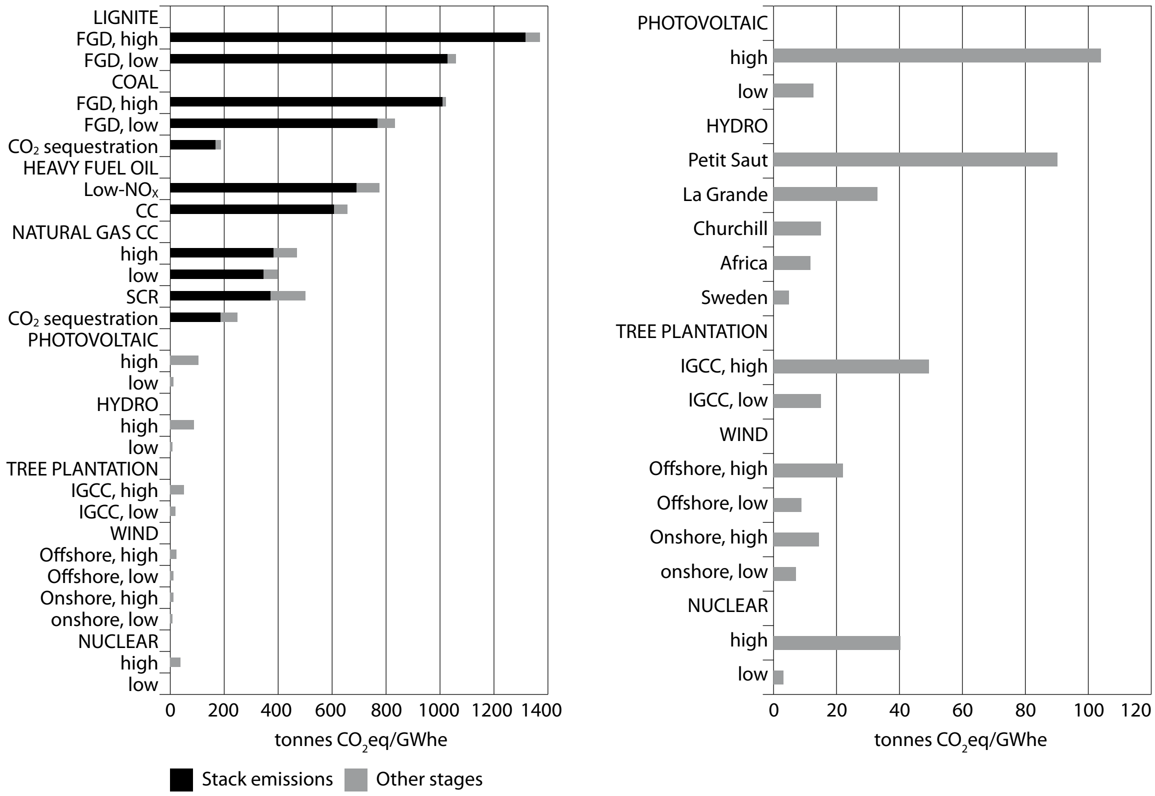
Other greenhouse gases such as methane and nitrous oxide are emitted, usually in small amounts, at various stages of processes for generating electricity. The individual greenhouse effect per unit of each of these two gases emitted is greater than for CO_2 (see e.g. World Energy Council 2004). The total greenhouse effect of a mixed emission is expressed in terms of the quantity of CO_2 that would have the same global warming potential as the mixture and is symbolised as CO_2eq. However, for the technologies considered here, CO_2 is the dominant greenhouse emission and the only one whose impact is included in the costings.

2.2.1 Life cycle assessment of CO_2 emissions

The bar charts in Figure 6 provide a synthesis of a number of life cycle assessments of energy systems (World Energy Council 2004). They are a useful introduction for considering CO_2 emissions connected with present or future electricity generating systems in Australia.

The chart on the left of Figure 6 includes several fossil fuel systems together with data for renewables and nuclear power. Stack emissions and other emissions attributable to pre- and post-generator stages such as mining, fuel transport, construction, decommissioning etc) are easily distinguished in this representation. Because CO_2 emissions are so much smaller for non-fossil fuels, for clarity they are shown separately with a magnified scale in the chart on the right. None of the examples in that chart has any direct CO_2 emissions at the generator.

Figure 6 CO_2 emissions from various generating technologies, attributable to power plant operation [black bar] and to other stages of the life cycle [grey bar], (World Energy Council 2004)



FGD = flue gas desulphurisation
SCR = selective catalytic reduction
IGCC = integrated gasification combined cycle

The important points to note are the much smaller overall levels of CO_2 emissions in the full life cycles for renewables and nuclear power, and the small proportion of fossil fuel CO_2 emissions attributable to non-generation stages for most of the fossil fuel technologies. Only with the lower CO_2 emission technologies, such as with natural gas fuel, do the non-generation stages start to show as a significant fraction of the total.

The level of emissions connected with non-generation stages will depend on the energy sources used in those stages. Most LCAs base the calculations for these stages on the present energy mix for their region. In future, as energy systems switch to low-carbon sources, the non-generation stages will contribute less and less to life cycle CO_2 emissions. The limit of that process will be determined by how far carbon can be eliminated from future energy sources. It seems likely that it will be the liquid or other hydrocarbon fuels needed for transport and heavy industrial processes like mining and extractive metallurgy that will set that limit.

KEY MESSAGE: Existing life cycle emission data show much lower CO_2 emissions from renewable and nuclear energy sources than from coal and gas power stations.

2.2.2 Choice of unit damage cost

The characteristic damage cost of the CO_2 emissions associated with a particular generation technology, in terms of a unit of power generated, is given by:

Damage cost (\$/MWh) = Emissions (kg CO_2/MWh) × Unit damage cost (\$/kg CO_2)

Establishing the 'unit damage cost' associated with CO_2 emissions is one of the central challenges in the field of energy externalities. There is a large body of literature on the subject. A brief summary of the ExternE position has already been given, including the conceptual difficulties in reducing the complex pattern of local and individual climate impacts to a single parameter representing a global damage cost per tonne (or kg) of emissions. The associated uncertainties are large and as a result the damage estimates are often quoted as a range. However, expressing all externality results in the form of upper and lower bounds complicates and obscures the data, so in what follows the aim is to use a single number where possible. The ramifications of using a single figure always need to be kept in mind. The compromises involved are discussed at length in ExternE work (ExternE update 2005, p.181-197).

Climate change theories use perturbations in the average atmospheric concentrations of greenhouse gases to feed into climate models. The emissions from any particular region contribute to the global emission burden in proportion to their quantity, the assumption being that they will eventually contribute to a homogeneously mixed atmosphere. Australia produces 1.5 per cent of global emissions (Garnaut 2008), a figure that is declining as the developing nations rapidly increase their emission. Therefore Australia contributes the same 1.5 per cent to the global damage cost.

Australia is generally considered to suffer disproportionately high damage costs because of its inherently hot and dry climate (Garnaut 2008). This might constitute an argument for using a higher-than-global damage cost for developing Australian energy policies or even for attaching such higher costings to Australian emissions. There would be many practical problems with such an approach. The same argument, for higher or lower damage costs, could be applied for other regions of the world and lead to an unwieldy heterogeneous compilation. A separate damage cost to match Australia's particular climate vulnerability would need to be determined. One would need to decide how far to go in extending such costings to regional levels in order to account for predicted differences of climate impact within Australia (Hennessy 2008).

These are interesting matters for future work. For the present the most extensive data on the cost of the CO_2 emissions come from ExternE and these relate to a single unified climate impact cost.

As noted earlier, the so-called central value of €19/t CO_2 adopted in the ExternE update (2005) will be used here as the figure for calculating climate damage costs for emissions from generators in Australia.

For application to Australia, the ExternE costings, as well as other data from European work, need to be converted to Australian currency. The rate adopted for this purpose, and used consistently through this report, is €1 = $A1.65, which was the average exchange rate during the 12 months to end-September 2008. Exchange rates have fluctuated since then, but as all costs in this report are derived from euro figures their relativities remain the same if a different exchange rate is used.

At that conversion rate, the European central value for the damage costs of CO_2 emissions becomes $A31/t CO_2.

KEY MESSAGE: The calculation of climate damage costs due CO_2 emissions from an Australian power station requires a figure for unit damage costs. Australia contributes to global climate damage costs in proportion to its CO_2 emissions. While Australia might be more vulnerable to climate change than other parts of the world, it would not be practical at present to try to use a higher damage cost than the conventional global figure derived from ExternE work. The cost adopted here is $A31/t CO_2, based on an exchange rate of €1 = $A1.65.

2.2.3 CO_2 Emissions Data

CO_2 emission figures for an individual power station depend on the fuel properties and the net thermal efficiency of the energy conversion process, as well as the load factor. These emissions are not measured directly but are derived from analysis of the energy conversion performance of the plant. In this sense CO_2 emissions differ from the other emissions considered here, particulate material (PM_{10}), sulphur dioxide (SO_2) and nitrogen oxides (NO_X), where stack emissions are measured directly.

In fossil fuel combustion technologies, the aim is to raise the generating efficiency of the combustion process, that is, the net electrical energy generated per unit of fuel consumed. Higher efficiency means lower CO_2 emissions per unit electricity generated. The main way of achieving this aim is by raising the upper temperature of the heat engine operating cycle, which basic thermodynamics mandates as the limiting factor in heat engine efficiency.

With the surge in interest in the environmental credentials of power generation, there have been many studies of the CO_2 emission characteristics of the various available technologies. This work relies on three major compilations, Connell Wagner (2007) referred to above, ISA-University of Sydney (2006) commissioned by the UMPNER Inquiry and hence referred to here as UMPNER/ISA, a Study by the Energy Supply Association of Australia (2005), and a report of the World Energy Council (2004). These compilations probably rely in some cases on the same source data, so they cannot be considered to be entirely independent.

The fossil fuel technologies of interest here are those in use in Australia or whose implementation is likely in the near term, though CCS (see below) has a longer time frame. Technologies are listed by their commonly used names.

Sub-critical with pulverised fuel is the main generation technology in current use in Australia. Finely milled coal is fed into a burner and the steam, generated at sub-critical temperatures, drives turbo-alternators. The figures below refer mainly to new power plants approaching best available performance.

Supercritical and ultra supercritical (USC) plants also burn pulverised fuel and are characterised by progressively higher boiler steam pressures and temperatures, which lead to higher thermal efficiencies and hence lower specific CO_2 emissions.

CCS refers to the process of **carbon capture and storage (or sequestration)** being developed to dispose of CO_2 emissions. It is described in further detail later in a later section.

Natural gas plants operate in **open cycle** or **combined cycle (NGCC)** mode, with the latter requiring an additional heat recovery stage and steam turbine, with extra capital costs. The combined cycle process is often called **combined cycle gas turbine (CCGT)**.

Integrated gasification combined cycle (IGCC) is a near-commercial technology in which coal is converted to syngas which is further processed and burned in a CCGT unit.

Table 12 lists emissions from the technologies listed below. These figures are taken from the compilations mentioned above.

Table 12 CO_2 emissions data for commercial power stations. Note that only some of these are Australian

Technology	Fuel	CO_2 kg/MWh	Source
Sub-critical pulv, new	Black coal (NSW)	860-1065	Connell Wagner p.6
Sub-critical pulv, new	Black coal	941 (843-1171)	UMPNER/ISA p.8
Sub-critical pulv, new	Black coal	898-1085 (5 plants)	WEC
Sub-critical pulv, new	Brown coal	1175 (1011-1506)	UMPNER/ISA
Supercritical	Black coal	863 (774-1046)	UMPNER/ISA
USC	Black coal	785-860	Connell Wagner
USC with CCS	Black coal	~100	Connell Wagner
NG open cycle	Natural gas	751 (627-891)	UMPNER/ISA
NGCC	Natural gas	345	Connell Wagner
NGCC	Natural gas	577 (491-655)	UMPNER/ISA
NGCC	Natural gas	426 (av. of 9 plants)	WEC
IGCC	Black coal	785-840	Connell Wagner
IGCC with CCS	Black coal	~100	Connell Wagner
Supercritical proj.	Black coal	740	esaa
USC proj.	Black coal	660	esaa
IGCC proj	Black coal	710	esaa
NGCC proj	Natural gas	370	esaa

Note: UMPNER/ISA and WEC data are full life cycle. Connell Wagner seems to be generator only. esaa figures are projections for the year 2030 (esaa 2006)

There is a more extensive list of individual power station CO_2 emissions given in Table 6.2 of the UMPNER/ISA Study. Those data are referenced to an earlier CCSD report.

Brown coal gives the highest emissions (and lowest energy conversion efficiency) because of the energy needed to lower the coal's high water content in preparation for its combustion. Natural gas gives the lowest CO_2 emissions of the fossil fuels as a simple consequence its chemical composition (higher hydrogen/carbon ratio) and correspondingly lower carbon content per unit energy produced. As a result, more heat is released and hence more electricity generated per unit of CO_2 produced.

Technologies that incorporate carbon capture and storage (CCS) show the lowest overall emission because CO_2 is largely eliminated at the generator through the use of additional processing steps. CCS will be considered further in a later section. At this point it is worth noting that CCS technologies consume additional energy, which has the effect of increasing the amount of fuel used and CO_2 produced in the course of capturing and disposing of a given proportion of that CO_2. As discussed later, the effective full life cycle reduction in CO_2 emissions is probably somewhat less than implied in the Connell Wagner report.

There is reasonably consistency in the table above between data from different sources. One outlier is the NGCC figure quoted by Connell Wagner, which seems about 20 per cent lower than the average of the nine European NGCC plants, all with quite similar emissions, quoted in the WEC compilation. There is no obvious reason for this discrepancy.

ESAA's Energy and Emissions Study Stage 2 (2006) provides some interesting projections of how far the emission figures for current technology might be reduced with advances introduced by the year 2030. These are included at the bottom of the above table.

2.2.4 CO_2 damage costs

Table 13 presents calculated CO_2 damage costs for the various technologies. To keep the results simple, a single representative performance figure for each technology is chosen. These are shown in the third column. The choice is somewhat arbitrary; there are both better and worse performing plants in Australia. It should be noted that the differences between full life cycle and direct stack emissions (see for example Figure 6) are smaller than the differences in the ranges of estimates from different sources in Table 12. For the present purposes, the representative performance figures in Table 13 are taken to be over the full life cycle.

Table 13 Calculated CO_2 damage costs for typical cases of fossil-fuelled power stations

Technology	Fuel	CO_2 kg/MWh	Damage cost $A/MWh
Sub-critical pulv, new	Black coal	950	29
Sub-critical pulv, new	Brown coal	1250	39
Supercritical	Black coal	900	28
USC	Black coal	820	25
NG open cycle	Natural gas	750	23
NGCC	Natural gas	580	18
IGCC	Black coal	800	25
USC, IGCC, with CCS	Black coal	100	3.1

From each CO_2 emission figure the corresponding climate damage cost is calculated using the relationship given above and a unit damage cost of $A31/t CO_2. Results are rounded to two significant figures but it should be remembered that the methodology does not justify quoting even that level of accuracy. The numbers in the last column are indicative only, but the relativities ought to be reliable.

In summary, the calculated damage costs of CO_2 emissions from technologies now used in Australia, as well as other established and prospective generating cycles, range from $A18/MWh to $A39/MWh. This range reflects the corresponding spread of energy conversion efficiencies of the various technologies, together with the inherently lower emissions from energy-rich natural gas fuel. The first two rows of Table 13 represent the bulk (82 per cent) of Australia's fossil fuel-generated power, with natural gas contributing 16 per cent and oil the remainder (ABARE 2008A).

