LOW-CARBON ENERGY
Evaluation of New Energy Technology Choices for Electric Power Generation in Australia

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

ATSE

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Executive Summary

KEY ISSUES

Australia faces a long period of heavy investment in low-carbon energy technologies, especially for generating electricity. This is required to meet the increasing demand for electricity and respond to climate change by reducing greenhouse gas emissions through application of an expected price on carbon. Given this environment, there is a need to facilitate improved investment decision-making associated with these technologies for both the energy sector and public policy makers.

This report explores the usefulness of a financial tool, Net Present Option Valuation (NPOV), in supporting investment decision-making. NPOV complements the more traditional calculation of future Levelised Costs of Electricity (LCOE). It is more amenable to incorporating uncertainties and variations in future technology costs and carbon prices and to understanding their impacts.

The key issues of the report follow.

The LCOE and NPOV results demonstrate that, should low-carbon electricity generating technologies be required to meet future reducing greenhouse gas emission targets, their financial viability will require electricity prices to rise substantially over time and that there will need to be a price on carbon that escalates as targets are tightened.

The LCOE and NPOV results demonstrate that with increasing prices for electricity and carbon emissions, a portfolio of low-carbon technologies can economically be deployed over time. No single technology is pre-eminent and different circumstances will determine the optimum choice for a specific place at a particular time.

NPOV provides additional insights into rankings of the attractiveness of alternative power generation technologies. While factors such as the cost of capital or the prices of carbon and electricity can change generic rankings, site-specific factors including infrastructure costs can also change the ranking given to a technology for a specific project.

NPOV indicates that an investment of some $10 billion in the period between now and 2030 to 2040 is justified in support of alternative technologies through further expenditure on RD&D, infrastructure, development of regulatory regimes and the like. However further work is required to validate this estimate.

The financial analyses in this work have the benefit of access to the most recent set of Australian cost data for power-generation technologies, including learning curves for future improvements and cost reductions, rising electricity price projections and potential carbon prices. Authoritative as they are, such data are inherently uncertain and will continue to change over time.

Technology-specific financial data can provide only a starting point for investment decisions. The newer technologies still face technical hurdles. Design of integrated power networks will need, at the very least, progress in these technologies and in understanding the costs of managing and delivering secure power from remote sites and intermittent energy sources like solar and wind.

The breakthrough value of this study is that the future rankings of the attractiveness of alternative power generation technologies that emerge from LCOE and NPOV modelling are similar, but with NPOV techniques explored here providing additional insights for future decision-making.

ATSE urges further development and adoption of the NPOV work it has presented here as a practical immediate step forward towards determining future sustainable energy generating options for Australia.

SUMMARY OF FINDINGS

LCOE and NPOV calculations were performed on technologies for which adequate information was available; namely: pulverised coal combustion, coal gasification, natural gas combustion in combined cycle gas turbines, each with and without carbon capture and storage; nuclear power; geothermal power; wind power; solar thermal technologies, with and without energy storage; and solar photovoltaic technologies. Information was not adequate at this stage to include wave, tidal, biomass or other energy sources.

The main findings from the current study of the set of technologies considered here are listed here:

- Technology rankings that emerge from models for LCOE and NPOV are similar, with NPOV providing additional insights.
- LCOE based on the latest Australian data generally agree with values and trends in international published studies.
- Only a few technologies, including wind, combined cycle gas turbine (CCGT) and favourably located geothermal, have LCOEs close to the projected 2020 electricity price. Costs of the other technologies are higher.
- By 2040, cost reductions due to 'learning' will bring the LCOEs of most of the technologies considered down to the point where they earn the cost of capital, potentially making them economic.
- In line with the LCOE results, only wind, CCGT and favourably located geothermal have significant NPOV in 2020.
- By 2030, NPOV increase, with gas-fired technologies, including gas-firing with carbon capture, having the highest values. By 2030 option values for wind and nuclear are moderately high, while for solar and coal-fired technologies, including those with carbon capture, they are low.
- By 2040, all of the technologies considered, except coal firing without carbon capture, have significant NPOV. The highest option values are associated with combined cycle gas plus carbon capture, wind, low-cost geothermal, solar thermal with central receiver, and nuclear.
- Future gas price represents a high financial risk factor for generators investing in gas technologies for base load generation.
- Cost of capital for the investor has significant influence on NPOV. The calculated NPOV is also sensitive to capital cost of installed capacity, thermal efficiency, and operating costs of the technologies.
- For solar thermal technologies, incorporation of energy storage improves NPOV slightly.
- Overall, the results suggest that future electricity generating portfolios could be drawn from a wide choice of individual technologies, provided that the anticipated level of technology learning occurs and the price of electricity rises at rates which are adequate to provide an attractive return on investment.
- The present NPOV of the portfolio of new technology options for investment in the period 2030 to 2040 is some $10 billion. This provides an indication of the investment that can be made now in support of these electricity generating technologies, such as infrastructure development together with R&D and technology development to accelerate learning. Further work is required to confirm the validity of this estimate.

The remainder of this Executive Summary covers material under the following headings:

- Improving the certainty of investment decision-making for power generation
- Levelised Cost of Electricity (LCOE) and Net Present Option Valuation (NPOV)

- Technologies covered and sources of data
- Limitations of the financial analysis
- LCOE results
- NPOV results
- Future activities

IMPROVING THE CERTAINTY OF INVESTMENT DECISION-MAKING FOR POWER GENERATION

Australia faces an uncertain energy generation investment climate due to the need to adapt to the likely imposition of carbon costs or other constraints such as mandated sourcing of certain forms of energy. National economic well-being has been underpinned by relatively cheap energy supply in the past half century. Consequently this necessary transition will have a critical impact on the national economy and living standards.

Given this environment, there is a need to facilitate improved investment decision-making associated with low-carbon technologies for both the energy sector and public policy makers.

Analysis of NPOV offers a method that provides new insights to guide investment decision-making in the face of these kinds of uncertainties. In the study leading to this report, an analysis of NPOV is applied successfully to several electricity generating technologies. The results compare favourably with results from other financial evaluation tools such as the LCOE.

This work is part of an ongoing program of The Australian Academy of Technological Sciences and Engineering (ATSE) on accelerating the development of energy technologies in response to climate change. The emphasis is on investment issues for power generation technologies. A previous ATSE report (*Energy technology for climate change – accelerating the technology response*) concluded that large capital investments, around $250 billion (2009 dollars), would be required in order to reduce greenhouse gas emissions from power generation to the target levels then being proposed for the year 2050. That report also concluded that such cuts would call for deployment of a portfolio of generation technologies and that investment in their further development of more than $1 billion a year for several decades would be needed.

In this new study, further financial analysis of both capital and operating costs of the key new technologies is undertaken, with emphasis on accounting for effects of future financial uncertainties. The NPOV methodology developed here is applied using these uncertainties to provide new insights into investment decisions and risks. In addition, LCOE for selected technologies at various times into the future are evaluated.

LEVELISED COST OF ELECTRICITY (LCOE) AND NET PRESENT OPTION VALUATION (NPOV)

LCOE is the constant dollar wholesale price of electricity that recoups cost of capital, fuel costs, taxes and other financial costs over the expected asset life. For the LCOE calculations in this report, a carbon dioxide (CO_2) price is included and held constant for the life of the facility. While a constant electricity and carbon dioxide price over decades is an unrealistic assumption, LCOE is a common method of comparing costs of different electricity generating technologies. It provides a starting point for judging future electricity prices that would offer commercial viability for a particular technology.

NPOV is a financial technique that is used in this report to evaluate a 'real' asset, like a project to develop commercially a piece of technology (as distinct from a financial asset). The NPOV parameter is introduced in this study to account for the risk inherent in the time-varying commercialisation investment for the new energy technologies. For NPOV in this work, the commercialisation investment by definition is discounted at the cost of capital of the firm to present value rather than at the risk-free rate for a fixed exercise price in conventional sharemarket options analysis. The NPOV reported here is therefore different to the option value calculated by conventional methods where the exercise or commercialisation price is, by definition, constant.

NPOV is the present value of a choice to make a future business or investment decision. It is particularly suited to evaluating an investment under conditions of uncertainty and volatility – in future prices, product demand and/or asset value. The method captures the value of any progressive resolution of future uncertainties as a project progresses and of the managerial flexibility to wait, abandon, or expand on an investment opportunity. It would therefore appear to have promise as a tool for assessing the value of future electricity generating technologies where costs and prices are explicitly uncertain – costs, because the technology is not yet fully developed or demonstrated and future fuel prices are subject to expected but unknown rises; and electricity price, because of unknown future policy responses to climate change, such as a price on carbon dioxide emissions.

NPOV represents the aggregated present value of those potential financial outcomes that have a positive (as distinct from a negative) net present value outcome associated with a future investment decision. Furthermore, it represents the maximum amount that could be expended now to have the future option for commercialisation in the event that a rate of return equal to the weighted average cost of capital can be achieved at the final investment. This preparatory expenditure could be allocated for a variety of purposes, such as technology research, development and demonstration or infrastructure development, with the ultimate aim of achieving the successful commercial deployment of the technology.

TECHNOLOGIES COVERED AND SOURCES OF DATA

The technologies for stationary power generation covered here are:

- pulverised coal combustion, for both black and brown coal, with and without geological sequestration of carbon dioxide;
- coal gasification (i.e. integrated gasification combined cycle) with carbon capture and storage via geological sequestration, for black coal;
- natural gas combustion in combined cycle gas turbines, with and without carbon capture and storage;
- nuclear power;
- geothermal power, including both hot sedimentary aquifer and enhanced geothermal (hot rock) systems;
- wind power;
- solar thermal technologies, with and without energy storage; and
- solar photovoltaic technologies.

The financial results presented here are based on a set of moderated data provided by the Stakeholder Reference Group established by the Australian Energy Market Operator and the Australian Government Department of Resources Energy and Tourism. The primary source data for this group were drawn from the Electric Power Research Institute (EPRI) report, *Australian Electricity Generation Technology Costs – Reference Case 2010*, moderated to reflect regional geographic considerations with implications for scenarios-based market modelling. The final input data for the stationary energy sector modelling are set out in the report *Preparation of Energy Market Modelling Data for the Energy White Paper – Supply Assumptions* prepared by ACIL Tasman. While these reports were confidential at time of writing, most of the data are in tables available on the AEMO website.

The rigorous approach to data collection and assessment means that the moderated data used here should be considered as the most authoritative available for Australia at the time of writing.

Technologies using tide, wave, biomass and other energy sources would also be amenable to the analyses used here but were outside the scope of the work because of lack of suitable (moderated) financial data. Similarly, this kind of analysis could also be conducted for energy efficiency projects if suitable data were available.

LIMITATIONS OF THE FINANCIAL ANALYSIS

The results in this report are for individual technology categories and cannot be directly applied to integrated networks of different technologies. They are not site-specific and do not include factors such as additional transmission costs from remote sites or the technological viability and risks associated with each technology. The results are applicable for each technology category considered in isolation. They do not consider the portfolio of technologies that could be deployed against specific demand scenarios. As a consequence, no consideration is given to the stability of an electricity supply grid that might need to cater for increased levels of intrinsically variable renewable energy sources as part of a portfolio of technologies. The analyses should not therefore be considered as examples of the approach that would be needed to evaluate specific projects. They do represent the starting point for the type of evaluation that would be needed for making decisions about specific projects and portfolios of electricity generating and distribution technologies required for particular applications.

The results presented here are based on a price being allocated to CO_2 (a 'carbon price'). Accordingly, no consideration is given to alternative policy choices, such as mandating or regulating various technology options or resource use. Nevertheless, the results presented here could assist in identifying such alternative policy options.

LCOE RESULTS

With these provisos, the LCOE results based on mean values of the input data are shown in the accompanying chart. It is also shown that LCOE results compare favourably with values and trends in other major published studies such as those from the International Energy Agency and the Electric Power Research Institute.

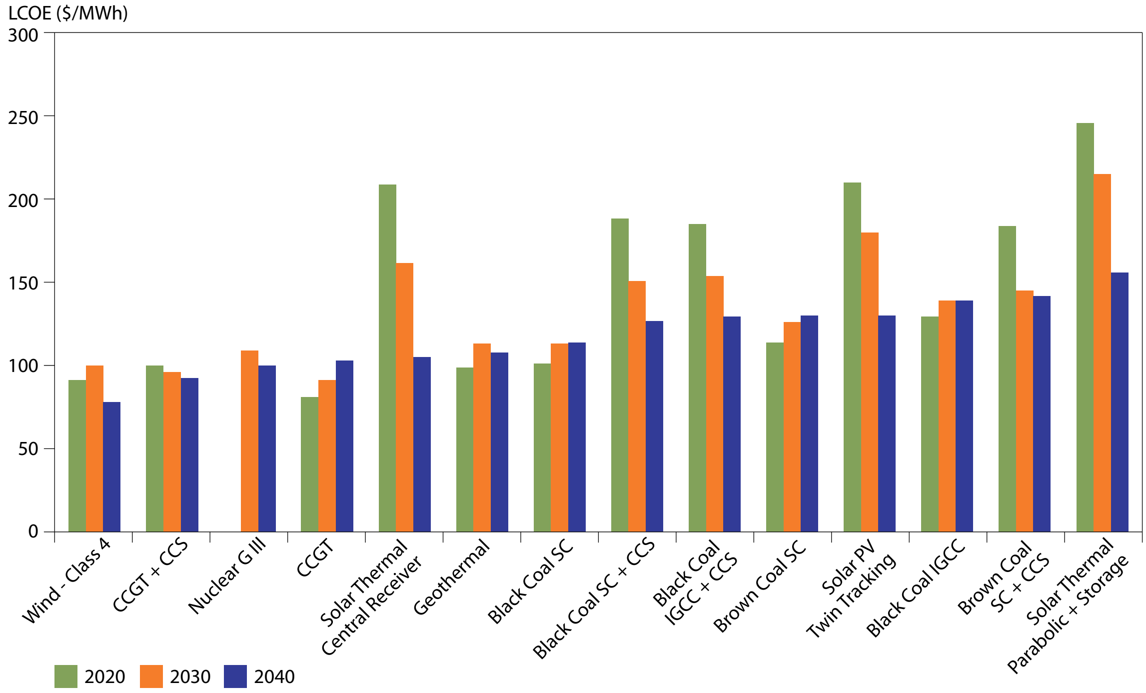
When future CO_2 prices – as projected in the Garnaut and Australian Treasury reviews of the economics of climate change, subsidies and future investment timelines – are taken into account, the present study shows that only a few technologies have levelised costs close to the projected 2020 electricity price. Wind, regionally low-cost geothermal and gas-fired CCGT technologies fall into this category, while other technologies have higher costs.

By 2030, combined cycle gas turbine with carbon capture and storage also has a levelised cost close to the expected price of electricity, but others such as the solar and coal-based technologies have higher levelised costs.

By 2040, the learning curves for the new technologies allow costs to fall low enough for many to achieve the cost of capital. These include the viable technologies for 2020 and 2030 plus nuclear (generation III) and solar thermal central receiver technologies. Other technologies, such as coal with carbon capture and storage and solar photovoltaic with twin axis tracking, are predicted to have levelised costs close to the wholesale price of electricity at the time.

Overall, these results show that there will in future be a wide choice of economic technologies to create a power-generating portfolio, provided the anticipated level of learning occurs and the electricity price has risen to a level that justifies the necessary investment.

Levelised cost of electricity results for 2020, 2030 and 2040 as a function of technology; ranked for 2040



Treasury projected Australian real wholesale electricity prices: 2020: $72/MWh, 2030: $95/MWh, 2040 $112/MWh.,and global CO_2 prices of USD $43/t$CO_2$, $67/t$CO_2$, and $90/t CO_2, respectively. Includes a Renewable Energy Certificate value of $50/MWh until 2030 and Treasury/Garnaut CO_2 prices

NPOV RESULTS

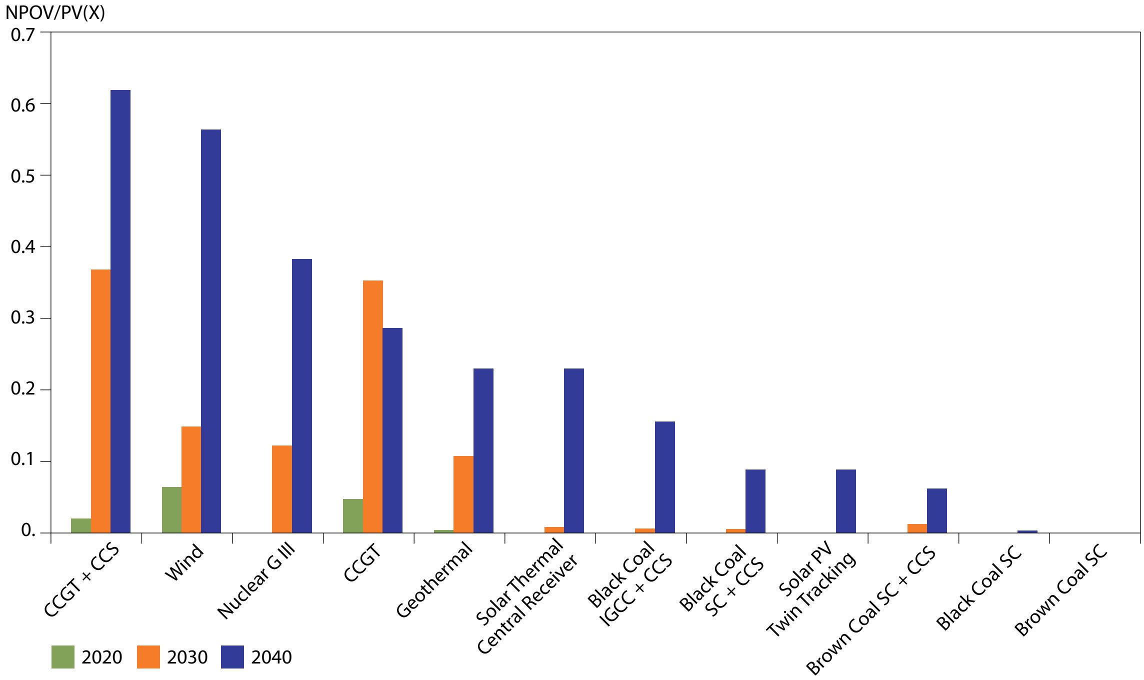
NPOV results are presented here as a further set of results (to the LCOE results presented previously) to aid decision-making choices for low-emission technologies. NPOV calculations use the same financial variables and CO_2 price projections as in the levelised cost calculations. However, there are some important differences that exist between both calculation methods:

- While the same variables are used, LCOE adopts a single point value (notionally the mean value of the financial parameter) whereas the NPOV technique uses the full statistical distribution for most of the random variables.
- LCOE adopts a single point value for the price of carbon (from the Garnaut and Treasury models) at the time of investment and holds that value constant over the life of the investment. It then calculates the price of electricity (which is assumed to be held constant over the life of the investment) that gives a zero mean net present value (NPV). On the other hand, the NPOV calculation adopts the full price trajectory over time for both the price on carbon and the electricity price (from the Garnaut and Treasury models) and also treats these as statistical variables. In addition, most of the other inputs in the NPOV technique are also treated as probabilistic variables.
- As the NPOV technique uses statistical distributions for the variables, the NPOV technique uses a Monte Carlo method to calculate the probabilistic distribution of the net present value.

NPOV results, as shown in the second chart, are found here to correlate with levelised costs via a non-linear relationship. While they follow similar trends, NPOV results offer a more sensitive indicator of the future financial viability of a technology.

NPOV is a measure of the current value of a particular technology investment. When divided by the present value of the capital expenditure, PV(X), the result is normalised. A positive NPOV/PV(X) is worthwhile and the higher the value the better.

Normalised net present option values (NPOV/PV(X)) as a function of technology for 2020, 2030 and 2040



Only a few of the technologies have a significant net present option value in 2020. As with levelised cost, these include wind, low-cost geothermal and combined cycle gas turbine. By 2030, the NPOVs increase – gas-fired technologies including carbon capture have the highest values. Wind and nuclear also have moderately high NPOVs in 2030. Solar and coal-fired technologies, including those with carbon capture, have low NPOVs.

By 2040, all the technologies, with the exception of coal firing without carbon capture, have significant NPOVs. The highest NPOVs are associated with combined cycle gas plus carbon capture; wind; low-cost geothermal; solar thermal with central receiver; and nuclear. Coal-based carbon capture, solar photovoltaic and regionally higher-cost geothermal technologies have moderate NPOVs, but NPOVs close to zero in 2040. Sensitivity analysis shows that with further technology development, the latter values could become positive for these technologies. Combined cycle gas turbine has a high net present option value due to gas price uncertainty in 2040, but its net present value is negative for investment then due to the high CO_2 price imposed.

The rate of change of CO_2 price over time adopted in the Treasury/Garnaut models has a significant effect on NPOVs. The CO_2 price trajectory must be close to that predicted by these models for the new technologies to have reasonable net present option values and positive net present values by 2030–40.

Gas price and its future trajectory are important variables for NPOVs of gas-fired technologies. Within the range of price escalators in future scenarios as published by the Australian energy regulator, gas-fired technologies can have high or low NPOVs. Future gas price therefore represents a high financial risk factor for generators investing in gas technologies for base-load generation.

The cost of capital for the generating company has a significant influence on NPOV, which is also sensitive to the capital cost of installed capacity, thermal efficiency, and operating costs of the technologies. For solar thermal technologies, incorporation of energy storage slightly improves net present option value.

A convenient way to visualise the suite of technologies and their value to an investor is to plot their location on a two-dimensional 'options space' diagram as a function of their net present values, NPOVs and financial volatilities. In this way, the trajectory of the technology in option value terms may be tracked with time, providing more insight into the effects of the financial parameters.

An analysis of the overall NPOVs of the new power generating technologies shows that the present aggregated net present option value of the portfolio of new technology options for investment in 2030–40 is around $10 billion, recognising that the present value of the commercial investment at that time is determined by discounting back to today's value at the firm's cost of capital. This $10 billion provides an indication of the investment that can be made now to support future commercialisation of these electricity-generating technologies such as infrastructure development, together with R&D and technology development to accelerate learning. Further work is required to confirm the validity of this estimate. However, several technologies, notably brown coal drying and gasification with CCS, were not included in this analysis (because of the lack of agreed moderated input data) and it has not been determined from this study how much of the power generation fleet will comprise technologies of this type. The aggregated NPOV today is very dependent on this uncertain investment parameter, as well as the technology improvements that are likely to occur. Therefore, with the current work it has not been possible to more accurately estimate the level of government support that is justified now for the development of these and other complex technologies to contribute to their financially viable in the future.

Overall, the results of this study show that the ATSE NPOV model can effectively discriminate between the financial viabilities of new power generating technologies and provide guidance for investment aimed at capturing the value of these technologies. It is recommended that the model be applied further in order to assist choices between technologies, their supporting infrastructure and their deployment options.

FUTURE ACTIVITIES

Focused research, development and demonstration (RD&D) programs are required to accelerate improvement of the key technology parameters in certain new power generating technologies, in order to facilitate their commercial deployment and their application in the portfolio of technologies that Australia will need for a secure electricity supply and to achieve reductions in the level of greenhouse gases. The financial opportunities and risks associated with these programs are an important part of the development process.

To facilitate the commercial deployment of these technologies, ATSE suggests that:

1 The NPOV model, shown here to discriminate effectively between the investment attractiveness of new power generating technologies, should be applied further to explore its applicability. This will include its contribution to the development of an energy policy, such as to assist in identifying the relative benefits of different technologies and to establish how much investment should go to:

a. RD&D in the near term, before deployment, or
b. other preparatory expenditure prior to a commitment being made in future to large-scale commercial deployment.

2 The ATSE NPOV model should be applied further to technologies that have not been considered here, including:

a. Integrated drying and gasification of brown coal, biomass combustion for power generation, ocean- and tidal-derived power technologies and technologies involving distributed networks such as solid oxide fuel cells;
b. Transmission costs for networked new technologies (such as remote wind, solar power and geothermal facilities);
c. Projects aimed at energy efficiency improvement, especially at large scale in industry; and
d. Analysis of specific choices, such as the size of initial CO_2 mitigation infrastructure developments in power generation hubs.

3 Further extension of ATSE modelling should be carried out to enable its application to identify a portfolio of new technologies in real power systems and networks. By 2040 there is expected to be available a wide range of technologies having high NPOV, including wind, nuclear, solar thermal with central receiver, and geothermal. Such analysis should be continued and tracked over time as new input data for developing technologies become available.

4 The applicability of the ATSE model to a specific site using a specific technology should be explored.

5 Further work should be undertaken to confirm the assumptions regarding matters such as: the volatility of the input variables; the relationship assumed herein between the price of CO_2 and electricity price, the change of these two prices with time and the future natural gas price.

6 Software should be developed to provide a user-friendly interface to the models so that they can readily be applied to specific projects and problems by both public sector and commercial users. Concurrently, the analytical tools intended for such general usage should be regularly updated with new input data concerning the subject technologies, as these become available.

Key Issues and Recommendations

The key issues of the report and the associated recommendations are listed below.

ISSUE 1

The LCOE and NPOV results demonstrate that, should low-carbon electricity generating technologies be required to meet future reducing greenhouse gas emission targets, their financial viability will require electricity prices to rise substantially over time and that there will need to be a price on carbon that escalates as targets are tightened.

Recommendation 1 – That for future low-carbon technologies to become financially viable the Australian Government will need to place a price on carbon emissions, and this will have to be increased over time, and that electricity prices will need to rise.

ISSUE 2

The LCOE and NPOV results demonstrate that with increasing prices for electricity and carbon emissions, a portfolio of low-carbon technologies can economically be deployed over time. No single technology is pre-eminent and different circumstances will determine the optimum choice for a specific place at a particular time.

Recommendation 2 – That a suite of low-carbon technologies, and infrastructure to support them, be developed for possible future commercial deployment.

ISSUE 3

NPOV provides additional insights into rankings of the attractiveness of alternative power generation technologies. While factors such as the cost of capital or the prices of carbon and electricity can change generic rankings, site specific factors including infrastructure costs can change the ranking given to a technology for a specific project.

Recommendation 3 – That further work be conducted to demonstrate the validity of the Net Present Option Value model developed in this study and to extend its application to generation sites and hubs, as well as to technology-specific studies. That the model used for this work be further developed (using external funds) and packaged as an open source program capable of being used for testing a range of input assumptions and project specific detail to assist in improving the quality of assessment of future energy supply options.

ISSUE 4

NPOV indicates that an investment of some $10 billion in the period between now and 2030 to 2040 is justified in support of alternative technologies through further expenditure on RD&D, infrastructure, development of regulatory regimes and the like. However further work is required to validate this estimate.

Recommendation 4 – That further work be conducted to demonstrate the validity of the Net Present Option Value model developed in this study, in order to provide better estimates of the investment that can be justified in RD&D for the technologies investigated here and to extend those estimates to other technologies (e.g. wave and tidal power) not considered in this study.

Acknowledgements

The Australian Academy of Technological Sciences and Engineering (ATSE) is most grateful to the contributions made by the author of the report, the Steering Committee established by ATSE to oversee the conduct of the project, input received from the Reference Group and funding provided in support of this project.

The principal author of the report was Dr John Burgess FTSE. John is a chemical engineer with wide experience in research, industry and academia. He is a Fellow of ATSE and has recently analysed in a separate ATSE report the capital costs required to create a portfolio of new technologies to satisfy Australia's energy requirements to 2050 in the context of strong CO_2 reduction targets.

This project was overseen on behalf of the Academy by an ATSE Steering Committee:

- Professor Robin Batterham AO FAA FREng FTSE – President, ATSE
- Dr Vaughan Beck FTSE – Executive Director, Technical, ATSE
- Dr Thomas Biegler FTSE
- Mr Kenneth Dredge FTSE
- Mr Peter Laver AM FTSE – Vice President, ATSE (Chair)
- Dr John Sligar FTSE
- Mr Martin Thomas AM FTSE
- Dr John Wright FTSE
- Mr Gary Zamel FTSE

The input and advice from ATSE Fellows to the direction of the project was invaluable and their contribution is gratefully acknowledged.

The study was supported by TRUenergy, the Energy Supply Association of Australia and the Victorian Government Department of Primary Industries. In addition, representatives of these supporting organisations formed a project Reference Group and provided useful information and guidance during the course of the project. Their important input is gratefully acknowledged:

- Department of Primary Industries, Victorian Government – Dr Richard Aldous;
- Energy Supply Association of Australia – Mr Duncan Loydell and Kieran Donoghue; and
- TRUenergy – Mr Geoff Gay and Allan O'Neil.

This project was established and managed for ATSE by Dr Vaughan Beck – FTSE, Executive Director, Technical, ATSE. The production of this publication was overseen by Mr Bill Mackey – Deputy CEO, ATSE. Dr Tom Biegler FTSE was the principal editor of the report.

An early draft of the report was reviewed by:

- Dr Richard Aldous, Department of Primary Industries, Victoria;
- Dr John Sligar FTSE; and
- Professor Terry Wall FTSE, University of Newcastle.

Several experts were consulted during the course of the study and these are referenced in the report. The input of this expert knowledge is gratefully acknowledged.

The data for capital costs, operating costs and efficiencies for the study are based primarily on moderated data provided by the Stakeholder Reference Group (SRG) established by the Australian Energy Market Operator (AEMO) and the Australian Government Department of Resources Energy and Tourism (DRET). The provision of this moderated data set was a key input to the study and ATSE thanks and acknowledges both AEMO and DRET for inviting it to participate in the SRG.

This ATSE study was conducted independently from the SRG and DRET, and the views expressed herein are those of ATSE and are not necessarily those of either AEMO or DRET.

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Contents

1 Aim and Scope of the Study

The Australian Academy of Technological Sciences and Engineering (ATSE) is undertaking a study program aimed at providing an expert view on the steps needed to accelerate implementation of energy technologies for low carbon emissions, in response to climate change. An important aspect of the program is to provide new information and hence insights that will contribute to the development of more reliable investment decisions regarding future electricity generation technologies.

In a previous report[1], ATSE examined the capital investment levels in new stationary electric power generation technologies required to meet the reduction targets for carbon dioxide (CO_2), the main greenhouse gas, often referred to simply as 'carbon', that are being proposed by many climate scientists, economists and politicians. It was found that large capital investments, around $250 billion (2009 dollars), would be required to achieve these targets by 2050. In the same report, each of the most prospective technologies was qualitatively reviewed and it was suggested that a portfolio of technologies would be required to achieve the required stable electrical power supply for Australia. ATSE also recommended the probable Australian Research, Development and Demonstration (RD&D) effort required. This amounted to over $1 billion per year (current dollars) ongoing over several decades.

Subsequent to that report, ATSE received a grant from the Australian Research Council (ARC) under the Linkage Learned Academies Special Projects (LASP) scheme[2] to continue and extend the study. The new study, reported here, was aimed at including in the analysis both capital and operating costs of the key new technologies, and their uncertainties. The inherent uncertainty of the future is taken into account in a new approach in which the financial analysis is based on the determination of 'net present option value' (NPOV), as explained below. In addition, the levelised cost of electricity (LCOE), essentially a wholesale cost that tests commercial viability based on Australian financial and technical data, for the technologies at various times into the future has been evaluated as part of the analysis.

A range of new technology choices for stationary power generation has been included in this work:
- advanced pulverised coal combustion, for both black and brown coal, with and without geological sequestration of CO_2;
- coal gasification with carbon capture and storage (CCS) via geological sequestration, for black coal;
- natural gas combustion in combined cycle gas turbines (CCGT), with and without CCS;
- nuclear power;
- geothermal power, including both hot sedimentary aquifer (HSA) and enhanced geothermal systems (EGS), and their regional effects;
- wind power;
- solar thermal technologies, with and without energy storage;
- solar photovoltaic (PV) technologies.

Other new technologies will be amenable to the kind of analysis presented here, provided that relevant financial data are made available. These new technologies could include brown coal integrated drying and gasification combined cycle (IDGCC), coal-oxy combustion, technologies such as wave and tidal energy, hybrid solar-fossil fuel technologies, biofuel power generation, distributed technologies like solid oxide fuel cells, and offshore wind installations. Energy efficiency projects in industry could also be analysed. For the present study, however, these technologies have not been considered.

The most significant inputs to any financial analysis of these new technologies extending into the future are:

- capital costs and the change in these costs with time (the "learning curve");
- operating costs, and their change over time, including factors such as thermal efficiency (broadly, the efficiency of converting heat energy into electrical energy) and its learning curve;
- wholesale price of electricity;
- the price set for carbon dioxide (CO_2) emissions and for those technologies emitting it;
- 'capacity factor' for energy generation (see glossary);
- the price of fuel, and fuel properties, for combustion based technologies;
- the value of any incentives, such as Renewable Energy Certificates (RECs).

A financial model calculating net present value (NPV) from free cash flows and incorporating all of the above variables relevant to Australia has been developed in this study. To calculate NPV for any set of deterministic variables, annual after-tax free cash flows are determined for the particular investments at future dates and discounted to present value at an appropriate cost of capital. The model is employed to calculate LCOE for a variety of new technologies at different future times[3]. An analysis is also undertaken in the study on the present option value of the various technologies using probabilistic values for the important financial variables, as detailed in Appendix A, using a probabilistic Monte Carlo calculation method.

Capital costs, operating costs and efficiencies for the study are based on moderated data provided by the Stakeholder Reference Group (SRG) established by the Australian Energy Market Operator (AEMO) and the Australian Government Department of Resources Energy and Tourism (DRET). The primary source data, including learning curves, were drawn from the Electric Power Research Institute (EPRI, www.epri.com) report *Australian Electricity Generation Technology Costs – Reference Case 2010*[4], moderated to reflect regional geographic considerations with implications for scenarios-based market modelling. The final input data for the stationary energy sector modelling are set out in the report *Preparation of Energy Market Modelling Data for the Energy White Paper – Supply assumptions*[5] prepared by ACIL Tasman (www.aciltasman.com.au). While these reports were confidential at time of writing, most of the data are in tables available on the AEMO website. Where necessary, values from the SRG were interpolated or extrapolated from the graphs of the learning curves.

In what follows the term 'SRG reference data' is used as shorthand for this set of stationary energy sector modelling reference data compiled by the Stakeholder Reference Group using the source data noted above. SRG reference data should be considered as the most authoritative set of financial and performance data available for electricity generation in Australia at this time.

The previous ATSE study mainly used data from the International Energy Agency (IEA) with input from a number of ATSE Fellows, so results presented here are different from the previous work in terms of capital costs (in this study they are generally higher). The estimated learning curves for the technologies are also different and in some cases steeper in the present work, as a result of stakeholder review arising from analysis by experts during the AEMO/DRET Reference Group process.

The LCOE results from the present study are also compared with other recently published results. These came from the 2010 report of the International Energy Agency[6], a joint report from Geoscience Australia (GA) and ABARE[7] and an Australian study by McLennan Magasanik Associates (MMA)[8]. The present results are similar to the results from these studies when the same financial assumptions are used, with the exception of MMA for some specific technologies (see below). In the present work, factors such as the price of CO_2 as a function of investment year have been included. This changes the LCOE for some technologies and therefore their relative financial ranking.

Future CO_2 and electricity prices are highly uncertain, especially when taken forward for a several decades and in the present international political climate. The most authoritative information on the possible scenarios for these prices for Australia were proposed and modelled by Garnaut[9] and the Australian Treasury[10]. In particular, the Treasury has provided a range of CO_2 and electricity price trajectories based on a global equilibrium model and global CO_2 trading to achieve target emission reductions. The trajectories arising from these Australian models have been used as a base for the present ATSE net present option value work reported here; some alternative trajectories are proposed for the sensitivity analyses.

The present study investigates an NPV-based option value to determine whether this methodology could be applied to new stationary power generating technologies under a range of scenarios. Real options valuation is a financial technique applicable to a 'real', as distinct from financial, asset, like a project to develop a piece of technology. Option value is the value of a choice to make a future business or investment decision concerning that asset. It is particularly suited for evaluating an investment under conditions of uncertainty and volatility, for example, in future prices, product demand or asset value. The method captures the value of any progressive increase in uncertainty in a potential project (viewed from today), and the value of the managerial flexibility to wait, abandon, or expand on an investment opportunity depending on what emerges over time. For example, when the time for the investment decision arrives, the investor can reject the investment if it is uneconomic at that time, that is, if the mean NPV is then less than zero.

Net present options valuation (NPOV) is a financial technique that is introduced in this report to evaluate a 'real' asset, like a project to develop commercially a piece of technology (as distinct from a financial asset). However, it is different from the "real option value" calculated using conventional option valuation approaches. For NPOV in this work, the commercialisation investment and revenues are by definition discounted at the cost of capital of the firm to calculate the NPV probability distribution and the NPOV. As explained further in Appendix B, most inputs in this study are treated as statistical distributions, a method that provides a range of revenue and cost streams for the net present options value financial model.

Viewed from today, an investment in a new technology could have a range of NPV outcomes (either positive or negative) and the net present option value is thus the probabilistic positive 'upside' today for the investment in the future (or positive part, greater than zero, of the future NPV distribution). By contrast, mean NPV is the value of the probabilistic distribution taking into account all future possible values, including those where NPV is less than zero. The rationale of NPOV is that, in the future, an investor could abandon the investment if the NPV was less than zero at that time and the opportunity to have this abandonment option provides value to the investor today. A new technology, viewed from today, could thus have positive option value but a negative mean NPV[11].

Net present option valuation would therefore appear to have promise as a tool for assessing the value of future electricity generating technologies where costs and prices (for example, electricity prices) are explicitly uncertain; in the case of costs, because the technology is not yet fully developed or demonstrated, future fuel prices are subject to expected but uncertain rises, and because of possible future policy responses to climate change, will result in an uncertain price on CO_2 emissions.