At the bottom end of damage costs are the highest efficiency coal combustion technologies (ultra-supercritical coal and integrated gasification combined cycle) that also incorporate carbon capture and storage. As explained, these technologies are still some time away. Also, as explained later, the claim that CCS could reduce CO_2 emissions to 100 kg/MWh probably does not represent a full life cycle analysis.

The above climate damage costs are not specific to Australian emissions. Provided the same CO_2 damage cost per tonne is used, similar figures could be calculated for plants anywhere in the world, with minor variations due to specific fuel characteristics.

KEY MESSAGE: Greenhouse damage costs of CO_2 emissions from Australian power stations are calculated using the unit damage cost of \$A31/tCO_2 and emission data already available for the various technologies in use. Damage costs range from \$A18/MWh for natural gas to \$A39/MWh for brown coal. The best technology currently in prospect for fossil fuel power, incorporating carbon capture and storage, should have significantly lower greenhouse damage costs.

2.3 HEALTH DAMAGE COSTS OF AUSTRALIAN POWER STATIONS – METHODOLOGY

The emissions covered in this section are particulate material (PM_{10}), sulphur dioxide (SO_2) and nitrogen oxides (NO_X). As discussed earlier, these are regarded as the main power station emissions contributing to health damage costs. They are associated with increased respiratory symptoms, reduced lung function, chronic bronchitis, asthma etc.

2.3.1 Transferring ExternE results between regions

Unlike damage costs for CO_2 emissions, health damage costs are site- and region- specific. Deriving costs from reference data such as provided by the ExternE project requires a methodology for transferring costs between regions. To develop such a methodology, the modelling used in ExternE work needs to be examined.

The parameters used in ExternE models to estimate health damage costs due to power station emissions include:

- quantity of an emission;
- stack height;
- population exposed to emissions;
- emission temperature;
- exhaust velocity; and
- deposition flux, which is the rate of removal of a pollutant by dry and/or wet deposition.

Further details of the models can be obtained from ExternE reports (e.g. ExternE 2005 update).

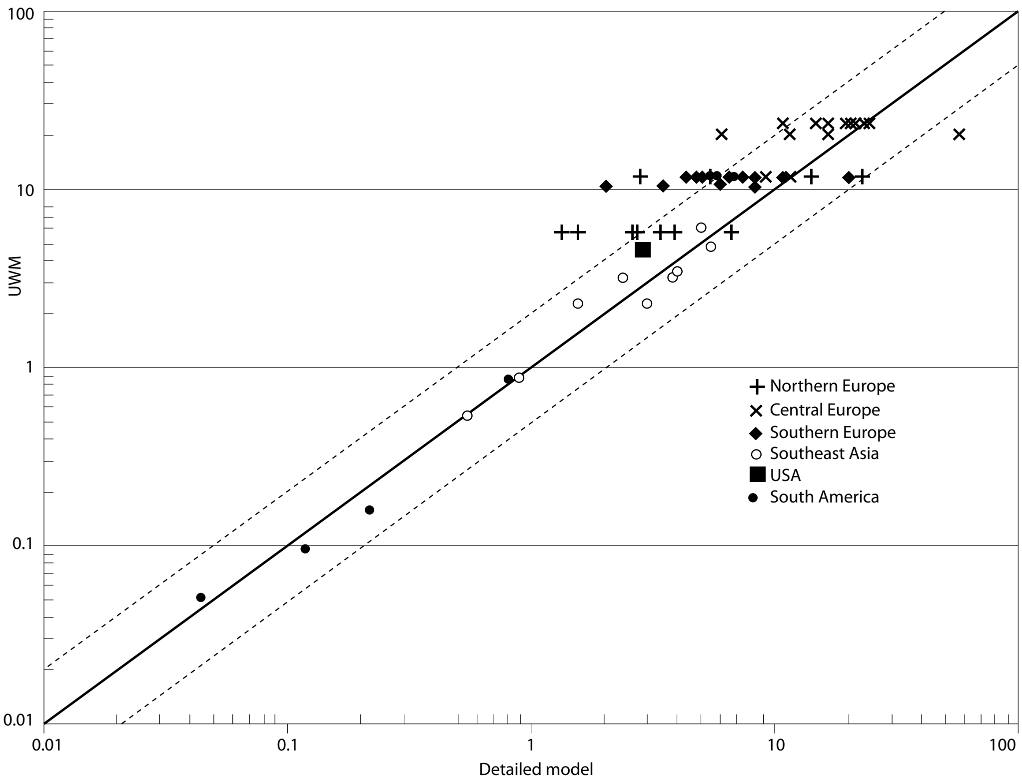
The models provide measures of the amounts or doses of harmful emissions to which a population will be exposed. From the dose-response function, the health damage costs are determined.

Several models are in use for these calculations and ExternE claims good agreement between them on the basis of results such as shown in Figure 7 (from ExternE 2005 update). Here the results for damage costs for particulate material PM_{10} from several models are compared with the so-called Universal World Model (UWM). The unit slope of the envelope of results indicates reasonable consistency between models.

The diagram also shows the strong influence of population density on the health damage caused by a given quantum of emission, in this case one kg of PM_{10}. Calculated PM_{10} damage costs for different parts of the world vary over a range of more than two orders of magnitude – from a low of around €0.05/kg in South America (low population density) to a high of around €15/kg in Central Europe (high population density). For the USA the damage cost is between €3 and €6/kg depending on which model is chosen. Clearly, the smaller the population exposed to a certain quantity of an emission the fewer the numbers suffering injury. At the limit, if nobody lives within the deposition zone then nobody can be injured.

It is beyond the scope of the present work to apply computer modelling to the problem of estimating analogous damage costs for Australian power stations. Models would need data on the dispersion and

Figure 7 Comparison between results for PM_{10} damage costs derived for the Universal World Model (UWM) and other detailed models. Damage costs are in Euros/kg PM_{10} (ExternE 2005)



deposition of emissions, which are not available. However, as already seen, there has been some previous work such as the 2004 CCSD study that was aimed at arriving at health damage costs using some simple assumptions and approximations, without such models. That work was reasonably encouraging and a similar approach will be used here.

ExternE provides some useful comments on the matter of the relationship between site-specific damage costs for different regions, (ExternE 2005 p.247):

> "How can the damage cost estimates be transferred from one site to another? To the extent that more than 95 per cent of the costs arise from health impacts, they are proportional to the size of the affected population weighted by the respective concentration increments. For precise results one would have to repeat the analysis based on local meteorological and population data, but for a rough first estimation one can use the following rules of thumb (Spadaro and Rabl 1999):
>
> - For primary pollutants emitted by vehicles in cities, the damage cost is roughly proportional to the population of the conurbation.
> - For secondary pollutants the damage cost is roughly proportional to the average regional population density within a radius of 500 to 1000 km; the radius of the region is smaller in regions with high precipitation such as Brazil. In regions where the unit costs are different, these would have to be adjusted as well."

KEY MESSAGE: The main emissions to consider for health damage costs of present power stations are fine particles (PM_{10}), sulphur dioxide (SO_2) and nitrogen oxides (NO_X). Health damage costs are specific to a site. Regional weather variations will have an influence but the main factor is the population density in the area around the site.

2.3.2 Calculating Australian health damage costs

In order to estimate Australian health damage costs with the help of ExternE findings but without using computer modelling, the following simplifying assumptions need to be made:

- stack heights of the power plants and dispersion and deposition mechanisms of the emissions are similar to European conditions;
- health damage cost for each unit of an emission component is proportional to the recipient population per unit area within a given distance from the emission source;
- each damage cost is proportional to the rate of the particular emission, expressed in consistent terms such as kilograms per Megawatt-hour;
- health damage costs per unit exposure per person are taken to be the same in Australia as in Europe;
- the non-greenhouse external costs in ExternE compilations are predominantly health damage costs;
- a linear scaling factor based on an appropriate parameter for the exposed population will enable conversion from the European to the Australian situation; and
- the sum of the costs due to the emissions PM_{10}, SO_2 and NO_X is a good measure of the total health damage cost. This means that the minor contributions of these emissions to other environmental costs (crops, buildings) are ignored, as are the health cost contributions from other emissions contained in the comprehensive list in Table 2.

The first of the above assumptions is probably the least accurate, since the real behaviour of stack emissions will certainly depend on weather patterns, rainfall, prevailing wind directions, temperature, etc. Also, the assumption that the health damage cost is simply related to the population density around an emission point can only be a rough approximation to the complete model. Models such as used in ExternE include functions for dispersion and deposition of emissions and they calculate and integrate exposures of the population within a set of grids around a site.

Once again, only detailed data acquisition and modelling will reduce the uncertainties in these approximations. Such modelling could be the subject of future extensions of this work.

To test the assumption about similar stack heights, some examples of Australian and European power stations (the latter are from ExternE reference cases) are listed in Table 14. Some Australian stacks are shorter than their European counterparts but most coal-fired power stations seem to have similar stack heights.

2.3.3 Scaling for population density differences

The assumption here is that the health impacts around two identical emission sites are directly related to the surrounding population densities.

The starting point for such a calculation is the relevant population density for the health costs as determined by ExternE. Now, ExternE results do not specifically refer to such a population density. Those results come from individual site models, integrated into national totals. ExternE models are said to account for the population within 500 to 1000 km of a generator. At such distances the areas of affected population in Europe must overlap to a major degree.

Table 14 Some representative power station stack heights

Location	Fuel	Stack height (metres)
Germany	coal	240
Germany	lignite	200
Germany	gas	250
France	coal	220
France	gas	110
Victoria, Loy Yang A	brown coal	260
NSW, Eraring	coal	200
Queensland, Stanwell	coal	210
Queensland, Swanbank B	coal	137
Queensland, Swanbank E	gas	40

However, a single population density that is representative of Europe can be derived with some simple and credible assumptions. Firstly, the power stations and their emissions that contribute to the total impacts measured by ExternE are more or less evenly distributed over the European land mass. Secondly, an allowance needs to be made for the extent of dispersion by adding to the perimeter of the affected area. Also, some account needs to be taken of the fact that some of this extension would cover unpopulated oceans.

Using the EU to represent the European area of interest, the total land area is 4.42 million km^2, the population 495 million and the population density 112 persons/km^2 (Wikipedia 2008). This density would reduce to around 100 persons/km^2 for the 'extended perimeter' receptor zone referred to above. This is the figure that will be adopted here as a reasonable estimate for the European situation. Note that the CCSD used 80 persons/ km^2 for their ExternE comparisons with the NSW grid, without giving how that number was derived.

With regard to Australia, there are some different approaches that can be taken in arriving at relevant population density figures. Power stations are obviously more widely separated than they are in Europe but they do occur in clusters in some parts of the country. So one could take a localised approach, look at an individual power station, or a cluster, and assume no emission impact from distant stations. Or one could take an extended approach, look at a large area of overlapping impacts and add together all of the emissions from the power stations included. Both approaches will produce approximations.

There is one additional piece of information that might act as a guide in this choice. Denison *et al* (2001) concluded that the health impacts of particulate matter in Melbourne attributable to emissions from generators in the Latrobe Valley, some 120 km away, were negligible. If that were generally true, then it would point to the use of the more localised area, say 100 km in radius rather than the above figure of 500 to 1000 km radius. Both alternatives are tested below.

For the 'localised' approach, the local government areas within an arbitrary radius of 100 km were found from relevant maps given by a search for Wikipedia, by local government areas and by State. These areas are of course not circular but the irregularities at the edges make little difference. Population data for Australia and the states came from Wikipedia and from ABS data for local government area populations (Australian Bureau of Statistics 2008A).

Using the above data, the population density potentially affected by Latrobe Valley emissions within a 100 km radius is estimated at 14/km^2. This area does include some fringe eastern suburbs of Melbourne. If they are excluded, the density becomes 7/km^2.

A similar localised approach for the area around the main NSW generators in the Hunter Valley gives a population density of about 20/km^2. The figure is larger than for the Latrobe Valley because the 100 km radius Hunter Valley zone includes the larger metropolitan centres of Maitland and Newcastle.

The 'extended' approach, with its linear dimensions of the order of 1000 km and much larger catchment, only makes sense when applied to an area such as the whole of the Australian eastern seaboard (including the Latrobe Valley). Such an area contains the bulk of Australia's generating capacity and major population centres. With a dispersion model extending to a distance of 500 km from the coast, the potential area of impact (including ocean) is roughly 2,500,000 km^2 and the population 16.7 million, giving a population density of 6.7 persons/km^2.

These numbers are listed in Table 15, together with some State and national population densities.

Table 15 Australian areas of emission health impact, based on various calculation methods

Region	Calculation basis	Population density (Persons/km^2)
Latrobe Valley	Localised	14
Latrobe Valley	Localised excluding metro	7
Hunter Valley	Localised	20
East coast	Extended	6.7
NSW - total	Geographic	8.4
Victoria - total	Geographic	21.8
Australia - total	Geographic	2.6
NSW (CCSD)	Unknown	2.6

Overall, the calculated population densities for regions where power station emissions might have an impact are not especially sensitive to the very different assumptions made. They range from 7 persons/km^2 for the extended area that covers the bulk of the eastern States' generating capacity to 20 persons/km^2 for the most populous area of generator concentration, the Hunter Valley. However, the results are more sensitive to the assumptions made about the radius of an affected area. For example, if it could be established that the health impact of Hunter Valley emissions is felt as far west as, say, Broken Hill, 1000 km away, then the relevant 'East coast' population density would immediately fall by half, to 3.4. An impact over such a distance does seem unlikely.

The population density figure that the CCSD used for their NSW grid calculations stands out as being unusually low. In fact it is the same as for the whole of continental Australia, 2.6/km^2, which seems an unrealistic density for the present purposes.

Once again, the uncertainties in the above approximations can only be resolved by proper measurements and modelling.

It is proposed here to use 7 to 20 persons/km^2 as nominal range that should cover, with a reasonable degree of certainty, the individual population densities around the main generation sites as well as their collective impact.

Given the above estimate of 100 persons/km^2 as a single representative figure for Europe, the scaling factor for transferring European results to Australia is 0.07 to 0.2 (7 to 20 per cent). The corresponding figure used by the CCSD was 0.0325, less than half of the lower end of this range, obviously as a result of the lower population density used in that study.

KEY MESSAGE: Comparison of population densities in Europe and relevant areas of Australia suggests that Australian health damage costs attributable to a given quantity of the main emissions PM_{10}, SO_2 and NO_X are between 7 per cent and 20 per cent of the corresponding figures for Europe.

2.3.4 Power station generation and emissions data

The next step in arriving at health damage costs for Australian generators is to quantify power station emissions as a function of electrical output.

The information needed to make such estimates is compiled in several Tables below. The sources for generator capacity and annualised electric energy generation include the websites of the operating companies and the publication Energy in Australia 2008 (ABARE 2008A), which lists the total outputs by each generation business. Emission data come from the National Pollutant Inventory (NPI), (www.npi.gov.au), which comprises a searchable database of annual emissions for some or all of 92 substances from 192 fossil fuel fired power stations in Australia, as well as total emissions by substance. Some of the annualised data are for a calendar year while others are for a financial year. The mismatch is not likely to be of any significance in the following analysis.

The power stations listed in Table 16 represent a sample for which data for both annual output and annual emissions are available. They are representative of Australia's larger generators.

Table 16 Generation data for some Australian coal-fired power stations

STATE	POWER STATION	OPERATING COMPANY	GENERATOR CAPACITY		GENERATION TWh 2006-07
			NOMINAL	TOTAL	
Victoria	Loy Yang A (brown coal)	Loy Yang Power	4 X 500 MW	2120 MW actual in 2007	17.0
	Hazelwood (brown coal)	International Power Australia	8 X 200 MW	1675 gross MW 1541 net MW	11.9
	Yallourn (brown coal)	TRUenergy	2 X 350 MW 2 X 375 MW	1480 MW	10.7
NSW	(Eraring coal)	Eraring Energy	4 X 660 MW	2640 MW	17.6
	(Bayswater coal)	Macquarie Generation	4 X 660 MW	2640 MW	26.6 (total Macquarie)
	(Liddell coal)	Macquarie Generation	4 X 500	2000 MW	
Queensland	(Tarong coal)	Tarong Energy	4 X 350	1400	11.9
	(Gladstone coal)	Comalco/NRG	6 X 280	1680 MW	8.8
	(Stanwell coal)	Stanwell Corp.	4 X 350 (Stanwell has 5 other generators)	1400 MW + 156 hydro & distillate	10.4, about 9.7 for Stanwell coal alone

KEY MESSAGE: Australian figures for quantities of various emissions per unit of electricity generated can be calculated from power station output statistics from various sources and emission data contained in the National Pollutant Inventory.

2.4 HEALTH DAMAGE COSTS OF AUSTRALIAN POWER STATIONS – COAL

2.4.1 PM_{10} emissions

PM_{10}, that is, particles less than 10 micrometres, is actually a complex category of emissions (see e.g. ExternE 2005 update for a discussion of the components). Here it is considered as a single group.

Table 17 lists a number of individual power stations with their generation output and annual PM_{10} emissions taken from the NPI database. From these two figures, the last column, kg PM_{10} per MWh, is calculated. A bulked figure for the whole of Australia's coal-fired power is also shown. The results are consistent with emissions compiled on a State basis in Energy Gas Australia (see Energy Supply Association of Australia 2008, Table 2.10).

Table 17 PM_{10} emissions from Australian coal-powered generators 2006-07

STATE	POWER STATION	GENERATION TWh from coal	PM_{10} EMISSION kg/year	PM_{10} EMISSION kg /MWh
All	**All**	**197***	**41,000,000**	**0.21**
Victoria	Loy Yang A	17.0	1,700,000	0.10
	Hazelwood	11.9	1,900,000	0.16
	Yallourn	10.7	2,300,000	0.21
NSW	Bayswater	26.6**	1,200,000	0.08
	Liddell	Included above	840,000	Included above
	Eraring	17.6	470,000***	0.03
Queensland	Tarong	11.9	4,400,00	0.37
	Gladstone	8.8	870,000	0.10
	Stanwell	9.7 (estimate)	1,000,000	0.10

*The total generation from all coal-fired power stations is derived from the national output of 260 TWh and the proportion attributed to coal, 75.6% (ABARE 2008A)
** Combined generation from Bayswater and Liddell
***The figure for each of the previous two years was 1,100,000 kg, suggesting that there was significant new particle cleaning equipment installed in the interim.

Natural gas combustion has low PM_{10} emissions so it can be assumed that the Australian total essentially all comes from coal. On that basis, the average emission rate of PM_{10} for all Australian coal-fired plants is 0.21 kg/MWh. The range for the above sample of individual power stations is 0.03 to 0.37. Omitting the outlying low figure from Eraring, the range becomes narrower, 0.08 to 0.37. It can be concluded that the national average figure is reasonably representative of most power stations.

The CCSD study used a figure of 0.19 kg/MWh for PM_{10} emissions from the whole NSW grid, close to the national estimate here. There are some other measures of Australian PM_{10} emissions available in the literature. World Energy Council (2004) gives 0.113 kg/MWh for Loy Yang and 0.081 kg/MWh for Bayswater, in good agreement with above.

For comparison, some representative figures for PM_{10} emissions from European power stations are given in Table 18.

Table 18 PM_{10} emissions from European coal-powered generators

Country	PM_{10} emissions kg/MWh
France	0.17*, 0.13***
The Netherlands	0.017*
Germany	0.057*, 0.182**
Germany (lignite)	0.511***, 0.947***
UK	0.16***

* ExternE (1999) Vol XX: National Implementation
** Krewitt et al (1997)
*** World Energy Council (2004)

The Australian data for PM_{10} emissions per unit electricity generated are generally consistent with the observed range of European emissions. The high PM_{10} emissions from two German lignite-fired power stations tend to confirm the superior performance of Loy Yang with its modern emission reduction technology.

KEY MESSAGE: PM_{10} emissions for a sample of Australian coal-fired power stations range from 0.03 to 0.37 kg/MWh. The national average is 0.21 kg/MWh. These figures are generally consistent with European emission figures.

2.4.2 SO_2 emissions

Using the same methodology as above gives the results for SO_2 emissions in Table 19. Because gas-fired power stations produce relatively little SO_2 emissions, the approximation is made that all of the Australian total in the top line can be attributed to coal combustion.

Table 19 SO_2 emissions from Australian coal-powered generators 2006-07

STATE	POWER STATION	GENERATION TWh from coal	SO_2 EMISSION kg/year	SO_2 EMISSION kg /MWh
All	**All**	**197**	**630,000,000***	**3.2**
Victoria	Loy Yang A	17.0	62,000,000	3.6
	Hazelwood	11.9	12,000,000	1.0
	Yallourn	10.7	20,000,000	1.9
NSW	Bayswater	26.6**	76,000,000	4.9
	Liddell	Included above	54,000,000	Included above
	Eraring	17.6	45,000,000	2.6
Queensland	Tarong	11.9	19,000,000	1.6
	Gladstone	8.8	31,000,000	3.5
	Stanwell	9.7 (estimate)	34,000,000	3.5

*Assumes all the SO_2 in the NPI total comes from coal
**Combined generation from Bayswater and Liddell

The Australian average for SO_2 emissions is 3.2 kg/MWh, while the range, 1.0 to 4.9 kg/MWh, is similar in spread to the data for PM_{10} emissions.

World Energy Council (2004) cites SO_2 emission figures for Loy Yang (2.83 kg/MWh) and Bayswater (3.6 kg/MWh), in reasonable agreement with above.

For comparison, some European SO_2 figures are given in Table 20.

Table 20 SO_2 emissions from European coal-powered generators

Country	SO_2 emissions Kg/MWh
France	1.36*
The Netherlands	0.41*
Germany	0.29*, 0.33**
Germany (lignite)	0.42***, 0.9-1.6***
UK	1.1***

* ExternE (1999) Vol XX: National Implementation
** Krewitt et al (1997)
*** World Energy Council (2004)

There is some overlap between these Australian and European emission figures but on the whole the latter seem to be smaller than the Australian average by a factor of about 2 to 10. Power plants in Australia are not required to install flue gas desulphurisation facilities but in Europe they are.

Therefore, in general, Australian power stations emit more SO_2 to the atmosphere even though they burn lower sulphur coals.

KEY MESSAGE: SO_2 emissions for a sample of Australian coal-fired power stations range from 1.0 to 4.9 kg/MWh, with a national average of 3.2 kg/MWh. European SO_2 emission figures are around 10 to 50 per cent of the Australian data.

2.4.3 NO_x emissions

Results for NO_X emissions are listed in Table 21, using the same approach as above.

The figure for the average Australian NO_X emissions at 2.5 kg/MWh seems somewhat higher than the European data, consistent with the widespread use of NO_X scrubbing technology in European power stations.

Table 21 NO_X emissions from Australian coal-powered generators 2006-07

STATE	POWER STATION	GENERATION TWh from coal	NO_X EMISSION kg/year	NO_X EMISSION kg/MWh
All	**All**	**197**	**490,000,000***	**2.5**
Victoria	Loy Yang A	17.0	32,000,000	1.9
	Hazelwood	11.9	27,000,000	2.3
	Yallourn	10.7	15,000,000	1.4
NSW	Bayswater	26.6**	30,000,000	1.8
	Liddell	Included above	19,000,000	Included above
	Eraring	17.6	40,000,000	2.3
Queensland	Tarong	11.9	32,000,000	2.7
	Gladstone	8.8	45,000,000	5.1
	Stanwell	9.7 (estimate)	36,000,000	3.7

* Assumes all NO_X emissions come from coal
** Combined generation from Bayswater and Liddell
The World Energy Council Report (2004) contains NO_X emissions estimates for Loy Yang, 2.13 kg/MWh and Bayswater, 2.23 kg/MWh, again consistent with above. Some European data from various sources are shown in the table below.

Table 22 NO_X emissions from European coal-powered generators

Country	NO_X emissions Kg/MWh
France	2.22*
The Netherlands	0.71*
Germany	0.52*, 0.56**
Germany (lignite)	0.79***, 1.1***
UK	2.2***

* ExternE (1999) Vol XX: National Implementation
** Krewitt et al (1997)
*** World Energy Council (2004)

KEY MESSAGE: NO_X emissions for a sample of Australian coal-fired power stations range from 1.4 to 5.1 kg/MWh. The national average is 2.5 kg/MWh. These figures are somewhat higher than the corresponding European emission figures.

2.4.4 Damage costs

The ExternE ranges of damage costs given in Table 4 are used as the reference data for the following calculations of health damage costs. For PM_{10} damage costs the range, €25–72/kg, is reasonably consistent with the cluster of European PM_{10} data points around €30/kg in Figure 7. CCSD used a figure of €15.40/kg for the European damage cost, somewhat below the range used here.

Based on the emission data and costs tabled above, a scaling factor of 0.07 to 0.2 as derived earlier, and a currency conversion of €1 = $A1.65 (as previously noted) the health damage costs of Australian emissions shown in Table 23 are obtained.

Table 23 Estimates of Australian health damage costs for the three main power station emissions: coal

Emission	Rate kg/MWh	European Damage cost in $A/kg	Australian damage cost $A/MWh	Australian damage cost mid-range $A/MWh
PM_{10}	0.08 - 0.37 (0.21)*	41 – 119 (49)**	0.23 – 8.8	1.4
SO_2	1.0 – 4.9 (3.2)*	8.9 – 26 (17)+	0.62 - 25	7.6
NO_X	1.4 – 5.1 (2.5)*	6.9 – 18 (12) +	0.68 - 18	4.2
TOTAL			**1.6 - 52**	**13.2**

*Average for Australia
**Value for cluster
+Average of range

The wide ranges of calculated damage costs are the result of the products of the extremes of three ranges. The mid-range estimates in the last column are the products of the bracketed figures (mid-range or average estimates) and a single scaling factor of 0.14, which is also the middle of the range.

The mid-range for total health damage cost is thus $13.20/MWh. Despite the different scaling factors used in the two works, this is reasonably consistent with the corresponding figure from the CCSD report, $5.51/MWh.

KEY MESSAGE: For the main emissions PM_{10}, SO_2 and NO_X, the mid-range estimates of health damage costs of Australian coal-fired power stations are $1.40/MWh, $7.60/MWh and $4.20/MWh respectively. The mid-range total is $13.20/MWh. The large, cumulative uncertainties in the underlying calculations need to be kept in mind.

2.5 HEALTH DAMAGE COSTS OF AUSTRALIAN POWER STATIONS – GAS

Table 24 shows emissions from two Australian combined cycle gas power stations and the annual generation figure needed to determine emissions as a function of power generated.

Table 24 Emissions from Australian combined cycle gas turbine plants 2006-07

Gas Generator	Generation annual TWh	PM_{10} EMISSION kg/year	SO_2 EMISSION kg/year	NO_X EMISSION kg/year
Swanbank E (Qld)	2.3	54,000	1,400	240,000
Pelican Point (SA)	2.8	61,000	5,500	940,000

In Table 25 the emissions from these plants are expressed in terms of a unit of power generated. Table 25 also includes data for an unidentified Australian plant listed in a published compilation of power station data (World Energy Council 2004), obviously for an earlier year.

Table 25 Emission of PM_{10}, SO_2 and NO_X from Australian combined cycle gas turbine generating plants

Gas Generator	PM_{10} EMISSION kg /MWh	SO_2 EMISSION kg /MWh	NO_X EMISSION kg /MWh
Swanbank E (Qld)	0.023	0.006	0.10
Pelican Point (SA)	0.022	0.002	0.34
Australia*	Not given	0.001	1.4

* These figures are for a gas generator at an unidentified Australian site, referenced in WEC 2004

It can be seen that the figures for PM_{10} emissions per unit electricity, around 0.02 kg/MWh, are about 10 per cent of the Australian average of 0.21 kg/MWh for coal-fired electricity. The SO_2 emissions range from 0.03 per cent to 0.2 per cent of the typical figure for coal power, 3.2 kg/MWh. And the NO_X emissions range rather widely from four per cent to about 60 per cent of the representative Australian figure for coal, 2.5 kg/MWh.

It is clear that the total emissions and associated health damage costs associated with PM_{10}, SO_2 and NO_X emissions from these gas combined cycle plants are considerably less than for plants that burn coal. There are not enough data to determine a credible average figure, but it seems reasonable to take the Pelican Point Plant as representative. For that case, the external costs calculated as before are shown in Table 26. The calculation is based on the 'mid-range' unit damage costs for each emission and on a single scaling factor of 0.14, as used for coal plants, to transfer ExternE unit damage costs to Australia. This is clearly a very uncertain approximation, especially as the location of the Pelican Point plant is not even in the area used to arrive at the earlier scaling estimates.

Table 26 Estimates of health damage costs for emissions from the Pelican Point (South Australia) combined cycle gas turbine plant

Emission	Rate kg/MWh	Unit Australian Damage cost \$A/kg	Emission damage cost \$A/MWh
PM_{10}	0.022	6.7	0.15
SO_2	0.002	2.4	0.005
NO_X	0.34	1.7	0.58
TOTAL			**0.74**

The total damage cost of these emissions for this gas plant comes to about six per cent of the average costs, \$13.20/MWh, calculated above for coal-fired Australian generators. This relativity between gas and coal emission damage costs is consistent with ExternE results. For example, from the bar charts in Figures 4 and 5 European damage costs for direct power plant emissions of PM_{10}, SO_2 and NO_X can be extracted as follows: for lignite fuel, €34/MWh; for hard coal fuel, €17/MWh; and for natural gas fuel (combined cycle), €1.2/MWh. That is, the European cost using natural gas is 3.5 per cent of the cost using lignite and seven per cent of the hard coal cost. The Australian coal data used here included both brown and black coal, so a properly weighted average (around 35 per cent of the power in the sample of coal-fired power stations considered above came from brown coal) would bring the Australian and European relativities very close.

KEY MESSAGE: Emissions and their health damage costs for combined cycle gas turbine plants are significantly lower than for coal-fired generators. The total damage cost of PM_{10}, SO_2 and NO_X emissions for a representative plant comes to \$A0.74/MWh, only six per cent of the corresponding figure for coal.

2.6 DISCUSSION OF DAMAGE COST DATA FOR AUSTRALIAN POWER STATIONS

2.6.1 Findings – health and total external costs

The main findings here are that, with some simple assumptions, ExternE methodology for estimating health damage costs of emissions seems applicable to Australian power stations, and that reasonable relative cost estimates result when the methodology is used to scale down health damage in proportion to Australia's lower population density.

A sample of Australian coal-fired power stations yields a health damage cost of around $A13/MWh. The sample contains both brown and black coal generators and these have not been distinguished here. Analogous European power station costs are €34/MWh ($A56/MWh) for lignite and €17/MWh ($A28/MWh) for black coal. The lower Australian costs for coal are the resultant of somewhat higher emissions combined with lower health impacts due to Australia's lower population density.

Gas-fired power stations have significantly lower health impacts. For the representative power station examined here, the costs per unit generation are only six per cent of the costs for coal. Gas accounts for 16 per cent of Australian electricity generated from fossil fuels and coal (brown and black combined) 82 per cent (ABARE 2008A), so at present gas generators contribute only about one per cent to the total economic health burden of emissions from power generation in Australia.

These health damage findings can be combined with climate costs derived earlier in Australian dollar terms (Table 13) to give the total external costs (rounded to two significant figures) for Australian power stations in Table 27. Other technologies for which climate costs are shown in Table 13 but which are not significantly represented in Australia's generation capacity, are not included here because the health cost data are derived only from measured power stations emissions.