There are several analytical methods for determining option values. However, these are mainly applied to sharemarket investments, which are different from the present investment case. This is because there is both increasing volatility and downward drift in the exercise price for new power generating technologies, owing to their technology learning curves and increasing levels of uncertainty. For this reason, the standard analytical methods are not used here. Rather, a 'Direct Monte Carlo' method is employed in which the estimated probabilistic nature of the variables involved is used and the net present option value is determined from the numerically calculated future NPV probabilistic distribution. The Monte Carlo method is nonetheless compared with some of the common analytical methods for a European call option (where the exercise price is constant), and found to give essentially the same option value as the analytical methods for a range of input variables. This validates the Direct Monte Carlo approach used in this study.

The Monte Carlo method is used here to calculate net present option values for new power generating technologies for a range of future years and scenarios. The primary aim of the present research is to establish whether the determination of net present option value for new power generating technologies is useful in discriminating between different technologies. The results from the developed methodology are shown to be sensitive to the financial parameters and energy efficiency of a variety of new technologies, as well as to future Australian economic scenarios in terms of carbon price and electricity price.

2 Financial Model for NPV

This study is essentially a financial analysis of new power generating technologies at various investment times into the future. It calculates two parameters: the levelised cost of electricity and the net present option value of each technology. These calculations are based on the fundamental parameter, net present value, or NPV. The following presents a summary of the calculation of NPV and the data inputs required.

Calculation of Net Present Value (NPV)

The relevant cash flows for an investment opportunity are the free cash flows (FCF)[12].
These are defined as:

$$FCF = EBIT\ (1\text{-}tax) + depreciation - capital\ expenses \quad (1)$$

where: EBIT = earnings before interest and taxes, after depreciation
= revenues – costs – depreciation
tax = tax rate = 30% in Australia (in 2010)

In the present study, free cash flows are calculated from equation (1) each year for the life of the investment in each new technology. These free cash flows are then discounted at an appropriate rate to determine the NPV, which is the sum of all the discounted free cash flows.

The appropriate rate of discount for the yearly free cash flows is the weighted average cost of capital (WACC)[13]:

$$WACC = \{(1\text{-}tax)K_D D + K_E E\}/(D+E) \quad (2)$$

where: K_D = cost of debt
K_E = cost of equity
D = amount of debt
E = amount of equity

For any given year, the free cash flows are discounted according to:

$$FCF_{n,disc} = FCF_n/(1+WACC)^n \quad (3)$$

where n = number of years since the start of investment, over the life of the investment.

The NPV is then given by:

$$NPV = \Sigma(FCF_{n,disc}) \quad (4)$$

In these calculations, the capital expenditures for the new technologies are made over one or more years and the positive cash flows assumed to accrue in subsequent years, for the life of the facility. Details on these assumptions are given in Appendix A for each technology.

Capital costs, operating costs and efficiencies for the new technologies considered in the study were taken from the SRG. These costs, including learning curves, were provided by international and Australian power generation consultants[14] and agreed by the SRG as the reference data set. AEMO has developed five scenarios for its energy generation demand models[15], and the data on the new technologies were defined for the five cases. These scenarios, including the SRG data, have been published by AEMO in spreadsheet form[16]. Site-specific special infrastructure costs such as mine rehabilitation or water supplies have not being included in the analysis.

Factors used in the NPV calculations were:

Initial negative cash flows

- SRG reference data capital costs ($/kW capacity) were used, together with the AEMO annual construction profiles of each technology. The overall capital cost was calculated and then proportioned over the construction years specified by the SRG reference data set. In the case of nuclear, a six-year construction phase was assumed, with capital costs as per the EPRI sources referred to earlier (reference 4). Details are given in Appendix A.

Revenues

- Revenue from sale of electricity was taken as the appropriate 2009 dollar price in the future. In the case of the LCOE calculation, the electricity price was an iteration variable to calculate a zero NPV. In the case of the option value calculation, it was taken from the Treasury/Garnaut CO_2 – electricity price relationship adopted for this study; see Appendix A.4.
- Revenue was taken from Renewable Energy Certificates (RECs), where applicable.

Fuel costs

- Coal prices were taken from SRG reference data, based on the assumption that new Australian entrant coal prices vary in 2009 dollar terms between $1.33/GJ in 2015 and $1.15/GJ in 2040 for black coal, and constant at $0.56/GJ for brown coal over the period 2010-2040. For the levelised cost of electricity calculations following, the coal price was held constant for the life of the facility from the investment date.
- In the five AEMO scenarios, gas prices varied significantly over a range of around +1% escalation per year to +5% escalation per year in real terms from a base price of $5.20/GJ in 2015. For the purposes of base-case gas price, a value of +2% per year was taken for the results presented here, but sensitivity analysis was also undertaken on options value for a range of gas price escalation from +1% to +4% per year. For the levelised cost of electricity calculations following, gas price was held constant for the life of the facility from the investment date.
- Nuclear fuel costs of $0.94/GJ were taken from the original EPRI report referred to earlier.

Further details on these fuel price data assumptions are given in Appendix A.

Operating costs

- Variable and fixed operating and maintenance costs were taken from the SRG reference data set, as outlined in Appendix A.
- For nuclear, the operating cost associated with remediation and waste disposal was taken to be the same as in the previous ATSE report, namely $3/MWh produced. Operating costs for mining of fossil fuels and mine rehabilitation have not been considered.

- For geothermal, capital and operating costs were taken from the SRG reference data set, which contains recent input by the Australian Geothermal Energy Association. This assumes that geothermal capital costs vary with region. The lowest capital costs were for northern South Australia for EGS technology and Victoria and south-east South Australia for HAS technology. Other regions had higher costs. Further details on these geothermal costs are given in Appendix A.

Capacity factors

- SRG reference data set capacity factors[17] were used, including the capacity factors for wind at Class 6 and Class 4 conditions[18] and for solar technologies under Direct Normal Irradiance (DNI) = 5, 6 and 7 conditions[19], and their sensitivities.
- For the solar thermal technologies, auxiliary power requirements (the extra power that runs plant facilities like pumps, cooling towers etc, affecting some performance measures) were taken from the SRG reference data. For all other technologies, the auxiliary power load was assumed to be incorporated into the thermal efficiency (fuel combustion technologies) or higher operating costs (geothermal technologies).

Thermal efficiency

- The SRG reference data set uses a thermal efficiency parameter based on "Power Sent Out – Higher Heating Value (HHV)". This definition of thermal efficiency means that internal auxiliary power load is incorporated into the effective thermal efficiency. This was confirmed to ATSE by EPRI[20] in the case of fossil fuel fired and nuclear technologies. For example, the above thermal efficiency of a coal fired plant with CCS is approximately 10 percentage points lower than a similar plant without CCS. This is equivalent to an auxiliary power load for 90% CO_2 removal and compression to a power loss of around 20% for the coal-based technologies. This definition of effective thermal efficiency is also similar to that employed by IEA[21] in their LCOE calculations. In the calculations here for CCS, the nominated thermal efficiency was used to compute the electrical energy exported from the combined facility relative to the facility without CCS in order to calculate the revenue stream. Auxiliary power loads associated with fossil fuel mining or other surrounding infrastructure have not been considered. Details on the learning curves for thermal efficiency by technology are given in Appendix A. These curves show that thermal efficiencies, expressed in the above terms, are likely to rise to greater than 50% in the future for coal firing without CCS.

Fuel chemistry and specific energy

- Fuel chemistry and specific energy values for black coal, brown coal and gas were taken from the EPRI report (reference 4) referred to above. These specific energies were used in the NPV analysis to calculate the amount of fuel required at the particular thermal efficiency to provide the energy needed for power generation. The chemistry (including fuel ash, moisture and carbon content) was used to calculate the amount CO_2 emitted by each technology. Fuel cost was input as $/GJ from the SRG reference data set, and the fuel cost for the NPV calculation was determined from the amount of fuel used and its specific energy. Further details on these calculations and the fuel data used are given in Appendix A.

CO_2 price

- Where used in the calculations, CO_2 prices in the future were taken from a linear approximation to the results from the Australian Government Treasury Report *Australia's Low Pollution Future*[22]. Section 3 and Figures 4 and 5 below provide details of these projected prices.

Carbon capture and storage

- Unless noted separately, carbon capture and storage technologies have been assumed to capture 90% of the CO_2 they are generating. Data from the Carbon Storage Taskforce[23] were used to determine the transport and sequestering costs of CO_2. Relatively modest costs were used to account for CO_2 transport and sequestering costs, based on these data. In the case of Victorian generators sequestering from either gas or brown coal generation in the Gippsland Basin, this cost was taken as \$10/tCO_2. In the case of black coal generators in either Queensland or NSW, the average transport and sequestering cost was taken from the AEMO data as \$30/tCO_2 for disposal in either the Surat or Gippsland basins from NSW. As noted in the Carbon Storage Task Force report, the latter cost is conservative and could be in the range up to \$100/tCO_2 for longer distances associated with the more remote basins. This cost, which is uncertain, will be important in dictating the viability of CCS technologies in the future.

Cost of capital and depreciation

- The after-tax WACC used for most calculations in this report was 7% (exclusive of inflation), which assumes a debt proportion in financing of 70% with a cost of debt of 6% and a cost of equity of 13% for a typical generator (see reference 4, also Geoscience Australia and ABARE[24], which used EPRI analysis as well). Sensitivity to this important parameter for different technologies has been explored for both levelised cost of electricity and option value.
- Depreciation was assumed as 3.3% per year straight line over the life of the facility until the written down value is zero.

Real vs nominal results and net present value

- All results in this work are based on real financial parameters. That is, no account has been taken for inflation and all results are in 2009 dollars. Except where otherwise noted, all results are in Australian dollars.
- Financial values in real dollars in the future are discounted at the uninflated cost of capital to determine the net present value.

3 Levelised Cost of Electricity

Levelised Cost of Electricity (LCOE) is the constant price of electricity ($/MWh) that the generator must earn over the life of the facility to achieve a return equal to the cost of capital of the firm.

If the firm's WACC is used to discount the cash flows associated with an investment using a constant electricity price exclusive of inflation, then earning the cost of capital implies a net present value (NPV) of zero. In this work, LCOE is determined by calculating the annual discounted free cash flows for a particular technology case for the life of the facility using a constant electricity price, computing the NPV, and then iteratively adjusting the constant electricity price until the NPV becomes zero. Equations (1) to (4) above are used to calculate NPV. Mean values only are used to define the input data. In the LCOE calculations here, carbon dioxide price is taken from the Treasury model results at the investment year in question, and held constant over the life of the facility.

3.1 COMPARISON WITH PREVIOUS STUDIES

Many studies on LCOEs for new power generating technologies have been conducted. The results obtained depend on a range of factors, including the assumed cost of capital, future fuel and CO_2 prices, capital and operating costs, and so on. For LCOE comparisons with the present work, three previous studies are considered:

1. A recent study by the IEA with the Nuclear Energy Agency[25].
2. Recent results published by Geoscience Australia and the Australian Bureau of Agricultural and Resource Economics (ABARE)[26], from a study undertaken by the Electrical Power Research Institute (EPRI).
3. Results published by the Australian Geothermal Energy Association, from a study undertaken for it by McLennan Magasanik Associates (MMA)[27].

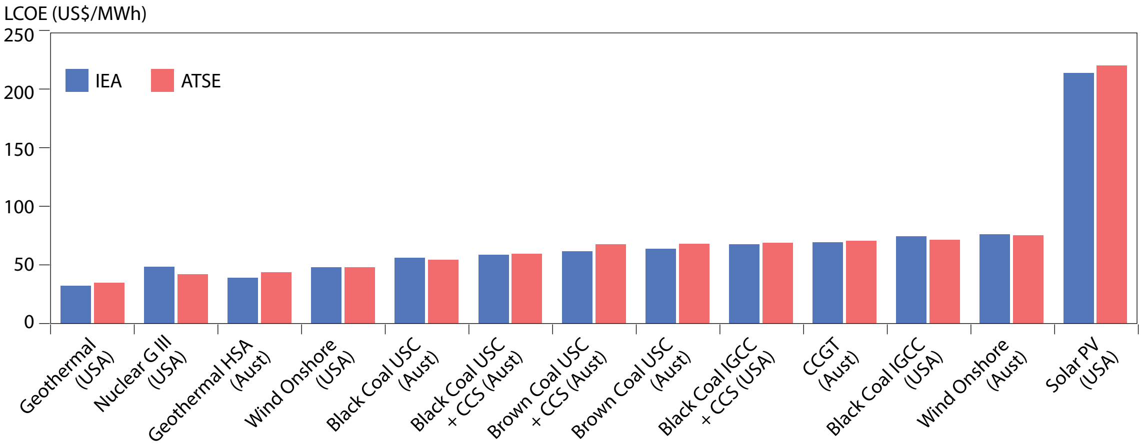
The base conditions for all of these studies are different. For example, the cost of capital varies in the range 5 to 10%. For comparison purposes, the same financial parameters used in the reported studies were used in the model developed for the present work. These parameters included factors such as the cost of capital and price of CO_2.

In summary:

- Comparison with the **IEA** work shows that the present cash flow model incorporating the IEA data set gives a good agreement between the present ATSE model and the IEA results using the IEA data for the new technology costs. This is shown in Figure 1 for 2015 for a WACC of 5% and a CO_2 price of $US30/t CO_2, with no tax or depreciation in the ATSE model. Overall, the ATSE LCOE results are slightly higher than the IEA results for the same assumptions.

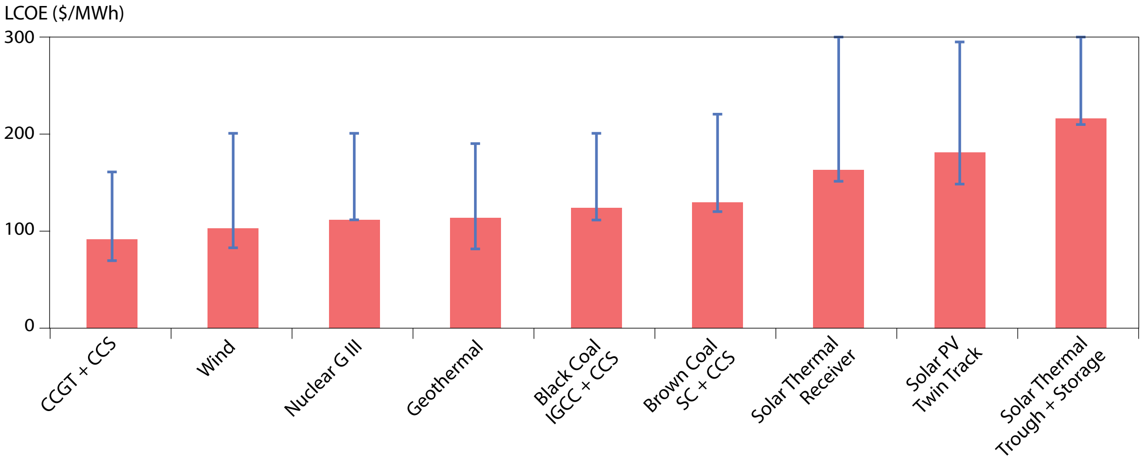
- Comparison with the **Geoscience Australia/ABARE** report using EPRI data shows that there is generally good agreement between the ATSE results and the lower end of the LCOE ranges shown in the report[28], under the same conditions. The comparison is shown in Figure 2 for 2030. Both results shown do not include a CO_2 price and use an exclusive of inflation before-tax cost of capital of 8.4%[29]. The ATSE results are based on the SRG reference data set. Overall, the ATSE results using the SRG reference data are slightly lower than the range of EPRI results. However, the variation in LCOE as a

Figure 1 Comparison between IEA reported LCOE values in 2015 and those calculated by the ATSE financial model



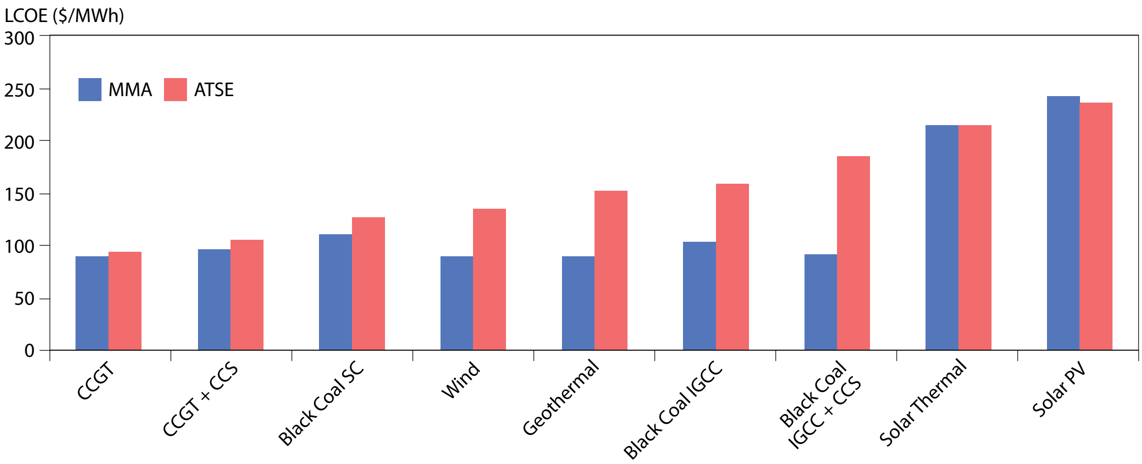
Blue histogram values are those reported by IEA and red values are as calculated by the ATSE model using the same input data as IEA. WACC = 5%; CO_2 price = US$30/t$CO_2$; no REC value; no depreciation or corporate tax; ATSE results use the IEA data set

Figure 2 Comparision between Geoscience Australia/ABARE reported LCOE values and those calculated by the ATSE financial model in 2030



Cost of capital = 8.4% before tax or WACC=7% after tax; no CO_2 or REC price included; ATSE results use the SRG reference data set
Red histogram values are those calculated by the ATSE model; dark blue error bars represent the range from the Geoscience Australia/ABARE report

Figure 3 Comparison between McLennan Magasanik Associates reported LCOE values and those calculated by the ATSE financial model in 2030



After-tax WACC=10.2%; CO_2 price US$67/t CO_2; no REC value; ATSE results use SRG reference data set
Red histogram values are those calculated by the ATSE model, while the blue histogram values are from MMA

function of the type of technology deployed is very similar in both cases, at least when compared with the lower end of the range of values for each technology.

- Comparison with the **MMA** results is shown in Figure 3. In both cases the after-tax WACC was 10.2% and the Treasury/Garnaut CO_2 model price in 2030 was used (\$67/t CO_2). Here, the ATSE calculated LCOEs using the SRG reference data are similar in some cases (for example, gas-fired technologies and solar technologies) but are significantly higher in the case of wind, coal fired and geothermal technologies. This is possibly due to the lower capital costs adopted for these latter technologies by MMA relative to EPRI and the SRG reference data set. It is assumed that the lower LCOE for IGCC with CCS technology compared with IGCC in 2030 is due to the relatively large CO_2 cost impost on IGCC in 2030 and the lower capital cost differentials between the two technologies in the MMA data set. In the ATSE analysis, the CO_2 cost in 2030 is insufficient to overcome the capital cost differential between IGCC and IGCC with CCS.