Table 27 Representative total externality costs (climate plus health) for Australian fossil-fuelled power stations

Technology	Fuel	Climate cost $A/MWh	Health cost $A/MWh	Total cost $A/MWh
Sub-critical, pulverised coal, new	Black coal	29	13	42
Sub-critical pulverised coal, new	Brown coal	39	13	52
NGCC	Natural gas	18	0.7	19

2.6.2 Issues

With health impact estimates of such significant magnitudes emerging from these calculations, the question must be asked as to how reliable they are. The many uncertainties in the process and the qualification concerning the absence of indicators of statistical uncertainty in the results have already been emphasised here several times. There are other issues to consider.

The assumption that the health impacts of the various emission components are additive is implicit in the above calculations. This is essentially the ExternE approach. However, questions have been raised as to the validity of adding these components and such a procedure may well overestimate the health effects (Amoako *et al* 2003).

Another fundamental issue is to do with the health impacts of emissions designated under the general category of particulate material PM_{10}. There is increasing recognition that the health impact of finer fractions such as $PM_{2.5}$ (particles less than 2.5μm) is greater than that of the remainder (World Health Organisation 2007). Particulate material will be differentiated on the basis of many characteristics such as particle origin, size, shape, chemical composition and surface area. Finer particles are known to penetrate into deeper areas of the lungs. Different health effects are only to be expected. However, at this stage the available data for power station emissions and their health costs relate only to the total PM_{10} fraction. The consideration of health impacts in this report therefore has to be limited to that category. Future work should no doubt consider later knowledge pertaining to such particles.

Also in regard to health impacts of fine particles, it should be noted that total reported PM_{10} emissions from the electricity generation industry comprise only some 3.4 per cent of the total such emissions, 1.2 million tonnes, from all sources within Australia, both man-made and natural (National Pollutant Inventory 2008). Mining (metalliferous and coal), controlled and uncontrolled burning, windblown dust and roads together account for over 25 times the PM_{10} emissions from power generation. Some of the other emissions sources will need to be included in future life cycle valuations of electricity externalities.

2.6.3 Reality checks

It would be useful to have some kind of independent test of the validity of the health costs derived in this report (and elsewhere).

The aggregated health cost burden of power station emissions can be derived from the estimates given above. With a mid-range health damage estimate of $13/MWh and the annualised coal-fired power output of 197 TWh, the annual health damage cost aggregated for Australia amounts to some $A2.6 billion. This should comprise the bulk of any health damage attributable to power generation. As it happens, this figure is quite similar to the 'gross economic burden' of health effects of traffic pollution in Australian capital cities reported by Amoako *et al* (2003), $A3.3 billion. The total health cost of these sources of air pollution would then be around $6 billion. This compares with the figure of €80 billion ($A132 billion at the exchange rate used in this report) referred to earlier for the aggregated air pollution health impacts of the electricity and transport sectors in Europe (di Valdalbero 2006). Europe has 25 times the population of Australia, so these numbers are about proportional to population. Some kind of difference due to population density or climate might have been expected.

To give the Australian figure another context, in 2006-07 Australia spent $94 billion on health (Australian Institute of Health and Welfare 2008).

The above-mentioned Australian traffic pollution study (Amoako *et al* 2003) concluded that the annual health impact included the cost of around 1200 pollution-induced deaths, which was considerably more than the number of direct motor accident fatalities, 740, in Australian capital cities in the relevant year (2000). Because the costs are similar, there is an implication that power station emissions produce a similar number of deaths, though there is no direct evidence for such a statistic.

These thought-provoking pieces of information might hold clues concerning the credibility of the various external cost estimates. Further analysis is outside the scope of the present study but could usefully be covered in further research.

KEY MESSAGE: ExternE methodology seems applicable to estimating health impacts of Australian power station emissions. Australian external costs per unit power are one-quarter to one-half of those in Europe. Total climate plus health costs for Australian power stations are $A19/MWh for natural gas, $A42/MWh for black coal and $A52/MWh for brown coal. Gas is confirmed as the cleanest of these fuels. The annual aggregated health cost from these estimates is $2.6 billion, not much different from estimates for health costs of traffic emissions in Australian capital cities. An independent method for judging the validity of the levels of health damage costs calculated here would be desirable.

3 Externalities of Some Prospective Energy Technologies in Australia

3.1 INTRODUCTION

This section deals with the externalities of selected energy technologies that are presently under development, or scrutiny, in relation to Australia's future electricity needs. The selected technologies are:

- wind;
- solar photovoltaic (PV);
- solar thermal;
- geothermal;
- carbon capture and storage; and
- nuclear.

There are other important technologies that must await extension of this kind of work.

Wind turbines are already in large-scale commercial use in Australia. Solar PV has some niche applications and the other technologies are the subject of significant developmental activities and/or public interest and debate.

The main aim here is to review the status of externality studies on these technologies and to identify any aspects of particular relevance to Australia.

Several of the technologies of interest have already been the subject of full life cycle assessments to establish CO_2 emissions. The report by the World Energy Council (2004) contains, as noted earlier, summaries of many such studies. The life cycle energy balance study conducted in Australia for the UMPNER Inquiry (the UMPNER/ISA Study (2006) referred to earlier) also includes much published data and its own analyses of LCAs. However, some technologies such as solar thermal and geothermal energy sources have not been well covered. Also, there are environmental impacts other than climate and health for these emerging technologies that merit further examination.

Wind, solar PV and solar thermal are intermittent sources of energy that need some form of additional energy storage if they are to provide continuous base load power. The following material does not include any externalities attributable to such energy storage, which should be the subject of further work.

KEY MESSAGE: Prospective technologies selected for detailed consideration of externalities are wind, solar photovoltaic, solar thermal, geothermal, carbon capture and storage, and nuclear. Full life cycle assessments for some of these technologies have been published.

3.2 WIND POWER

Wind power can be regarded as a mature renewable technology for electricity generation, with global installed capacity of 94,000 MW (World Wind Energy Association 2008). In Australia, where hydroelectricity has reached close to its full generating potential, wind power tends to be regarded as the only renewable technology ready for installation for meeting newly mandated, increased renewable energy targets. Indeed, as the Connell Wagner (2007) Report says, "*the emergent Australian wind industry has primarily resulted from the Mandatory Renewable Energy Target Scheme (MRET) introduced by the Federal Government in 2000*".

The installed Australian wind generating capacity was 818 MW in 2006 (ABARE 2008A), producing 1703 GWh, which because of the intermittent nature of wind energy is around 25 per cent of the maximum possible. Almost as much capacity was at or near the construction phase in late 2007, and sites with a further 4000 MW of wind potential had then been identified (Connell Wagner 2007).

As is well known, wind turbines themselves do not generate any greenhouse gases during their operation. However, there are still some external costs, as illustrated in Figures 4 and 6, which according to life cycle assessments (e.g. ISA, University of Sydney 2006, ExternE-Pol 2005) arise in stages of the energy chain other than the generation process itself, such as component manufacture and site construction works. Factors like the different lifetimes of the foundation structure, the tower and the grid connection all need to be considered in the LCA process (see for example ExternE-Pol 2005). In Europe, there is a trend towards off-shore wind installations and, as can be seen in the above figures, there are significant differences in external costs between on-shore and off-shore installations.

The dominance of non-generation externalities in LCA studies suggests that any contributions from the ongoing maintenance needs of the generators are negligible.

CO_2 emissions (that is GHG impacts) comprise only around 20 per cent of total wind power external costs (Figure 5). The UMPNER/ISA Study considered around 80 individual generators and arrived at an arithmetic average for CO_2 emissions of 27kg CO_2/MWh, a statistical range of 13 to 40kg CO_2/MWh, and a 'typical figure' of 21kg CO_2/MWh. The UMPNER Report took that last figure as a best estimate for the life cycle emissions of wind generators.

A similar range, around 7 to 14kg CO_2/MWh, is reported by the World Energy Council (2004).

As for monetary valuations, the ExternE project has estimated costs of external impacts of emissions attributable to the wind generation energy cycle (ExternE-Pol 2005). For onshore wind, external cost of emissions is €0.90/MWh, slightly less than for offshore wind, €1.20/MWh. At the currency conversion rate used here (€1 = $A1.65), the external costs for the two cases of wind power equate to $A1.50/MWh and $A2.00/MWh respectively.

As mentioned above, the GHG impact is only about 20 per cent of these costs, with health impacts comprising the remainder. The GHG impact depends on the carbon intensity of the electricity supply mix where manufacturing processes occur (ISA, University of Sydney 2006), which means that wind installations in Australia, where coal supplies the bulk of such energy, might have external costs at the higher end of the ranges quoted above. However, any more detailed local assessment will not change the low-emission status of wind power.

In Australia the main environmental issues raised about wind farm developments have tended to be visual intrusion, noise, and the potential to harm birds, especially rare species. These environmental impacts are not included in the above valuations, though some have been evaluated in ExternE work. Even when such valuations are accounted for, most wind farms still very low overall impacts, in part because they have been intentionally sited far from population centres or at sites of reduced environmental values (ExternE 1999).

KEY MESSAGE: Wind power has low life cycle greenhouse gas emissions, with various published estimates in the range 7 to 40kg CO_2/MWh. External cost estimates, including health impacts, for European onshore wind power installations equate to around $A1.50/MWh. Actual costs for Australia, where most of the energy for manufacture and construction comes from coal, may be at the high end of estimates, but wind energy's low emission status will be unaffected.

While these kinds of environmental impacts are site-specific and therefore not directly suited for drawing generalisations, the ExternE approach does give some useful indicators as to how any future Australian studies aimed at evaluating wind energy impacts might be conducted. The following is an example of work conducted on wind generators in Germany (ExternE 1999).

The study involved the Nordfriesland Windpark in Schleswig-Holstein, which comprises 51 turbines rated at 250 kW.

Noise: Noise arises aerodynamically (interaction of blades with air) and mechanically (moving parts in the generator). The number of residents affected was 219 from 70 households, including 48 farms and one restaurant. Sound level measurements showed that 57 households were affected by an increase between 0.5 and 1.5 dB, 6 households by an increase between 1.5 and 2.5 dB, and 7 households by an increase between 2.5 and 3.5 dB. Results for willingness to pay (WTP) of 1.97 DM (= 1.02 ECU) per month for a noise reduction of one dB were taken from prior work on the monetary value of disbenefits caused by traffic noise (Rennings 1995). This corresponds to a change in property values of around one per cent per dB.

Expressed as WTP, this is about 0.89 DM (=0.46 ECU) per dB per person-month. The calculated damage cost based on these figures is 0.064 mECU per kWh, which equates to about €0.064/MWh in current terminology.

Visual intrusion: Wind farms tend to be built in open countryside and are therefore visible over long distances. There appears to be a dearth of valuation studies for the cost of such impacts. ExternE work has used data from willingness-to-pay studies for 'intact countryside' for the purpose of vacations. Based on a 2 km zone around the wind farm, ExternE arrived at a figure of 0 to 0.6 mECU per kWh, with a best estimate of 0.06 mECU per kWh (€0.06/MWh). Later ExternE work (2005 Update) suggests that a more recent study on willingness to pay for less intrusive transmission tower designs (Atkinson *et al* 2004) might be useful for pricing visual intrusion by wind farms but on the whole there is little information on which to base the value of loss of visual amenity.

Effect on bird life: The ExternE work concluded that the impact of the particular German wind farm on bird life was negligible but that it could be significant of there were a large bird population or where there was a bird migratory route across the site.

In summary, the ExternE costings of external impacts of wind farms in the German example chosen are as follows (ExternE 1999):

Noise (power generation) €0.064/MWh
Visual impact (power generation) €0.06/MWh
Human health (other fuel cycle stages) €0.31/MWh
Climate impact (other fuel cycle stages) €0.03–1.0/MWh

Noise and visual impact therefore add €0.124/MWh (about $A0.2/MWh) to the $A1.50/MWh quoted above.

Other impacts: There are other impacts of wind power not costed in the above. These include changes in land values for reasons other than noise, and effects of extended transmission lines on amenity and biodiversity.

For the case of off-shore wind farms, the list of potential impacts is somewhat different and includes (NEEDS 2008A):

- collision risk to birds;
- barrier for migrating or feeding birds;
- physical loss of habitat for birds, since the turbines may occupy an area with food resources;
- impact on marine mammals because of the physical presence of the wind turbines and the effects of construction activity, in particular the noise generated by pile driving. Underwater noise during the operation of turbines is another factor that can affect marine mammals; and
- a wind farm may function as an artificial reef and act as a sanctuary for threatened species and create improved food resources for fish (a positive impact).

There seems to be limited progress on attaching monetary values to these impacts. However, they are at this stage not relevant to Australia, which has no offshore wind generation.

So, evaluation of impacts of wind farms leads to small economic values. Nevertheless wind farm proposals still encounter opposition from local communities in Australia. In this respect Australia is not unique. The NEEDS (2008A) Report points out that there are often objections early in the planning stages but these generally give way to acceptance as the public focuses on the positive elements of the situation, in particular the perceived environmental friendliness of wind power.

> "A Danish survey of public attitude towards offshore wind farms one or two years after their construction shows that most protests are against wind farms situated close to the shore, and thus visible from the shore. At the same time, the survey also shows that people in areas with offshore wind farms nearby in fact are more positive towards wind farms, than people in a randomly selected group of the Danish population. However, this is the people's opinion after the establishment of wind farms, when the local population has learned to live with the wind farm or has experienced that the impacts are not as considerable as they feared."

The question still remains as to whether the economic tools being used for quantifying, in monetary terms, the environmental values that individuals feel are being damaged have any bearing in the public debate. It would follow that their present usefulness in public policy setting is questionable.

KEY MESSAGE: Certain less tangible impacts of wind energy on amenity have been valued in ExternE work. In total, such monetary valuations amount to only about 15 per cent of the climate and human health impacts. The strength of opposition to wind farms on environmental grounds seems inconsistent with the results of monetary valuation techniques.

3.3 SOLAR PHOTOVOLTAIC

The direct conversion of solar energy to electricity by photovoltaic (PV) devices is a well-established technology, in limited application (in terms of total power generated) in Australia, mainly for decentralised power generation at the level of individual residences or community groups. It is presently one of the more expensive energy conversion technologies. Connell Wagner (2007) quotes capital costs of the order of $12,000/kW and power costs of $250 to $400/MWh. The ATSE report referred to earlier (ATSE 2008A) estimates solar PV capital costs at $5,000/kW by 2020 and $2,000/kW by 2050, consistent with claims of proponents of solar PV technology that the downward cost trajectory will make it suited to base load power generation before too long. However, solar PV was not included in the Connell Wagner list of technologies that could be used for NSW base load power in 2013-14.

While solar PV is presently restricted to niche applications, the technology is of sufficient long-term interest for its externalities to be considered here.

Emissions related to solar PV technology mainly arise in the pre-generation stages – during raw materials extraction, transport, manufacture, construction etc. The figures tend to be site-specific and country-specific, depending greatly on the prevailing source of energy used in those stages.

The compilation carried out by the World Energy Council (2004) shows a wide range of CO_2 emissions, from a low of 12.5 kg/MWh to a high of 104 kg/MWh. Data for individual European generators in the 1 kW to 13 kW range are clustered around 43 to 55 kg/MWh (WEC 2004, Table 6.2). The UMPNER/ISA Study quotes somewhat higher results, with a range of 53 to 217 kg/MWh and a 'typical value' of 106 kg/MWh. The latter figure was adopted in the UMPNER Report as a 'best estimate' for the CO_2 emissions from a 100 MW nominal solar PV installation.

The UMPNER/ISA Study (2006) also referred to a prior CCSD Case study (2000) of life cycle CO_2 emissions from the 400 kW solar farm located at Singleton NSW. The CCSD study arrived at an emissions figure of 29 kg/MWh, based on a capacity factor of 14 per cent and a 30-year lifetime. This figure is reasonably consistent with the range give in the WEC compilation.

On the basis of the UMPNER/ISA typical figure for life cycle CO_2 emissions of 106 kg/MWh and a damage cost of $A31/t CO_2, the external cost amounts to $A3.30/MWh. According to the WEC 2004 compilation, greenhouse damage costs for solar PV comprise around 40 per cent of the total. So if other life cycle emissions are included the total solar PV damage cost becomes about $A5/MWh.

ExternE arrived at estimates of €2/MWh to €4/MWh (that is $A3.30/MWh to $A6.60/MWh) for the external costs associated with PV emissions (ExternE-Pol 2005). The main determinant of cost was the location of the manufacturing operations, reflecting the energy mix and associated emissions used at those locations.

So, the Australian-based estimates and those from ExternE are in reasonable agreement. Of course they are based on some common data, especially in regard to life cycle emissions and specific damage costs. These results ought to be applicable to solar PV generation in Australia, though it would be useful to have some confirmation through specific Australian life cycle assessments.

KEY MESSAGE: Life cycle CO_2 emissions for solar PV systems amount to 106 kg/MWh, yielding a climate impact cost of $A3.30/MWh. With other life cycle emissions included the total solar PV damage cost comes to about $A5/MWh.

In order to make a significant impact on Australia's total electrical energy needs, solar PV installations, whether on rooftops or solar farms, will cover large areas. Some idea of the areas involved can be obtained by reference to works aimed at determining the potential electrical energy contribution obtainable from building-mounted solar PV installations, for example International Energy Agency (2002), NEEDS (2005). For Australia the total roof area of 422 km^2 could, according to such calculations, supply 46 per cent of its electricity.

The recent ATSE report on the investment requirements for accelerating Australia's technology response to carbon emission reductions (ATSE 2008A) used scenarios with various electrical energy contributions from different generating technologies. One scenario for a 50 per cent reduction in CO_2 emissions by 2050 called for 10 per cent of the supply coming from solar PV. According to the above estimates, and ignoring the increase in power consumption over the period, that contribution would need solar PV collectors of area equivalent to over 20 per cent of Australian roofs.

The above estimates suggest that the installation of solar PV electricity at levels needed to meet emission reduction targets would require major new industrial activity. The resource supply chain involved in the required level of manufacture and construction, including transmission and possible energy storage requirements, could create some as yet unquantifiedexternal impacts.

3.4 SOLAR THERMAL

Solar thermal generation uses solar radiation, generally concentrated by some form of optical concentrator such as mirrors, so as to allow temperatures to be reached capable of heating a working fluid and, usually, generating steam to drive an electrical generator.

There are many different designs of concentrators, tracking systems, heat collectors and generators, all aimed at maximising the efficiency of collection and optimising costs. Designs include parabolic troughs, linear Fresnel collectors, solar thermal towers with a tracking array of heliostats, and solar dish systems. Key parameters are the fraction of incident solar heat that is collected and the efficiency of the generation stage. For continuous base load power, some form of energy storage is also needed. Various storage systems have been tried, including molten salts, concrete, and phase change materials.

There is a further design, the solar updraft tower or solar chimney, in which hot air generated under a circular translucent roof rises through a central chimney, driving pressure staged turbines to generate electricity. A 50 kW version has been trialled in Spain while a 200 MW concept has been promoted in Australia (www.enviromission.com.au/IRM/content/home.html).

Solar thermal stations can be standalone or integrated with a conventional power generator in such a way that the irregular solar output supplements the continuous power station and allows reduction in greenhouse emissions.

Connell Wagner (2007) quotes solar thermal power costs in the range $170 to $210/MWh, with recent improvements cutting the lower limit to $120/MWh and prospects for further decreases as technology and knowledge improve. Capital costs are around $3000/kW under American conditions. Other ATSE work (ATSE 2008A) estimates the same capital cost in Australia for 2020 and $2,000/kW by 2050. For further details of the various solar thermal systems, the Connell Wagner report is a good source of information.

The largest solar thermal plant built so far is the Solar Energy Generating Systems (SEGS), in California's Mojave Desert. Rated at 354 MW, it uses parabolic trough collectors (www.nexteraenergyresources.com/). SEGS is actually a series of nine connected solar steam-generator power plants constructed at different times between 1984 and 1991. They are said to have been providing clean and relatively maintenance free energy since then. The combined power stations use over one million mirrors and cover an area of approximately 6.4 km^2. Individual turbine capacity ranges from 14 to 80 MW.

This Californian site has sunshine for 340 days a year, with direct normal radiation averaging around 7kWh/m^2/day (620 W/m^2, 12 hours daily). Photographs of the arrays of collectors indicate that they occupy around one-third of the total land area, allowing for adequate access and maintenance.

In Australia, the company Solar Heat and Power is promoting its compact linear Fresnel reflector (CLFR) design claimed to produce the world's lowest cost large-scale solar concentrators. The technology has been installed at the Liddell power station to provide preheated boiler feed water.

Like other renewable technologies, there are no emissions directly due to the operation of the solar thermal power station itself. Emissions all arise in the pre-generation stages, just as with solar PV technologies.

The ExternE project has not published externality valuations for solar thermal generation. The potential for solar thermal in Europe is restricted to Mediterranean countries and presumably this limitation imposed a lower priority for ExternE attention. However, solar thermal emissions have been subjected to full life cycle assessment (NEEDS 2008B). The results show life cycle CO_2 emissions at around 30 kg/MWh. This is about one third of the figure adopted above for evaluating external costs for solar PV (106 kg/MWh), but is just below the cluster of European figures for solar PV quoted earlier from the WEC study.

While there are some uncertainties, it is reasonable to conclude that solar thermal and solar PV have similar external costs caused by emissions generated in the materials and construction stages. This conclusion puts the external costs of solar thermal at around $A3 to $A7/MWh, consistent with other conclusions that solar thermal external costs would be only a small fraction of the total cost of this form of solar power.

KEY MESSAGE: Externalities associated with solar thermal systems all arise in the pre-generation stages, just as with solar PV. Life cycle CO_2 emissions for solar thermal systems are about 30 kg/MWh and total external costs $A3 to $A7/MWh, similar to solar PV generation.

Certain other potential environmental impacts of solar thermal technologies have been noted. For example, the Connell Wagner report mentions water usage and occupation of large land areas. According to Connell Wagner, water requirements are similar to conventional fossil fuel plants. Also, dry cooling can be substituted for water cooling. Life cycle materials flow analysis for solar thermal power published by NEEDS (2008B) indicates that annual operating water requirements range from 10 to 20 ML per MW capacity. On that basis solar thermal power stations with a nominal 10 per cent of Australian capacity (4.5GW) would consume about 45 GL to 90 GL of water per annum.

As for land requirements, the impact of biofuels on global food prices is a reminder that any major change in land usage need to be considered for its possible impacts on markets and possible associated externalities. Land requirements for solar thermal are certainly large. There are several sources for basing estimates of the required areas.

Using the SEGS plant as the base case for a calculation, the 354 MW power station occupies 6.4 km^2. Australia's present generating capacity is 45 GW. So, on that basis, to create for example, solar thermal power stations with a modest 10 per cent of Australian capacity (4.5 GW) would require an area of around 80 km^2. But solar power stations actually need to have generating capacities four or five times that of present base load generators if they are to replace electrical energy rather than power (ATSE 2008A). This is because solar generation is intermittent. Hence, solar power stations capable of supplying 4.5 GW could replace, say, 2.5 per cent of Australia's electrical energy needs. To replace 10 per cent of those needs would therefore require an area of about 320 km^2.

The annual output of the Californian SEGS operation (Price 2007) is around 650,000 MWh. On that basis, it would need around 34 SEGS plants to replace 10 per cent of Australia's total annual generation of 220 TWh. The land occupied would then be 218 km^2, in reasonable agreement with the above estimate because it is based on the energy output of a solar power station rather than its power rating.

Another source for estimating solar land requirements is the Connell Wagner 2007 report. Their estimate is that the area needed to supply an electrical output equivalent to a typical NSW 660 MW coal-fired generator is 49 km^2. On that basis, 10 per cent of the energy output from Australia's 45 GW generating capacity would need a solar farm of some 334 km^2.

Finally, the 46 MW Andasol I parabolic trough solar farm in Spain occupies 2.225 km^2 (NEEDS 2008B). At this scale, 98 such plants would be needed to supply 10 per cent of Australia's 45 GW generating capacity and these would occupy 218 km^2. The area would be about four times larger, say 870 km^2, to supply 10 per cent of Australia's electrical energy needs.

Further work would be needed to clarify the above differences but it seems clear that with current technology a large scale solar thermal farm takes up at least 0.05 km^2 for each MW of generating capacity. As the latest technologies, such as the CLFR design, claim greater efficiencies and hence smaller area requirements than existing plants like SEGS, there seems little point in delving any further at present into the precise area requirements of solar thermal plants.

However, there is enough information to be able to address the question of whether the occupation by solar plants of land areas of these magnitudes has any significant external impacts. The common claim by solar proponents is that the area needed to generate solar power is insignificant in a country the size of Australia. The above calculations support that claim. In Australia the withdrawal of land due to introduction of large scale solar energy technologies would in itself have no major external impact.

Nevertheless, the moderately intensive development of large land areas that amount in the above sample case (10 per cent of Australia's present generating capacity or 2.5 per cent of its electrical energy consumption) to around 10 per cent of Sydney's metropolitan area does raise the issue of whether construction of solar power stations and associated infrastructure would produce stresses on the supply chain (other than land availability) that could have adverse consequences in other parts of the economy, analogous to the biofuel experience. This question is examined briefly here.

According to the recent NEEDS report on solar thermal technologies (2008B), the major materials, in terms of quantities, used in the above-mentioned 46 MW Spanish solar thermal plant were 56,027 tonnes of concrete, 16,596 tonnes of reinforcing steel and 1995 tonnes of organic heat transfer fluid *Therminol VP-1,* which comprises 73.5 per cent diphenyl oxide and 26.5 per cent biphenyl. If these quantities are typical, then the construction of 4.5 GW of solar thermal plants to provide around 2.5 per cent of Australia's electricity needs would consume around 5.5 million tonnes of concrete (1,200 t/MW), 1.6 million tonnes of reinforcing steel (360 t/MW) and 195,000 tonnes of organic heat transfer fluid.

Australian concrete production (Australian Bureau of Statistics 2008B) is around 27 million m^3 (about 60 million tonnes) per annum and reinforcing steel around 800,000 tonnes per annum (Australian Steel Institute 2006). On the face of it, concrete production should easily cope with the increased demand from solar power plant construction at this kind of scale but the steel market might be perturbed. The impact of the large quantity of organic heat transfer fluid is unknown. There are many other inputs to the solar thermal supply chain and these probably should be examined in detail to see how increases in demand might impact on the overall market.

In summary, the impacts on supply chains involved in major construction activities for solar power stations could in some cases be significant. These will largely be market impacts but there may be some associated externalities. More consideration of these is justified.

In order to maximise solar radiation, it has often been proposed that solar power stations would be located in northern regions of Australia, in general distant from consumers. This isolation means long transmission lines, with potential impacts where they traverse sensitive environments. Such impacts would be in addition to technical concerns about power losses over long transmission distances.

KEY MESSAGE: On current performance data, solar thermal power stations need 10 to 20 ML of water, 0.05 km^2 of land, 1200 tonnes of concrete and 360 tonnes of steel for each MW of generating capacity. The potential externalities associated with some of these large inputs merit further examination.

3.5 GEOTHERMAL ENERGY

An extensive MIT (Massachusetts Institute of Technology) review on the Future of Geothermal Energy (MIT 2006) provides a thorough description and analysis, including environmental impacts, of the subject of geothermal energy. The brief comments below are intended as a context for considering the associated externalities. They are based on the MIT review as well as other references noted below.

Geothermal energy is heat energy contained in Earth and potentially exploitable for use. Earth's crust is around 30 km deep and its temperature ranges from 15˚C near the surface to 540˚C near the base of the crust. Most of the heat is generated from the radioactive decay of potassium, thorium and uranium isotopes present in the crust as well as the mantle and core. There may also be a contribution from the residual primary heat contained in the planet via the mechanism of its formation, such as the collision of rocky asteroids. It is now generally accepted that the radioactive decay mechanism is what has kept Earth from cooling to become a sterile lifeless planet.

As is well known, in some volcanically active areas hot groundwater naturally reaches the surface, or near-surface regions, and can be exploited directly as a source of energy for generating electricity or heating buildings. Such 'conventional geothermal (or hydrothermal) systems' are already in use and account for about 0.5 per cent of electrical energy worldwide (Etheridge 2007).

Far greater quantities of heat energy are contained at depths of several kilometres. In favourable geological formations, these resources are considered exploitable with existing technology. When tapped, these heat sources are called Hot Dry Rocks (HDR) or Engineered (or Enhanced) Geothermal Systems (EGS). EGS is now regarded by the technical community as the correct terminology.

Because such heat sources are in principle large enough to make an impact on reducing the usage of fossil fuels, they are presently the subject of major investment and development activity, especially in Australia. According to Geoscience Australia (2007), 29 companies had applied for geothermal exploration licences in Australia as at August 2007.

While EGS is considered by many to be a highly prospective technology, it is yet to be commercially exploited, though geothermal energy promoters claim that technical barriers have been reduced or eliminated. According to Etheridge (2007) none of the EGS projects had, in 2007 at least, met the criteria needed to prove long term heat recovery and power generation. However, more recently there is news that EGS projects at Soultz in France and Landau in Germany have begun to generate power (Garnish 2008). Given the timelines published by the main developers (e.g. Geodynamics plan to operate a 50 MW generator by 2012 – see Geodynamics 2008) and the imminent introduction in

Australia of economic incentives for low-carbon energy, it should soon be possible to see these claims substantiated here.

The main technical uncertainties are:

- estimating the heat resource properly;
- risks associated with deep drilling of large bore holes;
- producing and maintaining fractured reservoirs capable of high flow rates over long periods of time; and
- efficient conversion of extracted heat energy to electricity.

Heat resource estimation is analogous to the estimation of conventional mineral resources and deposits. That is, there needs to be sufficient exploratory drilling to define the limits of the resource and its properties, which include temperature and geotechnical properties such as fractures and amenability to further fracture stimulation. Because a hot rock resource is likely to have fewer 'grade' discontinuities than typical mineral deposits, where grades can change dramatically over a few metres, geothermal resource estimation may well need fewer boreholes. On the downside, the boreholes are much deeper and more expensive than is common in mineral exploration. Geoscience Australia (2008) is increasing its efforts at enhancing the knowledge base about geothermal resources, collecting new heat flow data across Australia and mapping resource characteristics.

The boreholes needed to circulate the hot fluids are large and deep, with a diameter up to 311 mm and depths of 4 to 5 km (see e.g. the Geodynamics website www.geodynamics.com.au). The risks and high costs associated with such boreholes have already been demonstrated in recent development work carried out in Australia (see Geodynamics progress reports on its website).

Managing the heat reservoir by creating/stimulating and maintaining fracture zones of the required properties is likely to be the largest uncertainty or risk in commercial development of geothermal energy. Hot water must flow between the input and production wells at consistent temperatures and at rates of the order of thousands of litres per second (in total for a production field, less for an individual pair of wells) for periods of several years. These specifications make heavy demands on the properties where effective fracture apertures, of the order of 1 mm, need to be maintained. The zones are subject to changes in the stress fields and chemical conditions. Apertures might open up to allow short circuits or close through leaching and precipitation processes, causing a fall in flow rates.