It is concluded from these comparative studies that the ATSE financial model based on the calculation and discounting of free cash flows shows the same trends in LCOE as most of the recently published work. However, the results are clearly sensitive to the assumptions on capital costs, cost of capital, fuel and operating costs, CO_2 price, and so on. In the results that follow, the SRG reference data set has been used for the input costs, while the CO_2 price has been taken from the Australian Government Treasury/ Garnaut modelling based on a global emissions trading scheme. The EPRI assumed after-tax weighted average cost of capital of 7% has been used throughout, except where noted.

3.2 CALCULATION OF LEVELISED COST OF ELECTRICITY FOR INDIVIDUAL TECHNOLOGIES

Following the above comparison with previously published LCOE data from other sources and under different assumptions, a standard set of conditions was chosen for applying the ATSE model to comparing new technologies, all on the same basis into the future. Assumptions in the calculation of LCOE (in addition to those already discussed) were:

- The SRG reference data discussed above and detailed in Appendix A was used for capital and operating costs for each of the technologies, except where noted previously for operating costs associated with nuclear technology[30].
- The learning curves from the SRG reference data were used to provide the relevant cost parameters at the year of investment.
- Different construction times were used for different technologies, as detailed in Appendix A. The overall capital cost from the Reference Data was allocated proportionately to each of the construction years, and discounting at the WACC commenced on all cash flows in year 1.
- The facility life of the technologies varied according to the technology, as detailed in Appendix A. Residual value at the end of the facility life was taken to be zero.
- A Renewable Energy Certificate (REC) price of \$50/MWh was credited as a revenue stream to the annual cash flows up to 2030 for eligible technologies.
- For the LCOE calculations, the mean CO_2 price (in US\$/t CO_2) as modelled by the Australian Government Treasury/Garnaut was used as the CO_2 price at the year of investment, and then held constant for the life of the facility (in a similar fashion to the mean electricity price). Figure 4 shows the Treasury/Garnaut CO_2 price trajectory over time, while Figure 5 shows the corresponding wholesale electricity price relationship. Based on a delay in a national or global emissions trading scheme following Copenhagen, the CO_2 price in assumed in this work was US\$20/t CO_2 commencing in 2010, with a \$0.90 AUD to USD exchange rate. A slope of +\$2.33US per year per tonne of CO_2 was assumed for the rate of change of CO_2 price, this rate of change being derived from a linear fit to the average of the Treasury/Garnaut model results. No relationship between the CO_2 price and electricity price was assumed for the LCOE calculations[31].

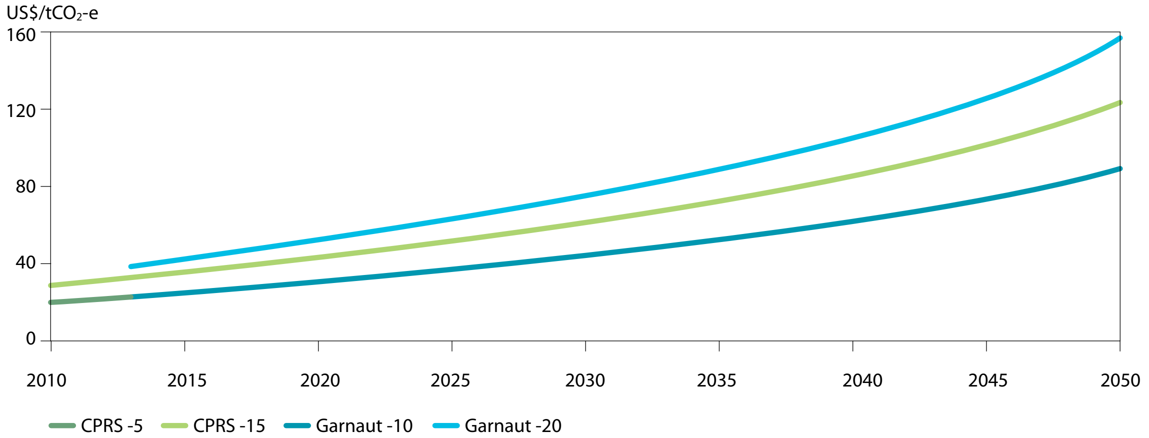
- For the LCOE calculations, fuel prices were taken as the price in the year when the investment first commenced and held constant for the life of the facility.
- Cash flows were discounted at the assumed after-tax WACC of 7% (exclusive of inflation).
- For the remote renewable technologies there was no extra cost impost assumed for new electrical transmission infrastructure.

Figure 6 shows the present LCOE financial model results for LCOE in 2020, 2030 and 2040 using the above assumptions. Figures 7, 8 and 9 show the same results ranked by technologies for each of the years. In the case of geothermal, the most favourable regional situation is shown, as assessed by the Australian Geothermal Energy Association for the SRG.[32]

LCOE Results Overall

The LCOE results in Figure 6 show that the cost of electricity required by an investor to achieve the cost of capital using the assumptions noted varies significantly with the investment year. For example, there are large reductions in LCOE for the solar technologies as time goes on because of their steep learning curves. Similarly, in the early years the renewable technologies receive the benefit of the Renewable Energy Certificates (RECs), while in the later years those technologies emitting CO_2 become more expensive as they are required to meet the additional cost associated with CO_2 emissions. Coal and gas-

Figure 4 Global CO_2 emission prices 2010-2050

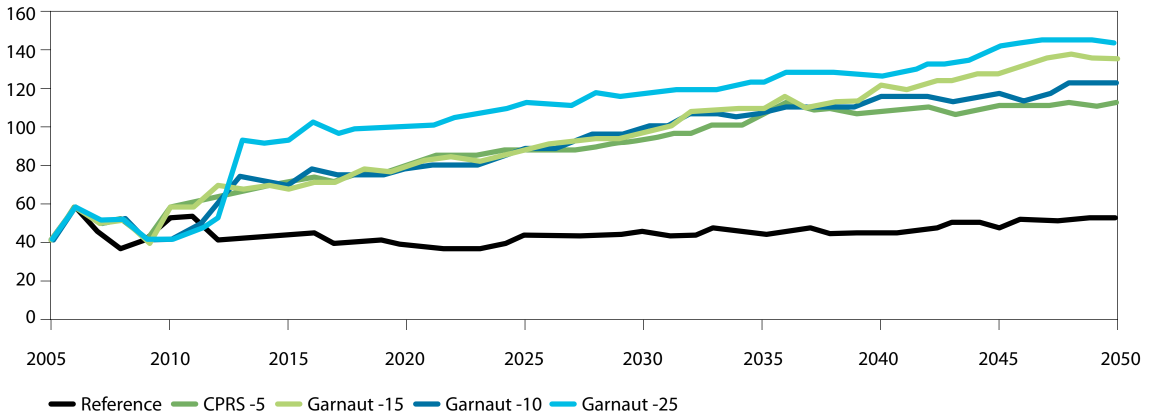


Note: Price in 2005 US dollars

Source: Treasury estimates from GTEM

(Reproduced from *Australia's Low Pollution Future: The Economics of Climate Change Mitigation*[33], with permission.)

Figure 5 Australian wholesale electricity prices 2010-2050



Note: Price in mid-2007 dollars

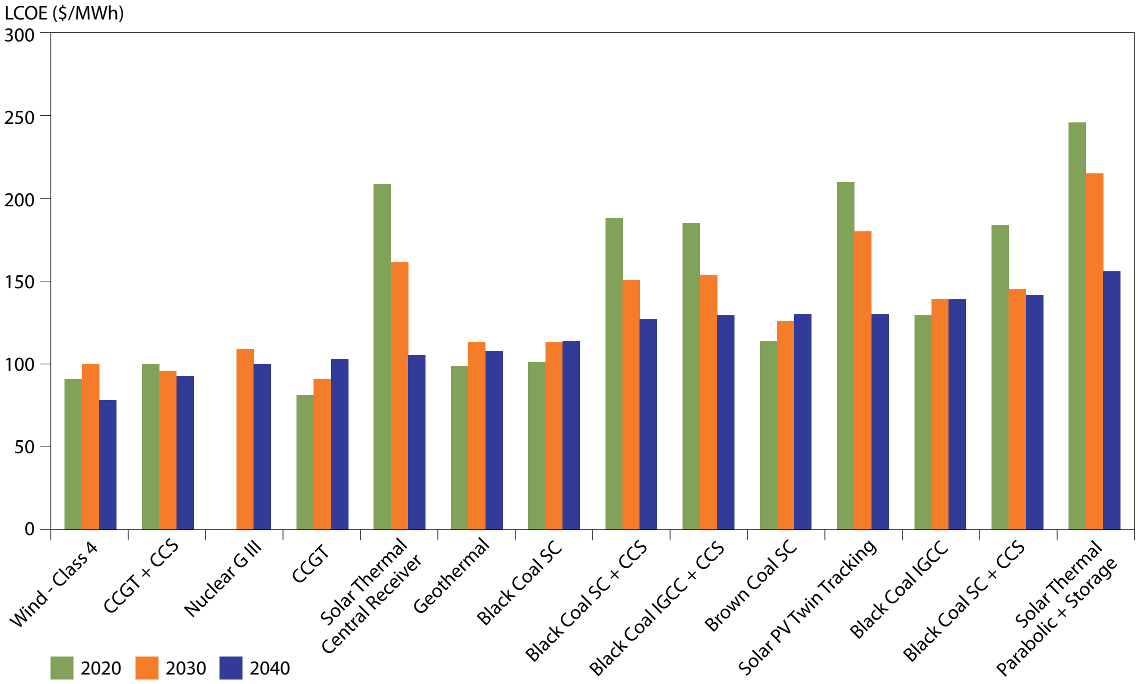
(Reproduced from *Australia's Low Pollution Future: The Economics of Climate Change Mitigation*[34], with permission.)

based technologies that utilise carbon capture and storage have relatively constant LCOE over time as the improvements in efficiency are matched by the costs of CO_2 emission and sequestration.

LCOE Results 2020

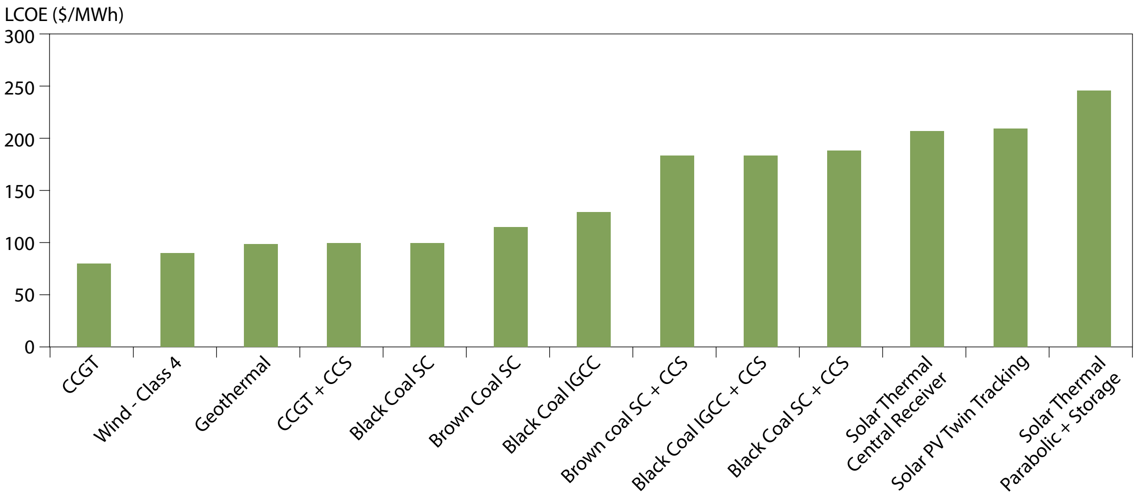
The LCOE results for 2020 are shown in Figure 7. A linear model fit to the Treasury/Garnaut model prediction for wholesale electricity price in 2020 gives a price of $72/MWh, with a CO_2 price of US$43/t CO_2 emitted. As can be seen this wholesale electricity price is lower than the LCOE for all technologies except wind power at good wind sites and geothermal technology in favourable regions, both with a $50/MWh REC benefit.

Figure 6 Levelised cost of electricity results for 2020, 2030 and 2040 as a function of technology; ranked for 2040



Including REC value $50/MWh until 2030 and Treasury/Garnaut CO_2 prices of US$43/t, US$67/t and US$90/t respectively from 2020, 2030 and 2040

Figure 7 Ranked levelised cost of electricity results for 2020 as a function of technology



Including REC value of $50/MWh until 2030 and constant Treasury/Garnaut CO_2 price of US$43/t from 2020
Predicted Treasury wholesale electricity price is $72/MWh

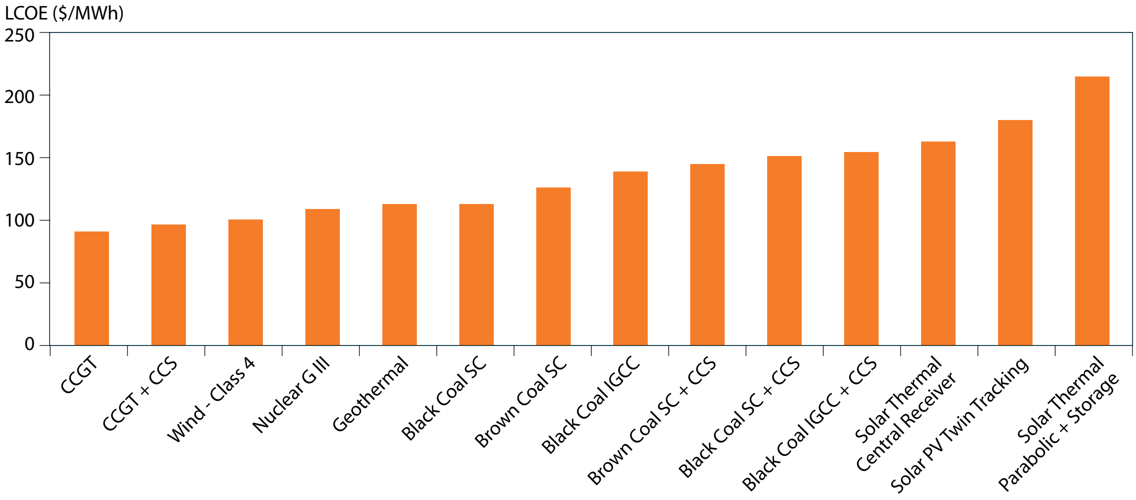
There are a number of technologies in 2020 having LCOEs between $100 and $150/MWh, and a second group having higher levelised costs, above $150/MWh. This latter group includes the coal carbon capture and storage technologies and the solar technologies. By the assumptions and measures used here, these technologies are clearly uneconomic at the electricity price envisaged in 2020.

LCOE Results 2030

The LCOE results for 2030 are shown in Figure 8. The Treasury/Garnaut wholesale electricity price in 2030 is $95/MWh, or approximately twice the current (2010) price exclusive of inflation. An investment in 2030 does not attract any of the current REC benefits, so the renewable energy technologies compete directly with the other technologies by 2030. Technologies that emit CO_2 now carry a significant CO_2 emission cost, even, to a lesser extent, in the case of CCS where a 90% capture rate for CO_2 has been assumed, along with a $10 to $30/t$CO_2$ geological sequestration cost.

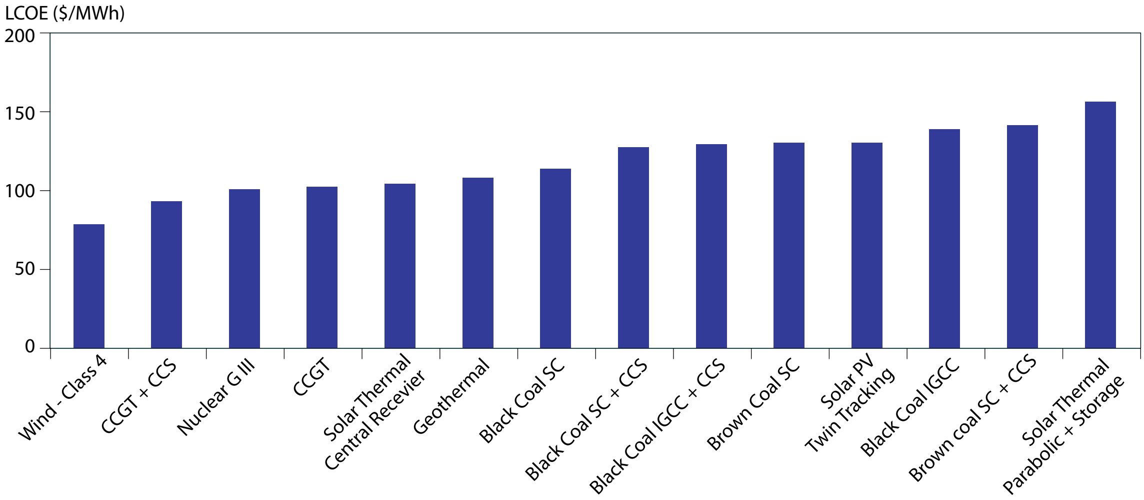
As can be seen for 2030 in Figure 8, with a Treasury/Garnaut US$67 CO_2 price and a $96/MWh wholesale electricity price, wind in less favourable sites (Class 4), geothermal in favourable regions and

Figure 8 Ranked levelised cost of electricity results for 2030 as a function of technology



Constant Treasury/Garnaut CO_2 price of US$67/t from 2030. Predicted Treasury wholesale electricity price is $95/MWh

Figure 9 ATSE levelised cost of electricity results for 2040 as a function of technology



Constant Treasury/Garnaut CO_2 price of US$90/t from 2040. Predicted Treasury wholesale electricty price is $112/MWh

CCGT technologies are predicted to be financially economic for investment in 2030 with LCOEs around $90/MWh. Nuclear power is becoming close to economic, while the coal-based technologies including CCS have LCOEs around $120-140/MWh. The solar-based technologies still have LCOEs over $150/MWh, notwithstanding their relatively rapid fall in cost over the preceding decade.

LCOE Results 2040

The LCOE results for 2040 are shown in Figure 9. In 2040 the Treasury/Garnaut CO_2 price is US$90/t CO_2 and the assumed wholesale electricity price has risen to $112/MWh in current dollars. In 2040, technologies that emit CO_2 have high costs associated with this emission under the Treasury/Garnaut model.

Figure 9 shows that the range of LCOEs in 2040 has become narrower, with all technologies in the range $70 to $150/MWh. This is due to their continuing learning curves and the balance between higher efficiency and their CO_2 emissions (if any). Many technologies have become lower in LCOE than the mean of the Treasury/Garnaut predicted $112/MWh wholesale price. These include (in rank order):

- Wind (Class 4)
- CCGT gas firing with CCS
- Nuclear Gen III
- CCGT gas firing
- Solar thermal central receiver (DNI=6 kWh/m^2/day)
- Geothermal, in favourable regions.

In addition, some of the remaining technologies are only marginally above the predicted wholesale electricity price, and this is no doubt within the uncertainty range attributable to uncertainties in the inputs to the LCOE model.

It can be concluded, therefore, that by 2040 there will be several technologies that could be economically used to generate power in Australia, provided there is price placed on CO_2 emissions (and therefore electricity) that is the same order as that proposed by Garnaut and Treasury.