The efficiency of conversion of geothermal energy to electricity is quite low because of the relatively low temperature of the hot fluid compared with the upper temperature limit of conventional power generators. Geoscience Australia suggests efficiencies in the range 10 to 20 per cent. The MIT report uses a different measure, the utilisation efficiency, which is the ratio of power produced to the maximum theoretical power. Practical systems show utilisation efficiencies of 25 per cent to 50 per cent, according to MIT, but these need to be adjusted for the maximum Carnot efficiency, which at a working temperature range between 250˚C and say 50˚C is 38 per cent. So these sources are consistent; some 10 to 20 per cent of the heat energy contained in hot water emerging from a geothermal well can ultimately be transformed into as electricity. Correspondingly, some 80 to 90 per cent of the heat reaching the surface will be released into the environment, most via the cooling system associated with the generating equipment.

KEY MESSAGE: Geothermal energy is the subject of major investment and development activity in Australia. A geothermal power station calls for hot water flows of the order of thousands of litres per second in production wells several kilometres deep, at consistent temperatures for periods lasting several years. There are several technical risks still to be overcome in reaching such goals.

Externalities

As with the other renewable discussed here, there are no CO_2 emissions directly connected with geothermal power generation. Greenhouse and health damage costs all arise in the pre-generation stages. There do not appear to be any quantitative data from life cycle assessments, but it is likely that such data would show the external costs of geothermal energy to be at the low end of the scale, similar to other renewables.

The MIT review concludes that geothermal energy is an environmentally benign source, with no greenhouse emissions during operations, modest use of land (7460 m^2/MW, compared with its closest rival, 10,000 m^2/MW for nuclear power), low visual profile, and good amenability to site restoration. The Geothermal Energy Association has recently issued A Guide to Geothermal Energy and the Environment (Kagel *et al* 2007), which presents a similar point of view.

Both of the above publications canvass some potential impacts that could arouse concerns about environmental costs. The MIT report (2006, Chapter 8) provides a comprehensive list, which is repeated below for completeness, together with comments on the specific relevance to Australia:

- gaseous emissions – hydrothermal systems often do contain objectionable concentrations of hydrogen sulphide that needs treatment. The hot water emanating from EGS is unlikely to contain significant amounts of hydrogen sulphide;
- water pollution – there will inevitably be some waste water generated in the geothermal energy production process and this will contain dissolved and suspended solids that might present minor problems for discharge into the environment. Such problems are unlikely to be significant in the Australian context, where geothermal plants are situated in remote dry regions;
- noise pollution – once again the remote locations of these plants mean that the normal industrial noise levels being generated are unlikely to create an environmental issue;
- land usage – the geothermal plant itself is claimed (see above figures) to have the lowest land use requirement of all the important generating technologies, including conventional fossil fuel plants (MIT report), especially when open cut coal mining (or strip mining) as the fuel source is included in the calculations. For the kinds and locations of geothermal plants envisaged for Australia, land use is unlikely to provoke environmental concerns;
- land subsidence – there were reports of subsidence in the early history of hydrothermal systems in New Zealand but the newer methods of reservoir pressurisation and the much deeper EGS systems in mainly granitic rocks mean that subsidence is not considered a significant risk;
- induced seismicity – seismic events that accompany the fracture stimulation process or that occur subsequently due to movement in the sheared rocks have been of concern to some geothermal project developers. Most such events are small, a few are large enough to be felt at the surface and an occasional seismic event, such as occurred at Basel, Switzerland in December 2006, attracts negative publicity. The largest event at Basel measured 3.4 on the Richter scale and triggered claims for building damage. However the circumstances in Basel, where the drilling rig sits in close proximity to urban buildings (see for example MSNBC 2007), are quite different from Australian prospective geothermal sites;
- induced landslides – according to the MIT review, there have been instances of landslides at geothermal fields, but these tend to be located in rugged terrain already prone to natural landslides. The risk seems irrelevant to Australian geothermal projects;
- water requirements – water is needed at many stages of geothermal development and operation. Also, water may be lost to surrounding rock during operation. Drilling, stimulation of the reservoir and operation of the fluid heat transfer system need an external water supply. Water cooling is preferred for the heat rejection stage of power generation. Air cooling can be used but results in lower efficiency and higher costs (see MIT 2006). The need for careful management of water for geothermal projects in arid areas of the USA is acknowledged and the same will apply in Australia.

For example, at the kind of flow rate needed for a 50 MW plant, say, one cubic metre per second, the loss of only one per cent of water into surrounding rock would amount to 864,000 litres/day, a significant amount in arid regions;
- disturbance of habitat and scenery – these are possibilities but unlikely in the Australian context. Geothermal plants have a low profile and are less conspicuous than most other energy conversion operations;
- catastrophic events – accidents such as well blowouts, ruptured steam pipes, generating equipment failures, plant fires and so on are possibilities, but they are not unique to geothermal projects and are unlikely to attract concern; and
- Thermal pollution – as already mentioned, geothermal energy inevitably produces large amounts of waste heat. Cooling systems can be around five times larger than for conventional power plants of the same electrical output. The isolated location of Australian operations means that heat dissipation is unlikely to be of concern.

Not mentioned in the MIT list is the potentially sensitive matter of radioactivity connected with geothermal operations. Because geothermal heat originates mainly from radioactive decay processes, concerns are sometimes raised that the circulating hot water will carry and release radioactivity. Geodynamics Pty Ltd has specifically addressed this issue (Geodynamics 2005), citing European geothermal studies to show that such concerns are without basis.

There is also the matter of the potential environmental impact of long power lines, as mentioned in connection with solar power. Most of the current Australian geothermal projects are located in regions remote from the main centres of population and industry, and the available thermal maps (see e.g. Budd 2007) suggest that most of the prospective geothermal regions are also remote. Recent work claims that Tasmania contains prospective regions not shown on earlier maps (KUTh Energy Ltd 2008). Presumably transmission costs and perhaps externalities will influence support for geothermal projects more favourably located in relation to existing grids or to centres of power consumption such as mine sites.

KEY MESSAGE: Like other renewables, geothermal power has no direct CO_2 emissions. Greenhouse and health damage costs all arise at pre-generation stages. No life cycle assessments are available but external costs of geothermal energy are likely to be at the low end of the scale. Of the potential impacts identified in other reviews, including gaseous emissions, water or noise pollution, land or water usage, subsidence or landslides, induced seismicity (a problem at one urban site in Switzerland), or thermal pollution, only water usage is likely to be of concern in the Australian context. Also, favourable geothermal areas are far from Australian cities and long powerlines might create environmental costs.

3.6 CARBON CAPTURE AND STORAGE

Principles

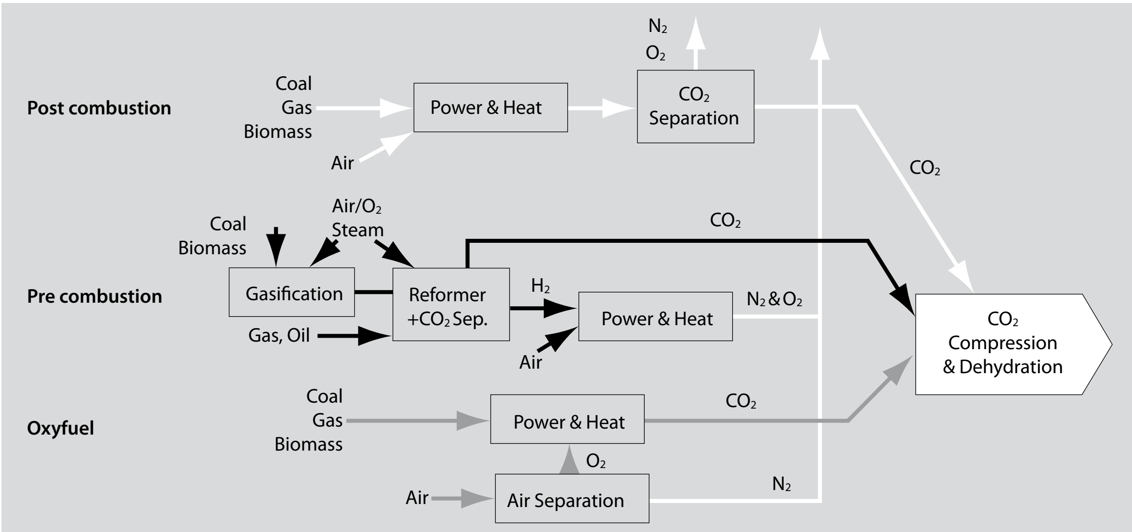
Carbon capture and storage (CCS) comprises a group of generic technologies for reducing carbon dioxide emissions, intended for use in conjunction with a range of fossil-fuelled energy conversion technologies. As such, CCS is worth separate consideration here in relation to the potential associated externalities.

There are many informative reviews of the various aspects of CCS technologies, including:

- capturing CO_2 – www.ieagreen.org.uk/glossies/CO2capture.pdf;
- storing CO_2 underground – www.ieagreen.org.uk/glossies/storingCO2.pdf;
- geologic storage of carbon dioxide – www.ieagreen.org.uk/glossies/geostoragesfty.pdf;
- chapter 'Review of carbon capture technologies' in Connell Wagner 2007; and
- 'The Future of Coal', MIT 2007 – http://web.mit.edu/coal/The_Future_of_Coal.pdf.

Figure 8 provides a useful overview of the various CO_2 capture processes and systems. It is taken from a report on recent studies of electricity costs prepared for UMPNER (EPRI 2006).

Figure 8 Overview of CO_2 capture processes and systems



All of the various approaches to CCS comprise the three stages of capture, transport and storage of CO_2.

The capture processes aim to extract, in as concentrated form as possible, the CO_2 generated by fossil fuel combustion. When fuels are burnt in air, the accompanying nitrogen passes unchanged through the process and becomes an expensive diluent that must be handled and pumped along with the target of the process, CO_2. The volume of untreated gases emitted from the flue of a base-load power station is very large indeed. According to Connell Wagner (2007), a typical coal-fired power station operating at its rated capacity of 660 MW produces flue gas at the rate of 900 to 950 m^3/sec. The CO_2 content of these streams can range from 3 to 15 per cent. Much of the development effort for CCS aims at increasing the CO_2 content of the combustion products and thereby reducing the cost of the CCS process.

Methods classed as 'post-combustion' are those that extract the relatively dilute CO_2 from flue gases emitted from conventional power generation. They are generally claimed to be amenable to retrofitting to existing generators.

Several extraction methods are proposed:

- chemical absorption, where the CO_2 is selectively dissolved in a solvent with appropriate properties;
- cryogenics, where the relatively high boiling point of CO_2 is exploited in a selective liquefaction process; and
- membrane technology, which aims to separate the CO_2 from other gases in the effluent stream by harnessing selective 'filtering' properties of certain polymer membranes.

Each method requires some process for recovering the concentrated CO_2, which is then cooled, dried and compressed for transport. Chemical absorption, in chilled ammonia, monoethanolamine or other amines, seems to be the presently favoured method.

The second class of CCS technologies, oxyfuel methods, involve replacing air for the combustion process with oxygen or oxygen-enriched air, containing 95 to 99 per cent oxygen, mixed with recycled flue gas. Reducing the proportion of nitrogen in the combustion gas stream lowers the costs of CO_2 separation from a flue gas stream that contains around 80 per cent CO_2 and 20 per cent water vapour.

The third concentration method employs so-called 'pre-combustion' processing systems in which the raw fuel is first processed chemically by gasification and steam treatment, converting it to hydrogen and CO_2. After a separation process, hydrogen-rich gas is fed to a combined cycle generating plant.

In the disposal option presently favoured in Australia (see for example CO2CRC, CRC for Greenhouse Gas Technologies 2008A), after any of these concentration and separation processes, the CO_2 stream is transported to a disposal site where it is stored underground. The favoured transport option is by pipeline, though shipping is a possibility in some circumstances. Underground storage requires porous rock structures at a depth of at least 800 metres, overlain with impervious rock strata. These are the typical characteristics of oil or gas-bearing rocks, so depleted oil or gas fields are considered ideal for the purpose of CO_2 disposal. Deep saline aquifers and some deep coal seams are also suitable, and deep ocean disposal is another suggested option, though environmentally problematic. The advantages, disadvantages and costs of these options are discussed at greater length in the references cited above.

Compared with present generating technologies, all of the CCS technologies use additional fuel and consume a greater proportion of the energy output. These energy and associated cost penalties affect externalities, as shown below.

Commercial Development

CCS is an emerging technology. It is not in commercial use as a greenhouse gas reduction method for coal-fired power generation. However, as its proponents point out, all of the various steps in proposed CCS processes are technically well advanced or are actually in use in the oil and gas industries, though at a much smaller scale than would be required to make a significant impact on emissions. Post-combustion capture and oxy-firing technologies for coal-fired power plants are in pilot or demonstration at a number of sites world-wide. There are at least four full-scale first-of-a-kind coal-fired IGCC plants in operation. A large-scale storage trial is in progress in Victoria (CRC for Greenhouse Gas Technologies 2008B). Commercial feasibility for use with commercial generators will depend on the success of scaling these processes up to the demands of large generation plants, on integration of process stages in combustion and CO_2 capture, and on the performance of large scale geologic storage facilities.

External costs of emissions

The direct emissions of CO_2 from generators with CCS are by definition lower than conventional plants but a proper insight requires full life cycle assessments.

The study published by the World Energy Council (2004) quotes three reports of model life cycle assessments of CCS processes. In one, a hypothetical US coal-fired plant with CO_2 sequestration, 90 per cent of the CO_2 is captured from flue gas by chemical absorption and is transported by a 300 km pipeline into an underground disposal site. In another, a hypothetical Australian plant with IGCC and carbon dioxide recovery, 90 per cent of the CO_2 is captured, compressed and disposed of in deep sea aquifers. In the third, a hypothetical US natural gas combined cycle plant with CO_2 removal and storage is modelled. The 90 per cent capture figure used in the models is generally considered to be the upper bound for what might be economic to capture, though higher fractions could be technically achievable.

The results of these three case studies (all hypothetical) are shown in Table 28.

Table 28 Life cycle emissions from hypothetical generation plants with carbon capture and storage (from WEC 2004)

Fuel	Process	CO_2 kg/MWh	SO_2 kg/MWh	NO_x kg/MWh	PM_{10} kg/MWh
Coal 600 MW	Post-comb. CCS	247	-	-	-
Coal 1000 MW	IGCC - CCS	130	0.15	0.81	0.028
Gas 600 MW	NGCC - CCS	245	-	-	-

Depending on the case, the life cycle CO_2 emissions with CCS equate to about 15 to 40 per cent of those for conventional generators. The highest of these figures (40 per cent) is for CCS with natural gas fuel, where the proportionate benefits are least. Note that these fractions are considerably higher than the 10 per cent that might be expected from the assumed 90 per cent direct capture rate, because of the additional fuel and energy consumed in the overall process.

With regard to other emissions, there is only one example in Table 28 where other gas and particulate emissions have been included in the modelling. In that case they amount to around 5 to 30 per cent of the average for present Australian generators, indicating that the models have probably allowed for best practice flue gas cleaning.

Using the latter example and the mid-range externality costings for the four emissions presented earlier, the total external damage cost for the above IGCC-CCS plant is about \$6/MWh. At around 14 per cent of the cost for a corresponding current black coal plant, this probably represents the low end of the range of external costs for these prospective CCS technologies.

Even without further data on the non-CO_2 emissions from the various kinds of CCS operations envisaged, it is reasonable to conclude on the basis of the above models that fossil-fuelled generators incorporating CCS will have full life cycle external costs in the order of 15 to 40 per cent of current technologies, depending on the fuel and specific technology. The improvement in external cost can be expected to track the reduction in life cycle CO_2 emissions, unless some of the other external impacts discussed below turn out to have significant associated costs.