The fossil fuel-based technologies are favoured by the above LCOE results. This is because the CO_2 price and natural gas price have been assumed to be constant over the life of the investment, like the electricity price. In reality, as shown by Treasury/Garnaut modelling, all these prices should increase with time and thus influence the costs, revenues and cash flows that a new technology experiences over its life. This issue is addressed in the following net present option value analysis.

4 Option Values – Background

4.1 INTRODUCTION

In finance, an option is a financial instrument that gives its owner the right, but not the obligation, to engage in a specified future transaction on an asset, commonly the purchase or sale of a traded stock. There are many kinds of financial options and many techniques, employing complex mathematics and statistics to assess the influence of future uncertainties, for estimating their values.

Real options valuation is a financial technique applied to a 'real', as distinct from financial, asset, like a project to commercially develop a piece of technology. A real option value[35] is also the value of a choice to make a business or investment decision. It is particularly suited for evaluating an investment under conditions of uncertainty and volatility, for example in future costs, prices, product demand or asset value. The method is intended to capture the value of any progressive resolution of future uncertainties as a project progresses, and of the associated managerial flexibility to wait, abandon, or expand on an investment opportunity.

Options valuation has been widely used to help determine investment strategies for research and development programs, which are prominent examples of activities having large uncertainties that tend to change as the program progresses. It is therefore logical to investigate it as a tool for assessing the value of future electricity generating technologies. In addition to their technical uncertainties (which are not included in the subject of this study), these technologies face explicit financial uncertainties. Their costs are uncertain because *inter alia* the technology is not yet fully developed or demonstrated and future prices of the fuel for that technology are subject to expected but as yet unknown changes. Future electricity price is uncertain and because of unknown future policy and market responses to climate change, a price on carbon dioxide emissions is also uncertain.

4.2 NET PRESENT OPTION VALUE

As discussed previously, this study introduces the concept of "net present option value", NPOV, in relation to electricity generating technologies. This is the option value calculated by discounting, to the present time at the firm's cost of capital, both the future commercialisation investment and the future net revenues from the investment, and determining the probability distribution of NPV. NPOV is then given by the aggregate part of the future NPV distribution where NPV is greater than zero. The rationale for this is that the investor would only proceed with the investment if the NPV is positive at the time of the investment in the future, and would abandon the investment if the NPV is negative. The ability to have this abandonment option has value to the investor today, since there is only exposure to the upside in the distribution of NPV for the investor in the future.

It should be noted that the NPOV calculated in this study is <u>not</u> the same as the real option value calculated by conventional option valuation techniques where the risk-free rate is used to discount the exercise price. It has been pointed out that conventional real option value approaches do not assume a form for the future probability distributions of the financial parameters, but use equivalent "risk-neutral" parameters[36]. As explained above, a different practical approach has been adopted in the present study, where the future NPV probability distribution has been used to determine the present value of the abandonment option, NPOV.

Further detail illustrating the concept of net present option value and methods for its determination is given below and in Appendix B. The following points provide an introductory overview of the concept of net present option value:

- Options capture the value embodied in the future choice available to an investor (or other stakeholder, such as a manager) to abandon or alter an investment strategy when further facts emerge about the financial viability of the investment.
- Net present option value is the upside in the net present value (NPV) probability distribution due to the variance in the distribution of NPV, or the uncertainty about the future.
- A firm should theoretically invest an amount, in today's dollars, up to the net present option value, in order to have the ability to make a commercial investment at the future date.

Net present option values of new generating technologies have characteristics that are different from LCOEs. Table 1 below outlines these differences.

Table 1 Comparison of the characteristics of LCOE and NPOV

LCOE	Net Present Option Value (NPOV)
Parameters are deterministic.	Parameters are probabilistic
LCOE is the constant electricity price when the mean NPV is zero.	Net present option value is the upside in the NPV distribution where NPV is greater than zero.
LCOE is the electricity price required for zero NPV at today's date.	Net present option value is the upside value at the investment date discounted at the cost of capital to today's date.
LCOEs for different technologies are compared relative to a constant electricity price.	Different technologies are compared in terms of NPV, net present option value magnitude and uncertainty in the NPV distribution.
In this work, there is a constant electricity and CO_2 price for the life of the facility.	Electricity and CO_2 prices, in this work, follow an upward trajectory for the life of the facility, with volatility.
	Net present option value gives an indication of how much expenditure could be made now to enable the option for commercial investment in the future, given specified learning curves for the technologies and future price scenarios.

Option value studies for electricity power generation in Australia have been conducted previously. The CRC for Coal in Sustainable Development published several reports examining options for electricity generation and the impact of carbon price uncertainty on investment decisions[37, 38, 39, 40]. This previous work undertook national generation portfolio modelling using CSIRO's Electricity Market Model to determine technology portfolios mainly comprising fossil fuel technologies in the future. It also used a real options approach to determine optimum investment timing for the different technologies under uncertain carbon pricing scenarios using the binomial method. While there are some similarities in the principles used, the present ATSE work is broader in scope, employs a different computational approach, and incorporates uncertainty in other parameters, such as the costs of the technologies, into the analysis.

4.3 PARAMETERS IN THE ANALYSIS OF NET PRESENT OPTION VALUE

The important basic parameters used for analysing net present option values are:

- S – the net present value of future annual free cash flows from an investment for time>t, not including the investment required in years 1 to t to secure these cash flows.
- X – the net present value of the investment required in years 1 to t to secure the free cash flows that make up "S".
- S/X – the ratio of S to X, where S/X = 1 is equivalent to NPV=0.
- σ – the volatility per year of values of (S-X), or S where X is constant.

In the Black-Scholes analytical method (see Appendix B), the value of "S" is the future value of the share price and the value of is "X" is the constant option exercise price. The Black-Scholes equation uses the parameters S/PV(X) and $\sigma\sqrt{t}$, where PV(X) is the present value of X discounted at the risk-free rate of interest. A comparison of option value results obtained using different calculation methods is given in Appendix D.

In the work here, "X" varies with time (the technology learning curve for capital cost) and is probabilistic and uncertain. The exercise price "X" is also not paid instantaneously in the present analysis when compared with a share market option, since there is a different capital expenditure profile for each technology over time. Depending on the technology the capital investment may be made over several years (see Appendix A). For the purposes of calculation of option values in this work both "S" and "X" have therefore been discounted at the cost of capital to today's value from the future cash flows to calculate the probabilistic NPV distribution. To distinguish this result from the well-known "real option value"[41], the option values for the distribution S-X, calculated by the Direct Monte Carlo method here, have been termed "net present option value" (NPOV). The relative cumulative volatility term associated with the distribution S-X is defined in Appendix B.4 and the assumed volatilities for the various parameters involved are discussed in Appendix A.7.

4.4 INPUT DATA AND LEARNING CURVES

In the results that follow, SRG data[42] were used, unless noted separately. However, these data do not contain probabilistic values for the parameters in the free cash flow model that is used to calculate "S", apart from the range of values in their scenario analyses. In the work here, the values of σ have been estimated as described in Appendix A to yield reasonable distributions of the important parameters at the future year in question, taking into account the range of values implied by the AEMO scenarios for the future[43]. Different annual volatilities have been assumed, depending on whether the new technology has been commercialised to date or not. Appendix A.7 also details the parameters that were ascribed probability distributions for the option value calculation and those that were not.

Apart from the CO_2 price trajectory information discussed below, the general assumptions used in the financial calculation were as discussed previously in the section on LCOE. This includes the natural gas price escalation assumption of +2% per year and coal prices for new coal technologies from the SRG reference data. Full details of the assumptions are given in Appendix A and sensitivity analysis of the key influencing parameters is provided in further detail below.

The learning curves from the SRG reference data set for cost reduction and efficiency improvement have been used to determine the net present option values for each of the new technologies.

Each new technology has been analysed independently, and no attempt has been made in this work to create a portfolio of technologies to satisfy Australia's energy requirements in the future. Similarly no costs have been allocated to electricity infrastructure developments such as new interstate or intra-state transmission lines. There is no feedback loop in the present study to determine whether the net present option value calculated for any particular technology is sufficient to achieve the learning curves assumed and provide the necessary enabling infrastructure. However, some sensitivity analyses have been undertaken and are presented later in the report where some learning curves have been modified and the resulting increase in net present option values determined.

4.5 CO_2 AND ELECTRICITY PRICE TRAJECTORIES

In order to calculate net present option values with the ATSE free cash flow model, estimates of the CO_2 and the wholesale electricity prices over time are required in the financial model. The Australian Government Treasury, together with Garnaut, have provided the most authoritative indication for future Australian prices of these variables, as shown in Figures 4 and 5 previously. In the work here, the relationship for CO_2 prices over time was fitted to a linear relationship for the mean CO_2 price. The standard deviation on the relationship to provide the volatility on CO_2 price was taken as the boundary provided by the Garnaut models, together with increasing price volatility with time due to uncertainty. The approximation used is very similar to the Treasury/Garnaut trajectory shown in Figure 4. Sensitivity of net present option value to the rate of change of CO_2 price based on this linear model is provided later in the report. In addition, several different model forms of the CO_2 price trajectory have been evaluated to determine the influence of the model form on calculated option values. See Appendix C for results that demonstrate the sensitivity of NPOV for different models of CO_2 price trajectory. A log-linear correlation was used to relate the CO_2 and wholesale electricity prices to match the Treasury/Garnaut model results in Figure 5 in order to calculate the revenue stream from sales of electricity for the parameter "S". Further details of this approximation are given in Appendix A.4.

5 Net Present Option Value Results

5.1 RESULTS FOR INVESTMENT IN 2020, 2030 AND 2040

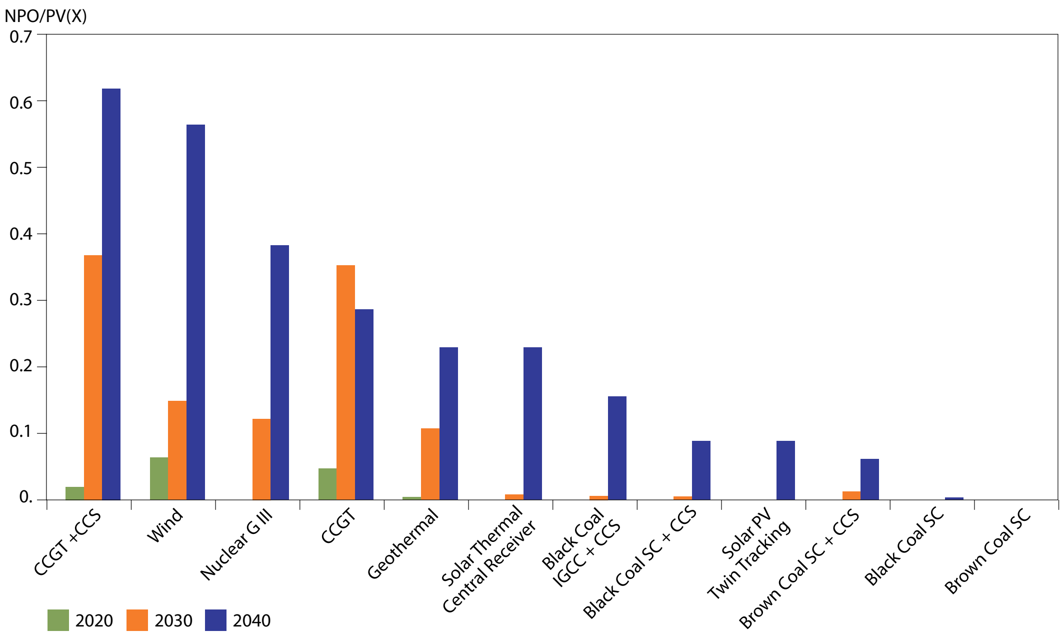
Using the Net Present Option Value (NPOV) approach, as described in Section 4.3, the normalised net present option values (NPOV/PV(X)) calculated using the direct Monte Carlo Method for a range of new technologies for power generation are shown in Figure 10 for 2020, 2030 and 2040. The technologies are ranked in this figure according to their 2040 values. The results have been normalised by dividing the NPOV by the exercise price to account for the wide range of capital costs at the different times for different technologies and scales of operation. Nuclear technology is not included for 2020 because it is assumed that Australia will not be ready for its introduction by then.

The results for net present option value are presented here in two ways. First, the normalised NPOV results are presented as a histogram comparing the technologies for investment at different times. Second, the results are presented in a two-dimensional options space diagram analogous to that proposed by Luehrman but taking into account the varying exercise price X.

NPOV for investment in 2020

The net present option values calculated for 2020 in Figure 10 are less than 10% of the exercise price. Only wind (Class 4) has values of S/X around 1.0 (i.e. positive NPV), with gas-based and geothermal technologies having S/X values around 0.7. This result agrees with the LCOE results presented earlier in terms of technology ranking. It is noteworthy that both of the gas-fired technologies have a relatively high net present option value. This is because they face increasing gas and CO_2 prices over their lifetime,

Figure 10 Normalised net present option values (NPOV/PV(X)) as a function of technology for 2020, 2030 and 2040



with the volatility generated by uncertainty in gas and CO_2 prices in the future increasing the net present option value. For investment (exercise) in 2020, CCGT has a higher net present option value than CCGT with CCS.

NPOV for investment in 2030

The net present option values for investment in 2030 in Figure 10 are significantly higher than those in 2020. This is because the exercise price "X" has decreased due to technology learning, and the positive cash flows "S" have generally increased due to increased wholesale electricity prices. Also, the REC benefit has now ended and the added price for CO_2 has increased for those technologies emitting CO_2. Thus, the net present option values of gas fired CCGT and CCGT with CCS are almost equal by 2030, with both having S/X > 1.

Wind (Class 4) and favourably located geothermal technologies also have relatively high-ranking net present option values in 2030 and S/X > 1. Nuclear power is also relatively high-ranking by 2030 and NPV positive. This is because nuclear power, although having higher capital costs, has a high capacity factor, a relatively low fuel price, and is not burdened by a CO_2 charge. Note that Australia has no nuclear power plants and has legislation in place preventing these plants from being constructed and operated.

Although the solar-based technologies have steep learning curves, in 2030 they still have high capital costs and this leads to low net present option values driven by their low capacity factors, even in solar conditions where there is relatively high direct normal irradiance (DNI) = 6[45]. Their NPVs are negative, with S/X ratios in the range 0.5-0.7.

Coal-based technologies are calculated to have low net present option values and negative NPVs for investment in 2030. The coal-based carbon capture and storage technologies have not by then progressed along the learning curve sufficiently to have significant net present option value for investment by 2030, even with the assumed relatively conservative transport and sequestration costs of \$10-\$30/t CO_2[46].

NPOV for investment in 2040

By 2040 the option values of the technologies have increased significantly under the influence of high wholesale electricity prices. Figure 10 shows that the technologies that have relatively high net present option values in 2030 continue to have high NPOVs in 2040. These include CCGT with CCS, wind, favourable-region geothermal, nuclear and CCGT.

By 2040 some of the other alternative technologies are now achieving significant net present option value, albeit lower than those mentioned in the previous paragraph. These include efficient solar thermal technologies in good locations and coal-based firing with carbon capture and storage. Solar photovoltaic technology, even with a steep learning curve and in a good location, has a smaller net present option value than these others in 2040. A more detailed sensitivity examination of solar thermal and geothermal technologies in terms of their NPOVs is given in section 5.8.

New black and brown coal supercritical pulverised coal combustion technologies have little or no net present option value in any of the years into the future under the Treasury/Garnaut CO_2 pricing model. This is because the predicted cost of their CO_2 emission outweighs the benefit from increasing electricity prices and improvements in efficiency due to learning.

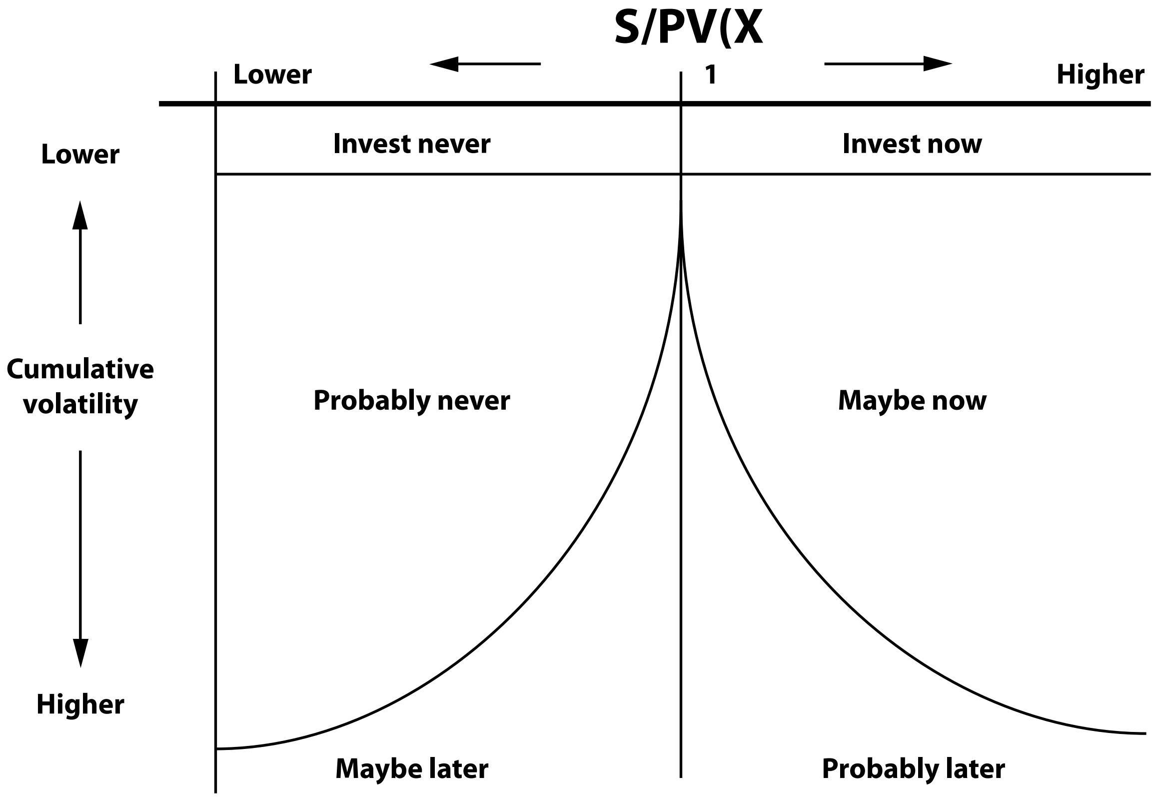
The previously cited studies by the CRC for Coal in Sustainable Development[47, 48, 49] did not publish numerical option values, but rather presented data on when an investment should be made in a technology, or not. They found that CCGT would be an optimum investment in the near-term (around 2015), but that CCGT with CCS technology would only be justified after the real carbon dioxide price became greater than \$70/tCO_2 (after 2025). Their results were also sensitive to the assumed gas price trajectory. They showed that there was no option value for supercritical pulverised coal plants without CCS at any time under their carbon-pricing regime. It was found that coal technologies with CCS were only justified in terms of option value for carbon dioxide prices in the range \$50 to \$100/MWh (real), depending on the technology. These conclusions are broadly confirmed by the numerical net present option value results presented here for the fossil fuel technologies.