In summary, taking the representative CO_2 emission figure for black coal as 950 kg/MWh (Table 13), the Australian external costs for black coal power as \$42/MWh (Table 27), and the reduction in health impacts with CCS to be in the same proportion as the reduction in CO_2 emissions, the Australian external costs for coal with IGCC-CCS will be around \$6/MWh and for coal with post-combustion CCS around \$11/MWh. It must be remembered that these figures are based on models only as there are no commercial plants to provide the data needed.

KEY MESSAGE: Carbon capture and storage technologies can remove 90 per cent or more of the CO_2 emissions from fossil fuel generators. When extra fuel and energy needs are taken into account, the full life cycle external costs are around 15 per cent (coal) and 40 per cent (gas) of present generators, depending on the particular technology.

Other external impacts

There are several potential external impacts of CCS that are specific to the capture and storage technologies, as distinct from the fuel combustion stages. Smekens and van der Zwaan (2004) list the following potential impacts that need consideration:

- acidification of groundwater;
- change of extraction potential of groundwater through change of hydrodynamic properties of geological layers;
- structural changes in, or dissolution of, rock strata;
- seismic activity and subsidence;
- leakage into the atmosphere;
- catastrophic well blowouts; and
- accidents during high-pressure transportation, in pipelines.

These authors also made some preliminary attempts to quantify these impacts and damage costs but conceded that there is not sufficient information to go further than outlining the models to be used.

Greenpeace International has recently released a vigorous critique of CCS (Greenpeace International 2008). Basically, the Greenpeace message is that, for the reasons listed below, CCS is inferior to, and diverts attention from, the already available renewable technologies for combating climate change. The report contains much informative and technically credible material about CCS, but the main interest here lies in the reasons why Greenpeace opposes it. Because of the particular Greenpeace perspective, its report can be expected to present an exhaustive catalogue of reasons that might generate opposition to CCS on environmental impact grounds. For this reason the full Greenpeace list of objections is worth repeating here, even where a Greenpeace assessment is rejected. Only some of the impacts could be considered as potential externalities.

CCS cannot deliver on time: This reflects a general concern that CCS is far from ready for commercial exploitation in power plants. The Greenpeace report quotes various estimates for commercial readiness ranging from 2030 to 2050.

CCS wastes energy: The energy penalty associated with CCS will depend on the kind of power plant. The highest penalties tend to be associated with pulverised coal plants, 24 to 40 per cent. For natural gas combined cycle and integrated gasification combined cycle plants, the energy penalties range from 11 to 25 per cent (IPCC 2005).

Storing carbon underground is risky: Here, Greenpeace is referring to the technical feasibility of creating sufficient storage sites (e.g. 6000 projects each storing one million tonnes of CO_2 per annum and within, say, 100 km of a power plant), the risks associated with managing all of these sites over long time periods, and the risks of leakage. For the latter risk, Greenpeace reiterates its oft-quoted case of the 1986 Lake Nyos, Cameroon, event where volcanic activity released a natural reservoir of CO_2 that killed 1700 people. In fact, the Greenpeace analogy is not technically appropriate and there is no logical connection between the Lake Nyos eruption and the kind of underground storage being proposed for power station emissions.

CCS is expensive and undermines funding for sustainable solutions: This is more of a 'political' objection and not directly relevant to externalities.

CCS and liability: risky business: Quoting this Greenpeace concern in full:

> "Large-scale applications of CCS pose significant liability risks, including negative health effects and damage to ecosystems, groundwater contamination including pollution of drinking water, and increased greenhouse gas emissions resulting from leakage. There is no reliable basis for estimating the probability or severity of these risks. As current regulations are not designed to adequately manage them, significant questions as to who is liable remain unanswered."

The two publications cited above (Smekens and van der Zwaan 2008, Greenpeace International 2008) should cover all of the external impacts of CCS technologies that might be perceived as creating environmental costs. Of these impacts the following seem most likely to emerge as the ones that could be of concern in the Australian context.

Energy costs and increased scale of operations

The energy costs of CCS mean that the scale of power generation will need to increase in order to deliver the required amount of power. For example, if brown coal were to be used in a CCS plant, Victorian brown-coal-fired generators would need to increase capacity by around 35 per cent and the quantity of brown coal extracted increase by the same amount in order to generate the same amount of power as at present. Similarly, the quantity of black coal mined and transported would need to be increased by the same order. Exports of coal to countries using CCS would also have to be increased if the coal-based generating capacity needs to be maintained at pre-CCS levels. The related increases in mining activities and infrastructure will undoubtedly arouse some community concern and opposition.

Processing plants, emissions

CCS will increase the size of the operations at power generators. If the preferred capture route is absorption in a solvent, there are various possible adverse impacts associated with the transport of large volumes of solvent and potential odours or other environmental impacts due to escape of organic or other vapours.

Pipelines

It is not yet known how the storage sites in Australia will relate geographically to the main regions of power generation. Unless they are close, the prospect of long pipelines is likely to arouse concerns about effects on amenity and ecosystems.

Geologic storage

The indications already are that the community will be apprehensive at the prospect of indefinite underground storage, of potential leakage, and of the impact of nearby underground storage sites on land values.

There is at present little on which to base monetary valuations for these potential impacts of CCS. Given the current high priority accorded CCS by government in Australia (Prime Minister 2008); this is an area that deserves consideration for further research.

KEY MESSAGE: Carbon capture and storage technologies will create external costs connected with increased scale of fuel extraction, transport and generating operations, with CO_2 pipelines and with apprehension about leakage from underground CO_2 storage. Attaching monetary valuations to such impacts will need considerable further work.

3.7 NUCLEAR POWER

Nuclear energy is a mature and commercial technology, with 439 nuclear power stations, rated in total at 372 GW, located in 30 countries, though not in Australia. In 2006 these generators produced some 2,600 TWh of electricity representing around 16 per cent of the world's electricity (World Nuclear Association 2008). There are many comprehensive and accessible sources of technical and economic information on nuclear power and only a few salient points will be repeated here.

The Australian Government's report on its Uranium Mining, Processing and Nuclear Energy Review 2006 (UMPNER) was commissioned to provide *"a factual base and an analytical framework to encourage informed community discussion"* (Commonwealth of Australia, UMPNER Report 2006 p.1) in a context of increasing Australian energy needs and an imperative to reduce greenhouse gas emissions. The UMPNER Report covers every important aspect of nuclear energy and the nuclear fuel cycle and contains a large database of original references.

Nuclear power involves the conversion to electricity of heat generated by controlled nuclear chain reactions (fission). These reactions themselves produce no greenhouse gas emissions but there are emissions associated with materials and processes that use energy upstream and downstream from the generator itself. Hence the considerable interest in establishing the rate of emissions and the energy balance over the full life of a reactor.

There are many designs of reactor, somewhat arbitrarily classified as Generations I to IV. Most use steam turbines to convert heat to electricity. According to the World Nuclear Association, Generation I reactors were developed in 1950-1960s and few are still running today. They mostly used natural uranium fuel and graphite as moderator. Generation II reactors comprise most of the world's present nuclear capacity. They typically use enriched uranium fuel, and are cooled and moderated by water. Generation III are the Advanced Reactors, the first few of which are in operation in Japan; others are under construction or being ordered. They are developments of the second generation with enhanced safety. Generation IV designs are still on the drawing board and will not be operational before 2020 at the earliest, probably later. They will tend to have closed fuel cycles and burn the long-lived actinides now forming part of spent fuel, so that fission products are the only high-level waste. Many will be fast neutron reactors.

Externalities

Externalities have tended to dominate attitudes towards nuclear energy. There are two conspicuous reasons. Firstly, the status of nuclear energy is controversial precisely because of its real or perceived harmful external impacts. Secondly, there is a special interest in nuclear power generation as a low greenhouse emission technology and this interest has heightened the debate, especially in Australia, as to whether its use should be expanded.

Nuclear energy's externalities have been the subject of many studies and reviews. Various ExternE publications (see below), the Nuclear Energy Agency of the OECD (Nuclear Energy Agency 2003) and the UMPNER Report are all good sources of information on the subject.

With regard to life cycle CO_2 emissions, the UMPNER/ISA Study (2006) included a substantial treatment of the life cycle energy use and greenhouse gas emissions associated with producing electricity from Australian-mined uranium. Its work reviewed 39 published life cycle CO_2 emission studies. Many parameters were found to affect the results, with ore grade and enrichment method being the most significant. The greenhouse gas intensity of the background economies where mining and enrichment stages were conducted was also an important influence on the final greenhouse gas intensity of the nuclear energy cycle.

The UMPNER/ISA Study (2006) found life cycle CO_2 emissions ranging from 2 kg/MWh to 84 kg/MWh. It put forward best estimates of 60 kg CO_2/MWh for a Light Water Reactor and around 65 kg CO_2/MWh for a Heavy Water Reactor and these are the figures adopted in the UMPNER Report.

WEC (2004) also reviewed published work on life cycle CO_2 emissions. The five cases it lists range from 3 kg CO_2/MWh for each of two Swedish power plants to 40 kg CO_2/MWh derived from a desktop study of a hypothetical Australian pressurised water reactor.

On the basis of the CO_2 damage cost used earlier, the emission of 60 kg CO_2/MWh (the figure used by UMPNER) would account for a life cycle damage cost of $A1.90/MWh attributable CO_2 emissions from a nuclear power station.

KEY MESSAGE: Nuclear power stations emit no greenhouse gases but associated mining, construction and decommissioning processes do. Life cycle CO_2 emissions can vary widely depending on ore grade and enrichment method. A best estimate is 60 kg CO_2/MWh, which translates to a life cycle greenhouse gas damage cost of $A1.90/MWh.

The external costs of nuclear power were evaluated early in the ExternE Project (summarised in ExternE 1999) for nuclear generators in five countries (Belgium, France, Germany, UK and The Netherlands). Follow-up evaluations (ExternE-Pol 2005) covered a typical light water reactor, for which data were extrapolated from various Swiss power plants, and a Swiss 1000 MW pressurised water reactor. The ExternE methodology covered the full nuclear life cycle, including mining (uranium), milling, extraction, enrichment and fuel fabrication; power plant construction and operation; spent fuel reprocessing; storage and disposal of high levels and intermediate level radioactive wastes. External cost calculations accounted for emissions of CO_2, SO_2, NO_X and PM_{10} as well as heavy metals, volatile organics and radioactive emissions. Accordingly, these ExternE results account for many more externalities than the greenhouse damage cost figures noted above.

This ExternE work (ExternE 1999) produced a rather wide range of valuations ranging from €0.6/MWh to €7/MWh ($A1/MWh to $A12/MWh) and depending significantly on the VSL and discount rate adopted. There are later results from ExternE (ExternE-Pol 2005) that lead to nuclear external costs around €2/MWh, or $A3.30/MWh.

According to ExternE, most (95 to 100 per cent) of the external cost is associated with stages of the energy chain outside the operation of the nuclear plant itself. Some 70 to 80 per cent of the cost is allocated by ExternE to radioactivity-dependent impacts on human health (see for example Figure 5 and the breakdown given below). The remaining 20 to 30 per cent is associated with the emissions from the fossil fuel power used at various stages in the construction and fuel cycles. Greenhouse gases account for less than 10 per cent of the total.

The detailed breakdown of these ExternE cost estimates is demonstrated in Table 29 for a representative example, a Belgian power station.

Table 29 External costs associated with a Belgian nuclear power station (ExternE 1999 p. 581)

External impact	Cost estimate €/MWh
Human health (power generation)	0.4
Accidents (power generation)	0.001-0.35
Human health (Other fuel cycle stages)	3.5
Global warming (Other fuel cycle stages)	0.02 – 0.7
Other (Other fuel cycle stages)	0.12

The components listed in Table 29 total €4.0-5.1/MWh, with a mid-range of €4.1-4.3/MWh (that is close to $A7/MWh). Once again, changing the discount rate has a significant effect on the valuations. Note that the global warming component in the table is, depending on which end of the range is chosen for comparison, slightly less or considerably less than derived above from UMPNER findings regarding life cycle CO_2 emissions, namely $A1.90/MWh.

The human health impacts of small radiation doses have been much debated (see UMPNER Report Appendix M). The human health impact costs evaluated by ExternE were mainly attributed to very small doses of long term radioactive emissions, such as radon, from abandoned mill tailings (ExternE 1999 and ExternE-Pol 2005) or to other isotopes with very long half-lives. This is a puzzling conclusion given that uranium mines and associated mill tailings are generally remote from habitation. The ExternE findings seem to rely mainly on a single reference case, Key Lake mine in Canada (ExternE-Pol 2005), which is a typical remote mine site.

Also, the quantification of nuclear power health impacts requires extrapolation of radiation dose-response functions to levels below those for which actual health effect measurements have been made. The problem is discussed in detail in the UMPNER Report, Appendix M. Accordingly, there are considerable reservations about estimates for damage factors due to such mine site radioactive emissions, which may well be overestimated (ExternE-Pol 2005).

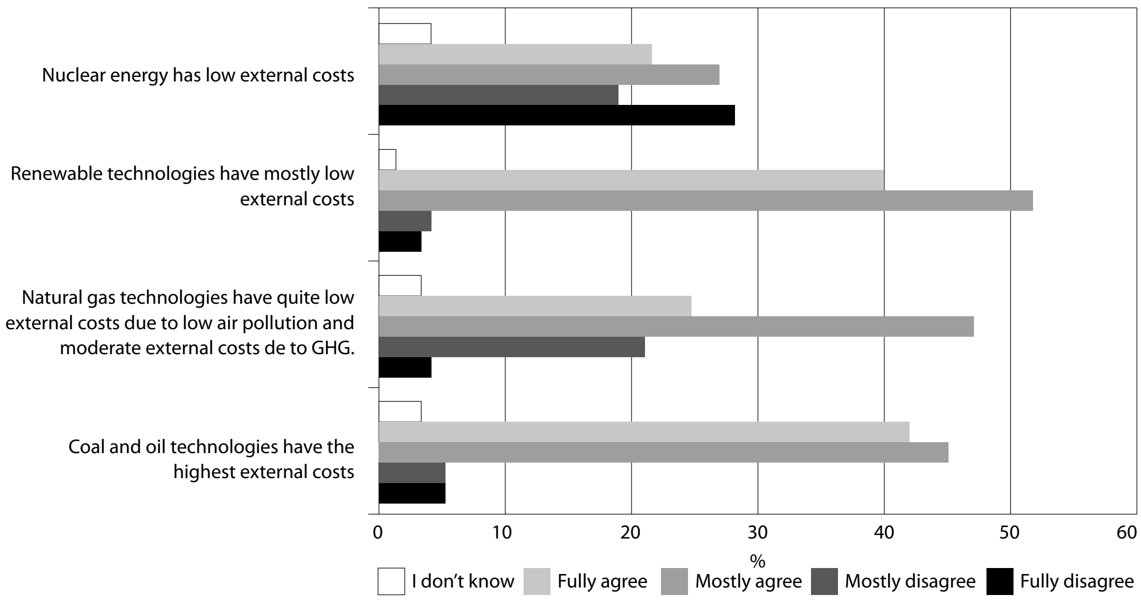
So, the already small externality costs of the nuclear energy life cycle as determined in the above studies may well be smaller, and are unlikely to be larger, than the reported results. Because of the uncertainties, the claimed health impacts should be revisited in future work.

KEY MESSAGE: Existing monetary valuations indicate total external costs of nuclear power in the vicinity of $A7/MWh (range ($A1/MWh to $A12/MWh). Almost all of that cost arises outside the power station operation itself, with 70 to 80 per cent due to radioactivity-dependent impacts on human health. The balance is attributable to the energy used in the nuclear life cycle. The dominant health cost component is said to be connected with small dosage emissions from mill tailings but this claim needs to be checked. Mine sites and associated mill tailings are in remote areas, the extrapolations involved are uncertain and these health damage estimates may be high.