5.2 OPTIONS SPACE DIAGRAM

Luehrman has published two key papers that provide a succinct analysis of real options application[50]. The second paper describes a method for graphically representing a portfolio of real options in terms of the two parameters S/PV(X) and cumulative volatility, $\sigma\sqrt{t}$. These parameters are those that determine the option value calculated by the Black-Scholes relationship (see Appendix B.3). Figure 11 shows this diagram, where it can be seen that there are zones where a particular project might sit in the "Options Space", and these zones indicate whether the project should go ahead now, go ahead later, or be abandoned. Thus, at high S/PV(X) and low $\sigma\sqrt{t}$ a project would be suitable for investment (its NPV is positive with little option value due to low volatility), whereas a project with low S/PV(X) and low $\sigma\sqrt{t}$ should be abandoned (its NPV is negative and it has low option value due to low volatility). Projects with other combinations of these two parameters sit on the diagram at various stages of readiness for investment. Thus, even though projects have a negative NPV (S/X<1), they could still reside in the "maybe later" part of the diagram due to high volatility, and so on.

Luehrman's analysis was based on projects with constant exercise price "X" and linear increase of the variance in "S" with time. Under these conditions the Black-Scholes equation can be used to calculate the real option value using the cumulative volatility parameter $\sigma\sqrt{t}$ and the NPV parameter S/PV(X).

Figure 11 Options Space Diagram



Source: Luehrman *op cit* (reproduced with permission)

5.3 RESULTS PLOTTED ON THE OPTIONS SPACE DIAGRAM

The options space diagram of Figure 11 was developed to describe real options calculated by the Black-Scholes relationship. In the case of new technologies for power generation there is drift and volatility on both S and X with time and the simple cumulative volatility term $\sigma\sqrt{t}$ does not necessarily apply. This is because the volatilities of both S and X, as well as the NPV term S/X, influence the net present option value. Net present option value here is also based on the NPV probability distribution in the future, rather than the Black-Scholes relationship. Nevertheless, it is worthwhile to examine whether the principles inherent in the diagram are useful in the case of NPOV. In this case an alternative relative cumulative volatility parameter has been used based on the variance of both S and X, as given in equations B.1 and B.2 in Appendix B.4.

Figure 12 shows the net present option values of the various technologies plotted on the described "Options Space" using the new relative cumulative volatility term Rv on the ordinate and the parameter (S/X) on the abscissa. Since both S and X are discounted at the cost of capital to calculate NPOV, the ratio of S/X is a measure of NPV, with a ratio of S/X=1.0 representing an NPV of zero at the given cost of capital. Figure 12(a) shows the diagram for investment (exercising the option) in 2020, 12(b) shows the diagram for investment in 2030, and figure 12(c) shows the diagram for commercial investment in 2040. In 2020, only those technologies with some net present option value are shown. In the diagrams, the size (area) of the bubbles is indicative of the relative net present option value. Higher cumulative volatility implies higher net present option value due to increased variance in the (S-X) distribution, while a higher ratio of positive cash flows to investment required (i.e. S/X) implies higher net present option value due to to increased NPV. A ratio of S/X > 1.0 implies positive NPV and ratios of S/X < 1.0 have negative NPV. The two geothermal bubbles refer to geothermal regional variations in Australia[51].

The diagrams in Figure 12 show how the net present option values for the different technologies grow over time as revenues increase due to the escalating electricity price. The two components of net present option value, the ratio S/X and the cumulative volatility, also both increase over time. The calculated net present option values are highest in 2040.

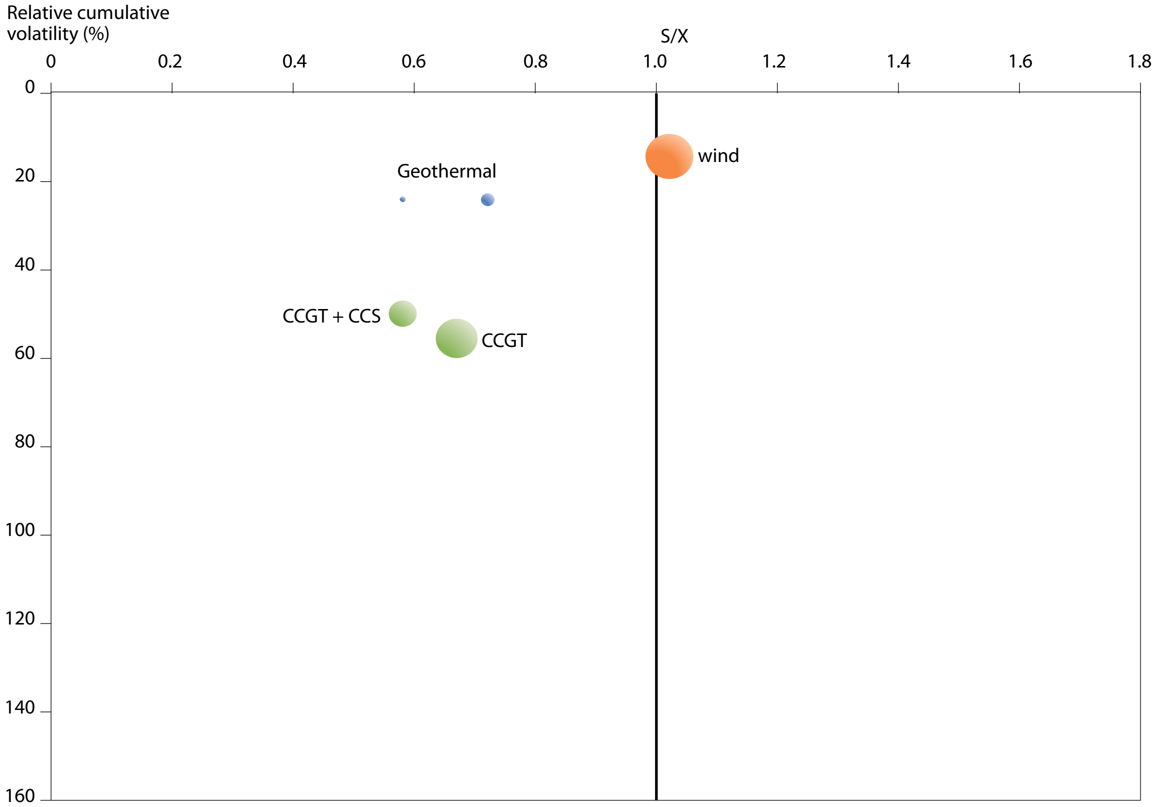
It is useful to make a comparison between the theoretical options space diagram of Figure 11 and the results in Figure 12(c) for investment in 2040, since by then most of the new technologies have a range of option values. As can be seen, the small bubbles in Figure 12(c) for coal-based pulverised coal (pc) technologies without CCS lie in the "probably never" part of the Options Space diagram in Figure 11, with a residual high volatility due to the CO_2 price uncertainty but with very low net present option values due to their low S/X ratios.

The solar thermal central receiver, favourable region geothermal, nuclear, and wind technologies lie in the "maybe invest now" part of the diagram, with positive NPV for investment in 2040.

The gas-fired CCGT with CCS technology has positive NPV in 2040, so is in the "maybe now" part of the Figure 12(c), with the high volatility component of its net present option value associated with gas price uncertainty. The gas-fired technology without CO_2 sequestration, CCGT, has a negative NPV in 2040 due to the high cost of CO_2 and lies in the "probably never" or "maybe later" part of the diagram for investment in 2040, with very high volatility due to gas price uncertainty relative to its capital cost.

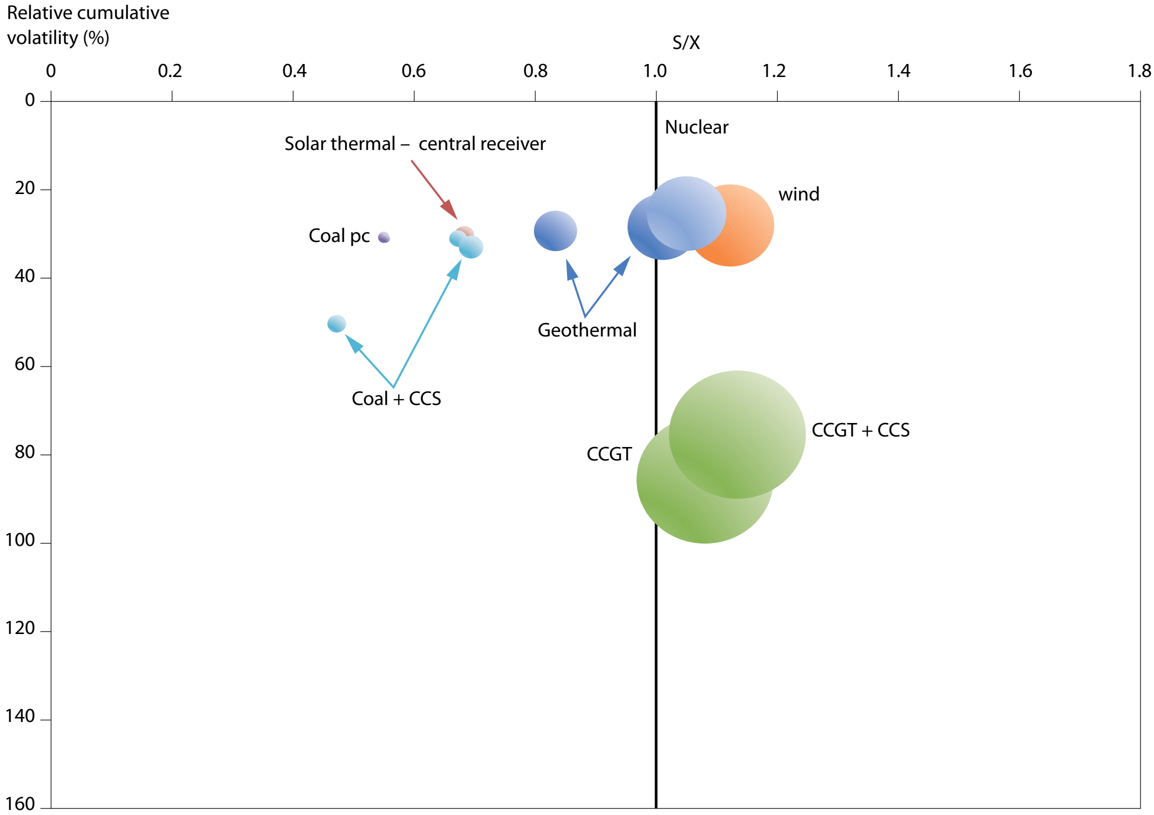
The coal-fired technologies with CCS, solar PV, and higher cost geothermal technologies appear to be in a border-line region around "probably never" and "maybe now" in 2040 based on their NPVs being close to zero and their moderate net present option values, assuming the principles inherent in Figure 11 apply.

Figure 12a Options two-dimensional space for different technologies – 2020



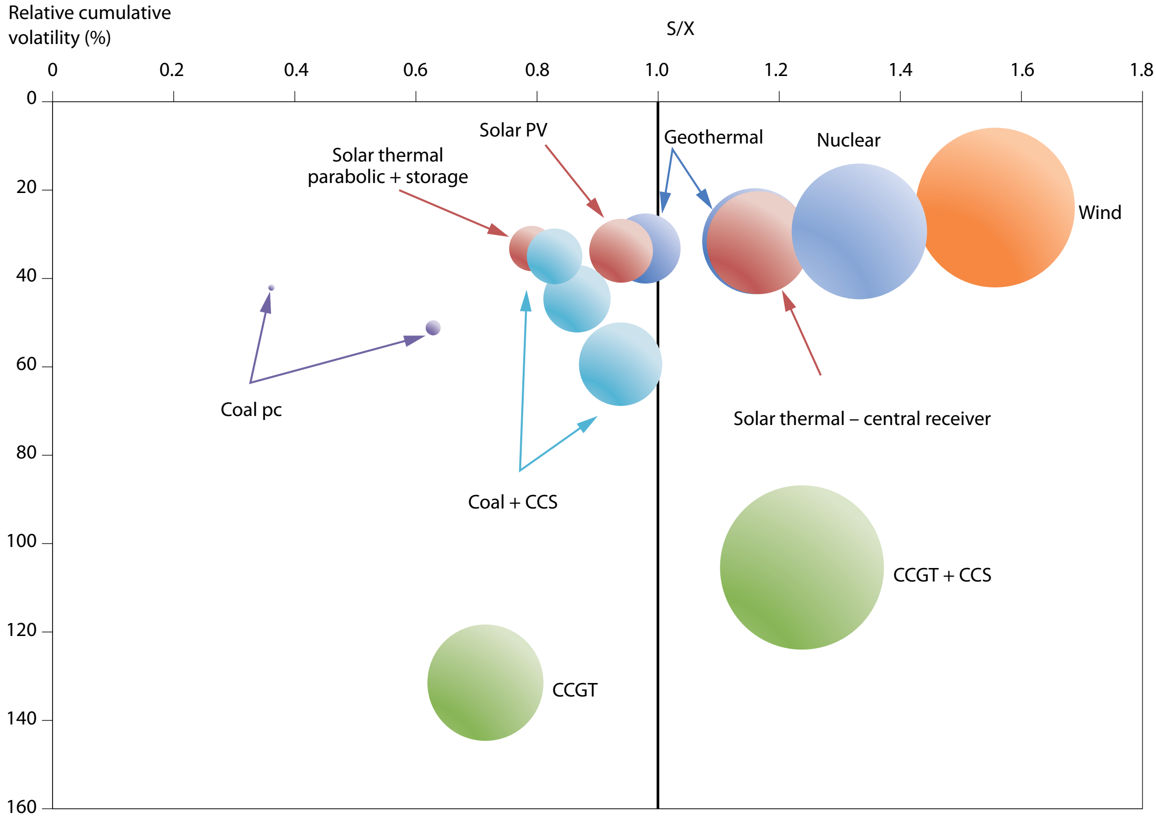
The area of the bubbles is proportional to NPOV/X

Figure 12b Options two-dimensional space for different technologies – 2030



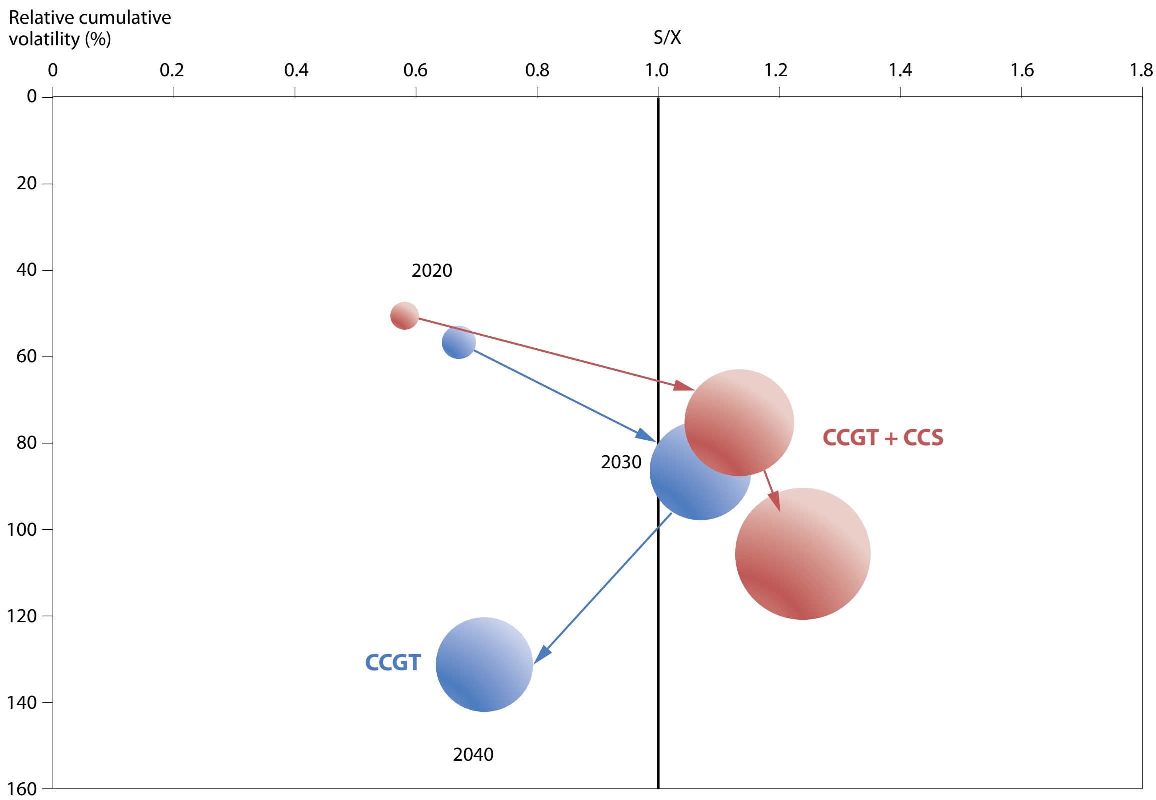
The area of the bubbles is proportional to NPOV/X

Figure 12c Options two-dimensional space for different technologies – 2040



The area of the bubbles is proportional to NPOV/X

Figure 13 Options space diagram for gas-based technologies showing trajectories from 2020 to 2040



Whether these investments will occur then will depend on the key financial parameters:
- the generating company's cost of capital;
- the cost of fuel at the time;
- electricity and CO_2 prices at the time;
- any financial subsidies and incentives;
- the technology learning curves, including thermal efficiency improvement;
- CO_2 elimination efficiencies and CO_2 transportation and sequestration costs for the CCS technologies; and
- location in Australia for the renewables technologies.

Based on this analysis and the assumptions used, further accelerated development work could be required to move these technologies fully into the "maybe now" part of the options space diagram where S/X > 1.0 by increasing the parameter S/X. Some case studies on this acceleration are considered for these technologies in further detail below.

Similar qualitative assessment of the new technologies can be made by comparing Figure 11 and Figures 12(a) and 12(b) for investment in 2020 and 2030. As can be seen, in 2020, wind is the only technology with a positive NPV (S/X>1), whereas by 2030 nuclear, wind, some geothermal and the gas-based technologies have positive NPV under the assumptions used in the study.

As a technology undergoes its learning curve and it is influenced by the external financial forces imposed upon it, its trajectory on the options space changes. Viewed from today, the cumulative volatility term increases due to greater uncertainty and variance in the S and X distributions, while the S/X term changes due to the projected future cash flows. This effect is shown in Figure 13 for the gas-based technologies, where the trajectory from 2020 to 2040 is shown for both the CCGT and CCGT with CCS technologies. As can be seen, the technology without CO_2 storage, CCGT, has highest NPV (or S/X) for investment in 2030. After this, the NPV becomes negative due to the imposed carbon price on its emissions even though the net present option value remains high due to uncertainty in gas and CO_2prices. By contrast, the CCGT with CCS technology increases in both net present option value and NPV after 2030 because its CO_2 emissions are lower.