It is important to recognise that none of the externality valuations discussed above takes into account the widespread concerns about low frequency/high impact events such as severe reactor accidents and threats of nuclear proliferation. The ExternE 2005 Update discusses possible methodologies for valuing such 'beyond-design accidents', the costs of which could be attributable to human deaths and injuries, mental trauma, evacuation, subsequent clean-up, food bans and land contamination. The point is also made that for such high damage/low probability risks, the public perception of risk differs from the kind of 'objective' risk evaluation undertaken in technical work such as conducted by ExternE. For such 'Damocles risks', according to ExternE, *"past attempts to quantify this effect have not been successful or accepted, so there is currently no accepted method on how to include risk aversion in such an analysis"*.

A recent NEEDS Project Newsletter (NEEDS 2007) is relevant to the 'Damocles risk' problem. It concerns a survey commissioned on the acceptability of monetary valuation of externalities. The results are shown below. A self-selected 11 per cent of the 2000 surveyed responded. The majority of the respondents agreed with the main principles that constitute the basis of the externality concept: the polluter pays principle, monetisation of externalities and government intervention to internalise external costs. Respondents claimed to be reasonably familiar with ExternE aims and methodology, and accepted the approach and the results. A large majority agreed that fossil fuels have the highest external costs, natural gas moderate external costs and renewable technologies low external costs. But when it came to the externalities of nuclear power almost half disagreed with the proposition that nuclear energy has low external costs. Presumably this is because that proposition is not consistent with common public perceptions of the Damocles risks mentioned above.

Figure 9 Responses to a NEEDS Project survey on attitudes to monetary valuations of external costs of various energy sources (NEEDS 2007)



Australia, a major uranium miner and exporter of uranium concentrates, is notably absent from the list of countries using nuclear power. The anti-nuclear sentiment in Australia is well known. In a formal sense, externalities dominate policy and decision-making on nuclear power in Australia. That is to say, Australians attach high costs, arguably higher than apply in countries that have nuclear power, to the externalities of nuclear power generation.

In their opposition to nuclear power, Australians focus on reactor accidents, waste disposal and nuclear proliferation. Accidents and proliferation belong to the category of high impact/low frequency events, the 'Damocles risks', for which monetary valuation is, and may always be, problematic. Waste disposal has actually been costed and those costs built into the price of nuclear power (Commonwealth of Australia, UMPNER Report 2006). Presumably there is another perception gap here between waste disposal costings and the levels of public concern about nuclear waste.

The present work looks at the quantifiable components of nuclear power externalities and arrives at figures that indicate they are lower than for many other forms of electricity generation. Given the above results of the NEEDS Project survey, it is reasonable to expect that the Australian response to the proposition that nuclear power has low external costs would show even greater disagreement than the above NEEDS survey.

KEY MESSAGE: The low external costs of nuclear power determined by the ExternE project seem not to have greatly influenced public attitudesin Europe. These external cost valuations do not seem to account fully for certain impacts that are important in public perceptions – reactor accidents, nuclear proliferation and waste disposal. Presumably these impacts dominate Australian sentiment and it is likely that an Australian survey of public attitudes to externality valuations would also show reluctance to accept the conclusion that nuclear power has low external costs.

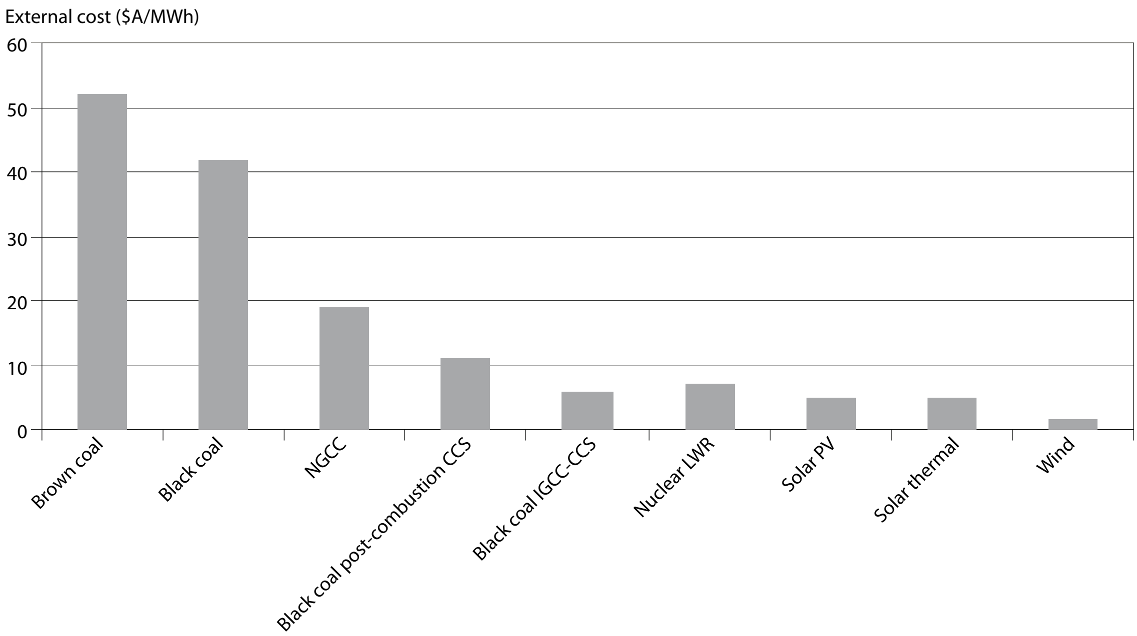
4 Summary of Externality Cost Findings

The externality costs derived throughout this review for the various electricity generating technologies are summarised in Table 30 and graphically in Figure 10. For convenience, the sources of each value given in the body of the report are repeated in Table 30.

Table 30 Summary of external cost estimates derived for Australia for various electricity generating technologies

Fuel/Technology	Source of estimate	Externality cost $A/MWh
Brown coal – sub-critical pulverised fuel	ExternE climate cost + health cost scaled to Australian emissions and population	52
Black coal – sub-critical pulverised fuel	ExternE climate cost + health cost scaled to Australian emissions and population	42
Natural gas – combined cycle (NGCC)	ExternE climate cost + health cost scaled to Australia	19
Black coal – post-combustion CCS	WEC life cycle emission model, combined with above sources for black coal	11
Black coal – IGCC-CCS	WEC life cycle emission model, combined with above sources for black coal	6
Nuclear - LWR	ExternE life cycle estimate	7
Solar PV	ExternE, WEC and UMPNER life cycle emissions	5
Solar thermal	NEEDS life cycle emissions	5
Wind	ExternE life cycle estimate	1.5

Figure 10 Graphical summary of external cost estimates for Australia



Note that the figures in Table 30 are **external costs only**. Capital and operating costs for the different technologies, and the associated generation costs and wholesale market prices of the electricity they produce, are a quite separate matter. Only a few of these costs are established for Australian conditions. Several of the technologies of interest are yet to be deployed on a large scale in Australia. Cost estimates and projections do exist but they cover a broad range. All are greater, in some cases by a factor of 10, than the present indicative wholesale price for power generated mainly from coal, $A40/MWh. For further information on these costs the reader is referred to reviews such as EPRI (2006) and Connell Wagner (2007).

Once again, it needs to be emphasised that the individual numerical values in Table 30 and represented graphically in Figure 10 are estimates reached via many assumptions and approximations. Each of the single values quoted has been selected from a band of estimates. It is not known whether that band represents the actual range of uncertainty; the probability is that it does not. Also, as discussed in the body of this report there are many examples of external impacts that have not been valued and therefore cannot be included in these estimates.

Even with all of the above qualifications, the diagram is probably a reasonable representation of the relative magnitudes of total evaluated climate and health damage costs for some of the most important generating technologies of interest to Australia.

5 Some Suggested Future Externality Topics

Several areas where externalities are worth exploring were identified at various stages of this work but in the event were not pursued. They are mentioned here as worthwhile for future study. In addition, given the frequent reference to uncertainty in this review, there is clearly a need to develop further the methodologies for estimating external costs as well as to ensure that the latest information on relevant advances made elsewhere is available to Australia.

5.1 BIOMASS

Biomass as a resource for generation of stationary energy in Australia is addressed in a recent report on a roadmap for bioenergy in Australia (Clean Energy Council 2008), which contains much information on resources and potential. On the related topic of liquid biofuels as substitutes for liquid transportation fuels, ATSE has recently prepared a report *Biofuels for Transport: A Roadmap for Development in Australia* (ATSE 2008B) and there are several other studies on biofuels in Australia (for example CSIRO, ABARE and BTRE 2003). The latter report deals in detail with environmental impacts at the 350 million litre scale of production and arrives at the view that they are manageable. More recently there have been concerns about market and other impacts of the rapid increase in scale of global biofuel production. The externalities of generating electricity using biomass as a fuel justify separate examination.

5.2 ENERGY STORAGE

Intermittent sources of energy like solar, wind, waves and tides need to be coupled with some kind of storage if they are to meet continuous electrical load requirements. Storage technologies such as pumped water, batteries, hydrogen, mechanical devices like flywheels, compressed air and bulk heat storage media such as concrete or molten salts are all accompanied by externalities. This is another large area of energy externalities that justifies separate study.

5.3 ENERGY SECURITY

Securing future energy supplies is clearly a major driving force for the introduction of new fuels and fuel technologies and in that sense it is of utmost importance. The extent to which a lack of security of future energy supply could be said to create externalities seems to be a matter of debate amongst economists. The ExternE Project has reported explicitly on energy security externalities (ExternE-Pol 2004), with models and valuations for some externalities, but arrives at the following conclusion: s

> "Measurement of energy security externalities remains a complex and difficult exercise. Problems of definition as to what constitutes these externalities make agreement on what the policy issue is hazardous. Additionally, the range of assumptions that need to be made in order to calculate quantitative estimates of the size of these externalities means that these estimates should be viewed as indicative only. There are also a range of gaps relating to oil price volatility and the potential macroeconomic costs of gas and coal supply disruption that suggest that the values of 0.04 and 0.3 milliEuro per kilowatt hour are much lower than the true costs, whether categorised as external or not."

This conclusion suggests that any future work undertaken on externalities of energy security would need to allow for a well-resourced effort.

5.4 EXTERNALITIES OF MULTI-TECHNOLOGY GENERATING NETWORKS

This report concentrates on assessing the externalities of power generation on a technology-by-technology basis. In other words, life cycle assessments are technology-specific. In practice, as new technologies are adopted, power networks designed to minimise greenhouse gas emissions will often need to comprise combinations of technologies, particularly when intermittent sources such as solar and wind power are involved. These sources need backup from electrical storage or from gas-fired or other fossil fuel generators. Already in Australia there are examples of wind farms backed up with coal fired generators and hydroelectric generators with overnight pumped storage driven by brown coal power. In order to understand the externalities associated with the electricity so produced, a life cycle assessment is required that considers the operating characteristics of the integrated system and is unique to that system. This kind of approach should be included in future extensions of the current work.

KEY MESSAGE: Bioenergy, energy storage technologies, energy security and multi-technology generating networks are some further topics with important associated externalities that deserve examination.

5.5 POLICIES FOR RESOURCING FURTHER WORK ON EXTERNALITIES

There are many areas covered in this report for which the externalities and their magnitudes are uncertain. External costs attributable to climate change, the health damage costs of power station emissions, the externalities that might arise from large scale deployment of technologies like carbon capture and storage and solar power are all examples where the degree of certainty is undesirably small, given the huge investments expected to occur.

The question therefore arises as to how the necessary further work should be prioritised and resourced. The first issue is one of funding. There are at least four Australian Government Departments that have portfolio interests connected with the introduction of new energy technologies for reducing emissions: Climate Change; Innovation, Industry, Science and Research; Environment, Water, Heritage and the Arts; and Resources, Energy and Tourism. These and perhaps other Departments should co-ordinate their attention in the field of energy externalities.

The second issue concerns expertise. This review found that attention given to research on energy externalities in Australia seems to be less than the field deserves in an economy where energy is so important. Research and capability in the field need encouragement. Given that Europe has led in this field, funding of collaboration with international agencies and expertise, especially in the European Union, should be a priority. Collaboration will help expand Australian capability and increase the effectiveness of use of resources

In its recent report *Energy Technology for Climate Change* (ATSE 2008A), the Academy endorsed the need for an over-arching Energy Research Council to oversee a range of existing funding programs for research, development and demonstration of new energy technologies. The Council would identify gaps and projects, avoid duplication and ensure quality. It would recommend to government the appropriate level of revenue from an emissions trading scheme that should be allocated to research, development and commercialisation of energy technologies.

It seems logical to include the general field of energy economics in the brief of any such Council. This would ensure that further work on externalities of electricity generation highlighted in this report is properly integrated with other efforts to ensure that maximum social benefits flow from the introduction of new low-emission technologies for electricity generation in Australia.

KEY MESSAGE: There is a shortfall in knowledge of externalities related to Australia's energy future. This should be remedied by funding from stakeholder Government Departments, with international collaboration as one of its objectives. The general field of energy economics should be included in the brief of the proposed Energy Research Council.

6 Abbreviations and Acronyms

ABARE	Australian Bureau of Agricultural and Resource Economics
ARC	Australian Research Council
ATSE	Australian Academy of Technological Sciences and Engineering
BTRE	Bureau of Transport and Regional Economics
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage (or Sequestration)
CCSD	CRC for Coal in Sustainable Development
CLFR	Compact Linear Fresnel Reflector
CO_2	Carbon dioxide
CPRS	Carbon Pollution Reduction Scheme
CRC	Co-operative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEST	Department of the Environment, Sport and the Territories
dB	decibel
DM	Deutschmark
ECU	European Currency Unit (precursor to the euro)
EGS	Engineered (or Enhanced) Geothermal Systems
EPA	Environmental Protection Authority
esaa	Energy Supply Association of Australia
EU	European Union
FUND	Climate Framework for Uncertainty, Negotiation and Distribution
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GJ	gigajoule
GL	gigalitre
GWh	gigawatt-hour (10^9 watt-hours)
HDR	Hot Dry Rocks
IEO	International Energy Outlook
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
km	kilometre
km^2	square kilometre
kWh	kilowatt-hour (10^3 watt-hours)
LCA	Life Cycle Assessment (or Analysis)
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
MJ	megajoule
ML	megalitre
MRET	Mandatory Renewable Energy Target
MWh	megawatt-hour (10^6 watt-hours)
NEEDS	New Energy Externalities Development for Sustainability
NGCC	Natural gas combined cycle
NIEIR	National Institute of Economic and Industry Research
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
NPI	National Pollutant Inventory

OECD	Organisation for Economic Co-operation and Development
PM_{10}	Particulate matter less than 10 micrometres
$PM_{2.5}$	Particulate matter less than 2.5 micrometres
PV	Photovoltaic
RET	Renewable Energy Target
SEGS	Solar Energy Generating Systems
SO_2	Sulphur dioxide
t	tonne
tC	tonnes carbon
tCO_2	tonnes carbon dioxide
TWh	terawatt-hour (10^{12} watt-hours)
UMPNER	Uranium Mining, Processing and Nuclear Energy Review
USC	Ultra supercritical
VOLY	Value of a life year
VPF	Value of a prevented fatality
VSL or VOSL	Value of a statistical life
WEC	World Energy Council
WTP	Willingness-to-pay
YLD	Year of life lost due to disability
µm	micrometre (10^{-6} metre)

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COVER PHOTO: Wind-powered turbine at the CSIRO Energy Centre, Newcastle, NSW.
Photo: CSIRO

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THE HIDDEN COSTS OF ELECTRICITY: Externalities of Power Generation in Australia

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