The results show that the "Options Space" diagram proposed by Luehrman, using the NPV probability distribution to calculate NPOV, appears to be a very useful tool for qualitative comparison of new power generating technologies in the future. The diagram provides a snapshot in time of value of a particular power generating technology to an investor in terms of both the NPV component and the volatility component, as well as the net present option value itself. The diagram should find application in future analysis of power generating options. It would also allow technologies to be "tracked" over time on the options space to commercialisation as more information becomes available. It may also prove useful in the analysis of different technology development scenarios in the future.

5.4 CO_2 EMISSIONS INTENSITY OF FOSSIL FUEL TECHNOLOGIES IN 2040

The net present option value results shown in Figures 10, 12 and 13 are a complex interaction of many factors. The CO_2 emissions intensity is a key parameter that influences the results. This is because the cost of CO_2 emission in 2040 becomes a significant financial impost and therefore a negative to the value of "S" by then for those technologies that emit CO_2. Table 2 shows the calculated CO_2 emissions intensity for some of those technologies that emit CO_2, projected to 2040 by taking into account the learning curves and the assumed higher thermal efficiencies in 2040 shown in Appendix A.

Table 2 Calculated CO_2 emissions intensity for several technologies in 2040.

Technology	CO_2 emissions intensity (tonnes CO_2 per MWh energy delivered)
CCGT with CCS	0.04
Black Coal SC with CCS	0.07
Brown Coal SC with CCS	0.09
CCGT	0.32
Black Coal SC	0.60
Brown Coal SC	0.66

With a CO_2 price of US\$90/tCO_2 in 2040, the cost impost on those technologies without CCS is obvious. The table also shows why CCGT with CCS, even with its higher capital costs and lower efficiency, has a higher net present option value and NPV in 2040 relative to CCGT. Coal technologies without CCS have essentially zero net present option value in 2040 (and in earlier years) due to this effect, notwithstanding their expected significant improvements in efficiency.

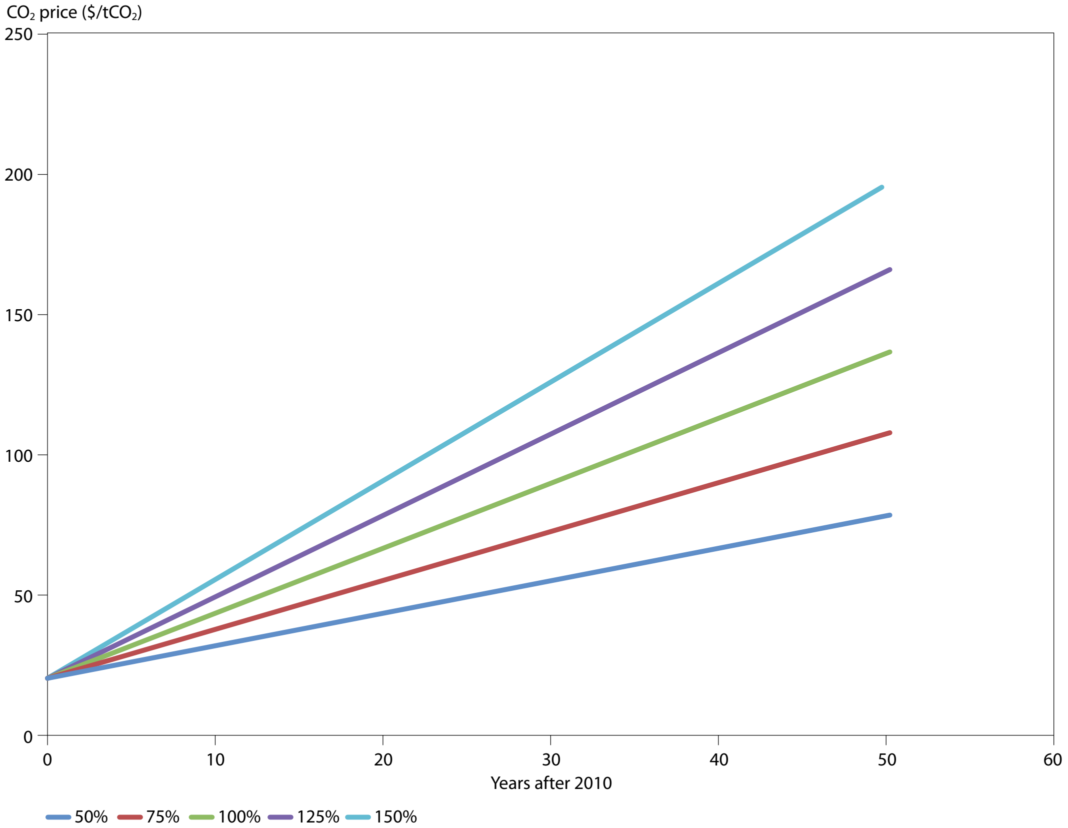
5.5 INFLUENCE OF THE RATE OF INCREASE OF CO_2 PRICE ON NET PRESENT OPTION VALUE

The linear approximation to the Treasury/Garnaut model of CO_2 price trajectory in this work assumes a slope of US\$2.33/tCO_2 per year, with a starting price of US\$20/tCO_2 in 2010. This CO_2 price trajectory, together with a volatility increase of 5% per year, gives the net present option value results shown in Figures 10, 12 and 13. However, the form of any future such price trajectory is unknown. In order to examine the sensitivity of the net present option value results to the rate of change of CO_2 price, a range of CO_2 price trajectories with different slopes has been examined as scenarios. These trajectories of the mean CO_2 price are shown in Figure 14. Superimposed on these mean values is a volatility increase of 5% per year in all cases to give an increasing variance in the CO_2 price distribution as time goes on. The impact of the shape of the CO_2 price trajectory is considered in Appendix C.

Figures 15 and 16 show the change in net present option values for different technologies with change in the rate of CO_2 price increase from 50% to 150% of the Treasury/Garnaut model rate.

It is clear from these figures that the rate of change of CO_2 price (and therefore electricity price) is an important parameter in determining the net present option values of the new technologies. Net present option values for a rate of increase in CO_2 price of half the Treasury/Garnaut model trajectory are only about one quarter of those at the full rate. Conversely, net present option values are significantly higher at 150% of the rate. From these results it is clear that CO_2 prices, and wholesale electricity prices, need to increase significantly in real terms if new technologies are to have investor value in the longer term. This implies the need, in any future scheme adopted, for either an increasing carbon tax or a carbon-trading scheme as a consequence of a decreasing CO_2 emission cap as time goes on. In the absence of such a CO_2 price trajectory, significant direct action in the form of financial subsidies from Government would be

Figure 14 CO_2 price trajectories into the future



Percentages refer to the rate of change of CO_2 price relative to linear approximation of the Treasury/Garnaut model results

Figure 15 Net present option values for different new technologies as a function of the rate of change of CO_2 price for investment in 2030

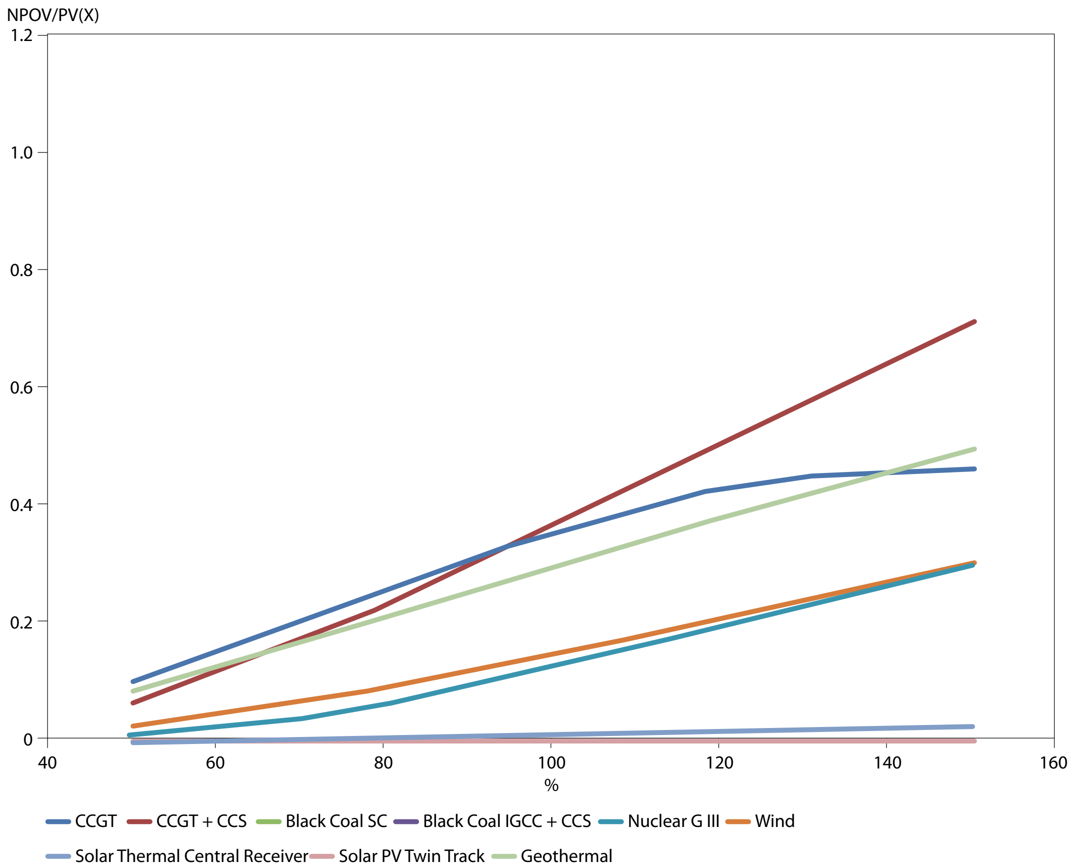
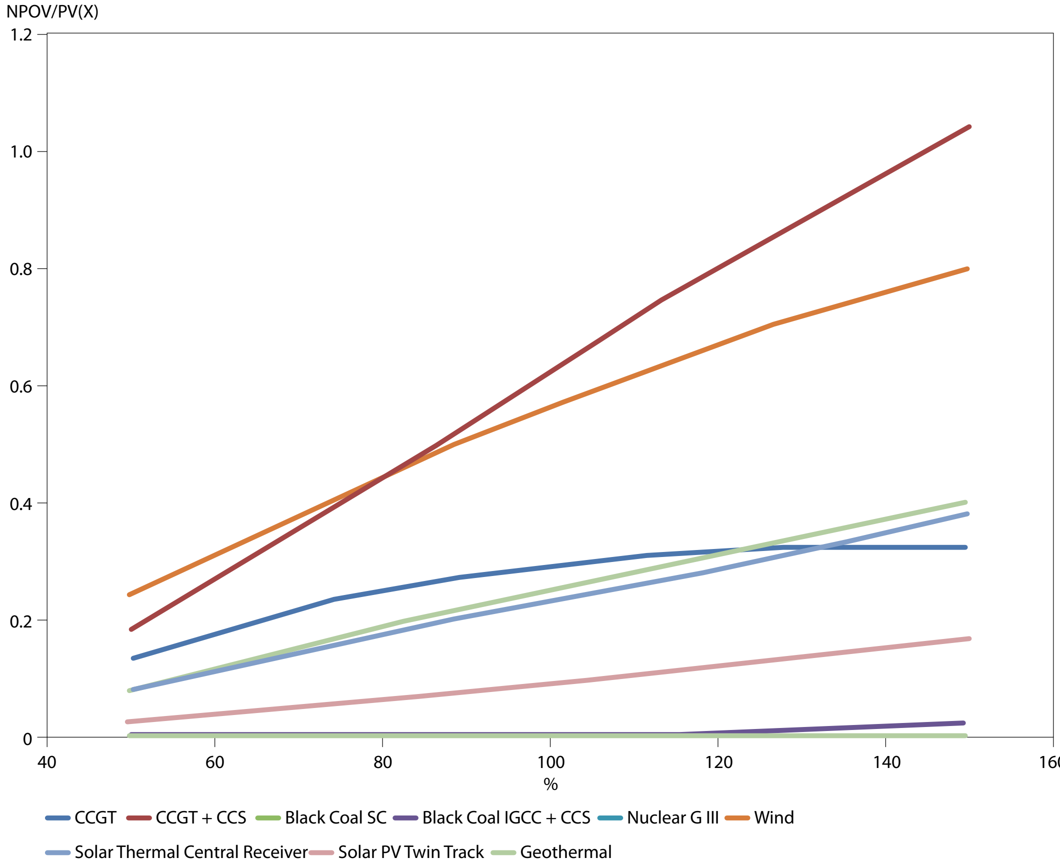


Figure 16 Net present option values for different new technologies as a function of the rate of change of CO_2 price for investment in 2040



required. The Treasury/Garnaut CO_2 price model and wholesale electricity price model trajectories seem from these results to be appropriate to ensure that several key new power generation technologies are commercially viable by 2040. The trajectories may even need to be steeper, depending on the outcomes of the learning curves of the technologies and the cost of capital for investors, since both these parameters also influence the net present option values.

The impact of an increasing CO_2 price on the net present option value of gas fired CCGT is significant. As can be seen for 2040, the net present option values for CCGT are relatively lower for higher rates of CO_2 price change due to the CO_2 cost impost. This is in spite of the relatively low CO_2 emissions intensity of CCGT. The effect of CO_2 price is even higher for the coal-based technologies without CCS in both 2030 and 2040. In both these years the net present options value for these coal-based technologies is essentially zero.

5.6 INFLUENCE OF GAS PRICE ON NET PRESENT OPTION VALUES OF THE GAS-BASED TECHNOLOGIES

The future price of natural gas will be important in dictating the financial value of the CCGT and CCGT with CCS technologies. With the burgeoning coal seam methane gas industry proposing new LNG production facilities in Queensland and other developments in offshore Western Australia, there is debate about future domestic gas prices in Australia relative to the higher world parity price.

Future gas price projections for new power generating entrants in Australia have been developed by AEMO for five scenarios from 2015 to 2030[52]. Supply and demand analysis has also been employed by AEMO to estimate future gas prices. The prices escalate over time within a large range, between +1% per year and +5% per year.

Figure 17 Net present option values for CCGT and CCGT with CCS technologies in 2020 (a) and 2040 (b) as a function of gas price escalation factor

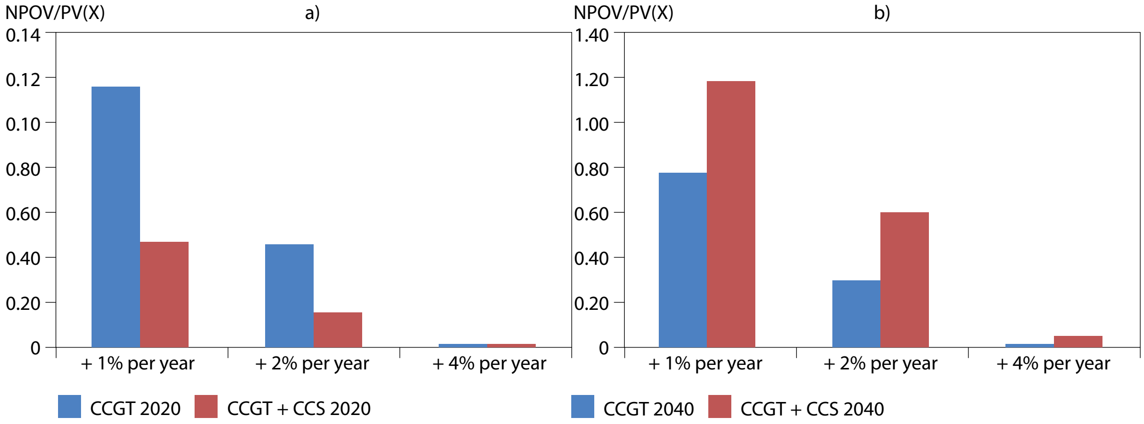
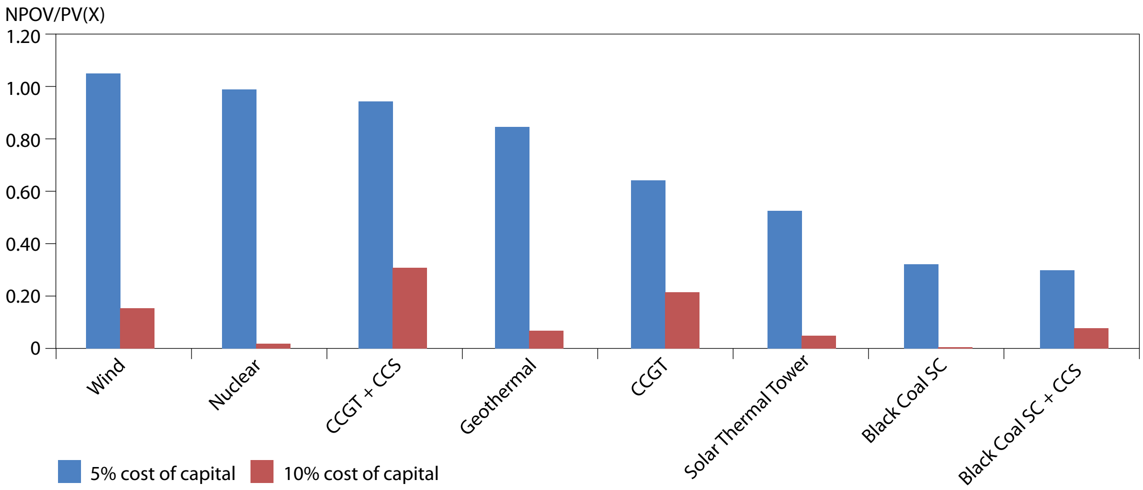


Figure 18 Sensitivity change in net present option values for selected technologies in 2040 as a function of WACC



The net present option values in the current work presented previously were calculated for an escalation factor of 2% per year, which lies close to the average of AEMO scenarios 2, 3 and 5. Scenarios 1 and 4 have a higher average escalation factor, around 5% per year. Gas prices into the future are clearly uncertain, and this contributes to the high volatility component in the net present option value results for gas-based technologies presented previously.

In order to estimate the effect of the AEMO scenario for gas prices on the calculated net present option values for the gas-based technologies, the NPOVs for these technologies were calculated as a function of the gas price escalation factor in the range 1% to 4% per year for the years 2020 and 2040. These results are shown in Figure 17.

Figure 17 shows that the net present option values for CCGT are higher than those for CCGT with CCS in 2020, while the opposite applies in 2040. This is due to the different price of CO_2 in these two years according to the Treasury/Garnaut model. Increasing the gas price escalation factor from 1% to 4% per year in both years causes the net present option values to fall significantly. Thus, under AEMO scenarios 2, 3 and 5 (1% to 2% per year escalation) the gas-fired technologies have higher net present option values for investment in each year, while under scenarios 1 and 4 (4% to 6% per year escalation on average) the gas-fired technologies have much lower net present option values. Based on these results, the timing of the investments relative to current and expected Australian natural gas prices in particular locations will therefore be an important consideration for investors in gas-fired power generation.

5.7 INFLUENCE OF COST OF CAPITAL ON NET PRESENT OPTION VALUE

Since many of the new power generating technologies are capital intensive, the cost of capital (WACC) of the generation firm will have a significant effect on the calculated NPV and hence the net present option value of the technology. This is because the commercialisation investment (X) and the stream of net revenue cash flows (S) occur at different times into the future and are therefore discounted by the WACC to different extents.

Figure 18 shows the effect of a change in cost of capital from 5% to 10% on the net present option value of selected technologies in 2040. The base case WACC in this study was 7%, yielding the NPOV results outlined earlier.

Clearly, the net present option values are a strong function of cost of capital, with a higher WACC leading to a lower NPOV. This is because most of the generating technologies are capital intensive and the operating life of the technologies is relatively long at 30 years. The ranking of the technologies also changes markedly with the cost of capital. For example, the gas-based technologies are relatively higher in net present option value at higher cost of capital, whereas capital-intensive technologies such as nuclear have relatively higher net present option value at lower cost of capital. This is because the NPOV of the gas-based technologies is more related to fuel costs, whereas the NPOV for nuclear is more related to capital costs.

The net present option value to investors in new technology in a particular company will depend on its financial leverage, tax rate, cost of debt and cost of equity (see eq. 2). This could vary between companies depending on their different financial strategies and ownership structures. Power generating companies may thus have different levels of appetite for the range of new technologies as a function of their cost of capital and investment strategies.

Traditionally, utilities such as power generating companies have a lower cost of capital than industries with higher financial risk such as those in the resources industry. However, under a carbon-trading or tax regime the power utilities will be presented with higher risk than in the past due to factors such as uncertain future electricity and CO_2 prices and new technology risk. This could tend to increase the WACC of the company and hence lower the net present option value of the new technologies to the firm.

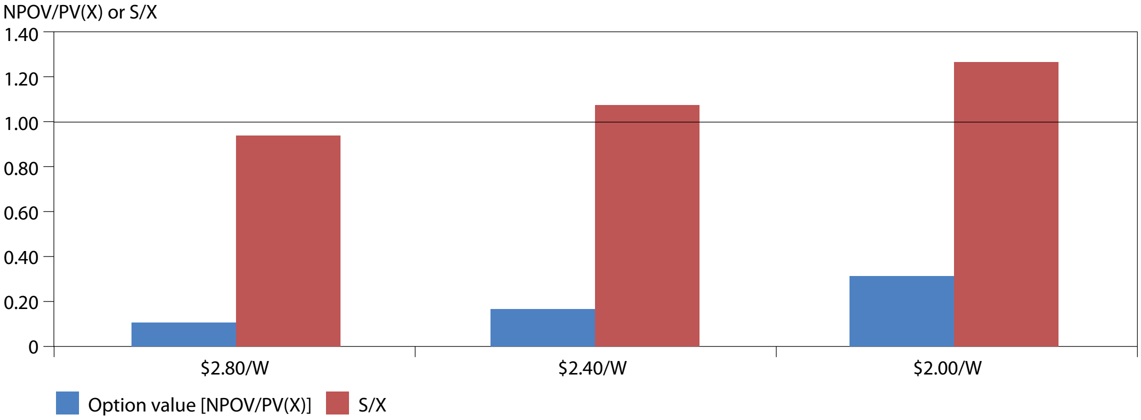
5.8 CASE STUDIES: IMPACT OF ACCELERATED IMPROVEMENTS IN THE NEW TECHNOLOGIES ON NET PRESENT OPTION VALUE AND NPV

With the 7% after-tax weighted average cost of capital assumed in this study using the SRG reference data, several technologies are predicted to be "borderline" in their economic attractiveness for investment in 2040. These include (referring to Figure 12 in terms of the S/X ratio):

- solar PV, and solar thermal with storage;
- geothermal in some regions; and
- coal-based technologies with carbon capture and storage.

These technologies have been analysed below in terms of sensitivity of their option values to the important input parameters in order to judge what improvements in their learning curves are required to make them NPV positive.

Figure 19 Sensitivity change in net present option values and net present values [S/X] for solar PV with twin axis tracking and DNI=6 kWh/m²/day in 2040 for different capital costs ($/W of capacity). NPV is positive for S/X>1.0



5.8.1 Solar PV technology

In the study here, solar PV technologies are considered in the context of large-scale power generation, as opposed to its use in distributed energy at the household level. In the latter case, solar PV competes with the retail price of electricity, which is currently priced in the range $150-$200/MWh. From the levelised cost of electricity results presented previously in this report, solar PV will clearly compete with retail electricity prices after 2030 as a distributed energy technology under the assumptions inherent in this study.

The learning curve for solar PV technologies is the steepest of all the new technologies. The previous ATSE report on accelerating energy technology development[53] assumed a value of $2.00/W for the capital cost of a large solar PV array in 2040, on the advice of experts on solar PV technology at the Australian National University[54]. This compares with a value of $2.80/W extrapolated linearly from the SRG reference data and used for the base-case results in Figures 10 and 12 here. A sensitivity of the option value of solar PV under DNI = 6 conditions with twin-axis tracking of the sun was thus undertaken to determine the sensitivity of this technology to a change in the steepness of the learning curve[55]. Figure 19 shows the solar PV option values and NPV in terms of S/X for a range of capital costs between $2.80/W and $2.00/W in 2040.

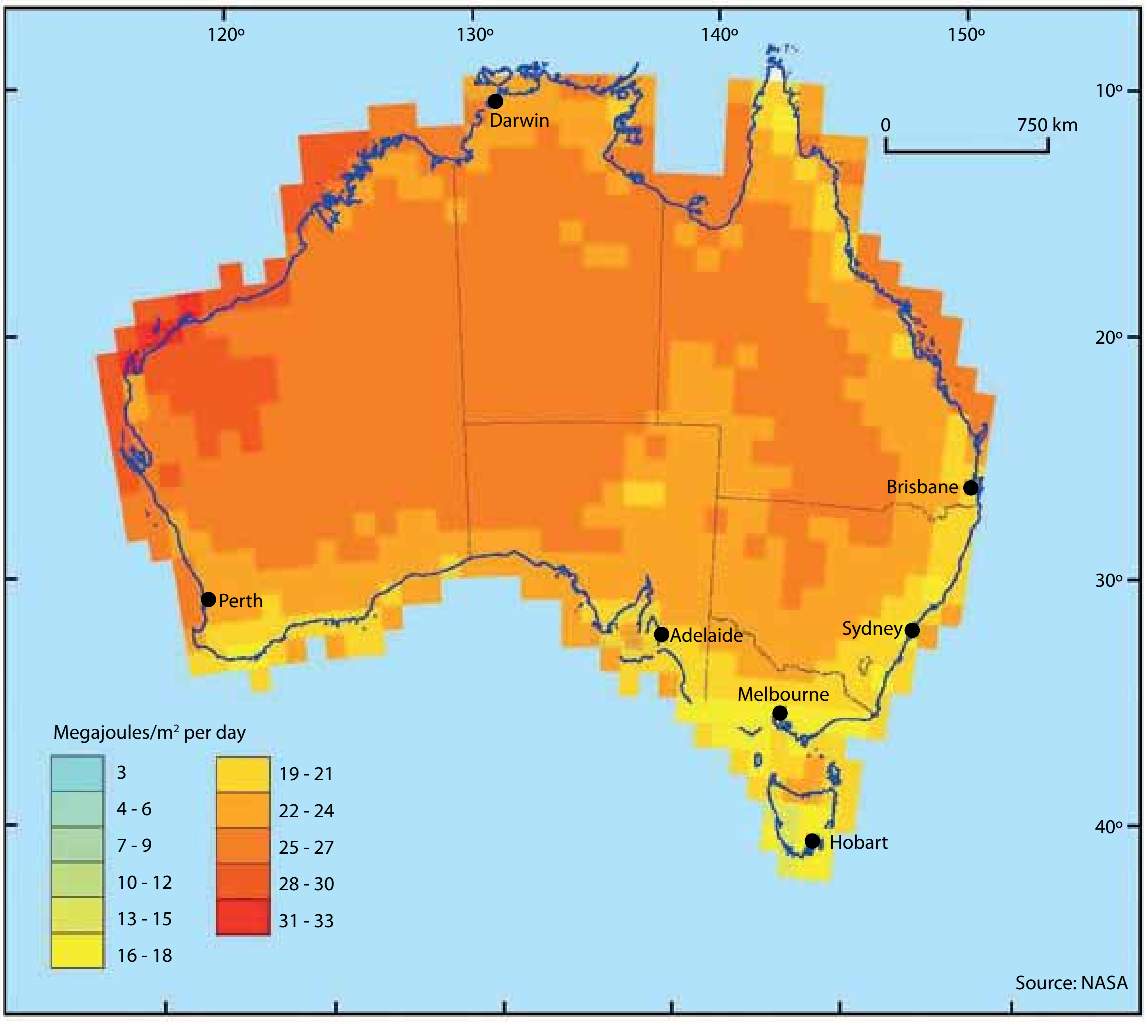
As can be seen from Figure 19, the calculated net present option values and NPV are indeed sensitive to the assumed capital costs, with NPOVs more than trebling with the assumed reduction in capital costs. Achievement of $2.00/W by 2040 would also make solar PV with twin tracking NPV positive (S/X > 1) under DNI = 6 conditions in 2040 for Treasury/Garnaut CO_2 and electricity price scenarios. Clearly, the focus on development projects and manufacturing technologies for solar PV should be on reduction of capital intensity, with a long-term target of less than $2/W of capacity for large-scale application. Should solar PV technology development achieve costs below $2/Watt installed, it will be amenable in the future to both large-scale and distributed power generation based on the analysis in the present study.

5.8.2 Solar thermal technologies with and without storage

The question of the attractiveness of solar thermal technologies with and without storage in different solar irradiation locations in Australia is an interesting one to explore using the net present option value method.

The capacity factor of solar thermal technologies varies with the solar irradiance (DNI) and hence location in Australia. The capacity factor also varies with whether or not local energy storage technologies are applied together with the solar thermal unit for use when the sun is not shining. The increased number of hours that energy is available increases the time per day that energy can be supplied, but increased capital

Figure 20 Map of Australia showing insolation in terms of Direct Normal Irradiance[57]



is required for the energy storage infrastructure. In principle, it is better for electricity stability of supply reasons to have a higher capacity factor. Sensitivity of net present option value to both these parameters has thus been determined.

Capacity factors as a function of solar thermal technology type, as developed by EPRI and contained in reference 4 above, are shown in Table 3. A map of Australia coded for solar irradiance is given in the recent Geoscience Australia/ABARE report[56] and is reproduced in Figure 20. As can be seen, irradiance greater than DNI = 7 (or 25.2 MJ/m²/day) occurs in large parts of north-west and central Australia, while irradiance less than DNI = 5 (or 18 MJ/m²/day) occurs only in relatively small areas of southern and coastal Australia.

Table 3 Capacity factor for solar thermal technologies as a function of DNI and type of technology.

Solar thermal technology	DNI = 5	DNI = 6	DNI = 7
Parabolic trough	20.1%	24.1%	28.1%
Parabolic trough + 6 hours storage	32.9%	39.5%	46.0%
Central receiver	20.1%	24.2%	28.2%
Central receiver + 6 hours storage	33.0%	39.7%	46.3%

Figure 21 shows the calculated net present option values for the capacity factors shown in Table 3 for 2040.

Figure 21 Sensitivity change in net present option values of solar thermal technologies in 2040 as a function of technology type and solar DNI

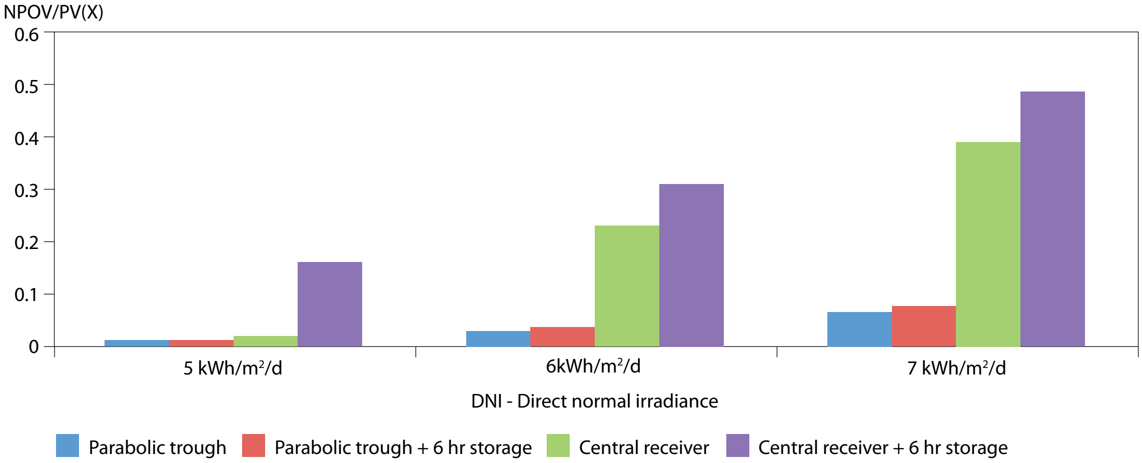


Figure 21 shows that solar thermal central receiver technology has significantly higher net present option value than the parabolic trough technology in all cases. This is a function of its lower capital costs for the solar tower technology in the SRG reference data set. Furthermore, the results indicate that the central receiver technologies have S/X greater than 1.0 (positive NPVs) as DNI increases whereas the parabolic trough technologies have all S/X values less than 1.0 (negative NPVs) in 2040 for all DNI values. That is, the parabolic trough technologies would lie in the "probably never" part of the options space shown in Figure 12 unless greater technology learning could be achieved. On the other hand, central receiver technologies would lie in the "maybe now" part of the space for investment in 2040 based on the SRG reference data set.

Figure 21 also shows that, in both technology cases, local storage of energy through (say) molten salt technology gives only a slightly higher net present option value than without storage. This is because the increased capital cost of storage is more or less balanced by the increased capacity factor in the SRG reference data assumptions. Even though the differences are small, however, it is better to have the higher capacity factor available for network stability reasons. The results therefore indicate that energy storage options should be pursued for solar thermal technologies, taking into account the balance between the extra capital costs and the increased capacity factor due to storage technologies.

The extra costs associated with new transmission infrastructure, especially at DNI = 7 locations, has not been included in the present analysis. The higher net present option values evident in Figure 21 with higher DNI will be reduced by these increased costs. The transmission costs allocated to a particular solar thermal facility will depend on the number of facilities connected to the transmission line at the remote locations and could therefore be a small factor per solar thermal unit with large-scale adoption of the technology. From the results here, it seems that the present net present option value analysis could assist in an optimisation modelling process to maximise option value in the deployment of these technologies through the inclusion of transmission costs. Similar arguments would apply to the remote geothermal EGS technologies.

5.8.3 Geothermal technology

The SRG reference data set contains regional variations in cost for geothermal technologies. The lowest costs are for geothermal HSA in parts of Victoria and south-east South Australia and geothermal EGS in northern South Australia. Researchers at the University of Melbourne[58] have commented that geothermal technologies in general have the capacity for significant improvement. On the other hand, the difficult engineering conditions associated with deep drilling, high temperatures and stimulatory

Figure 22 Sensitivity change in net present option value for geothermal with improvement in capital and operating costs with technology development by 2040

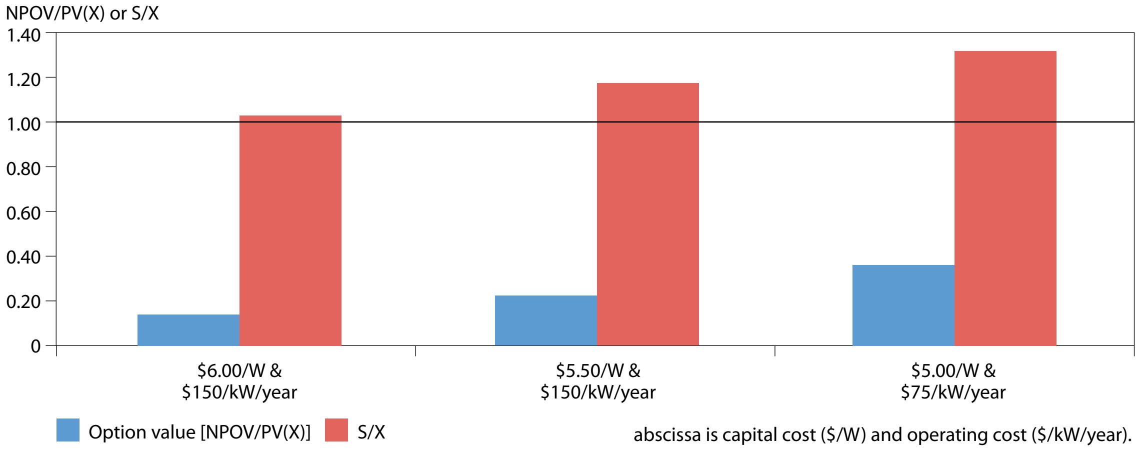
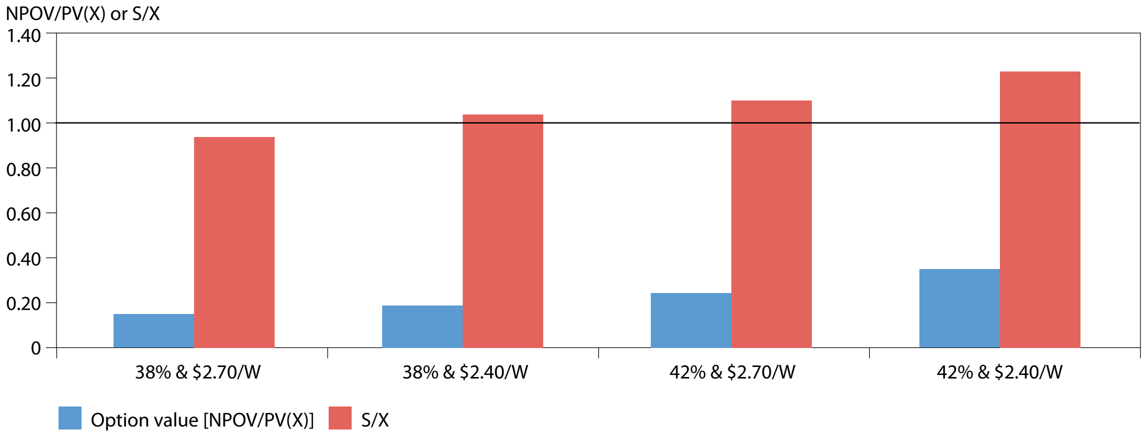


Figure 23 Sensitivity change in net present option value for IGCC with CCS with improvement in capital costs and thermal efficiency (HHV out) with technology development by 2040



rock fracturing at depth may militate against geothermal technology achieving the current postulated learning curves.

Notwithstanding the technical challenges, several longer-term new technology developments have been proposed to reduce the costs of geothermal. These include:

- Increases in turbine efficiency due to design and better materials.
- New binary circuit fluids, for example biphasic metal-organic heat carriers (MOHC)[59], that increase heat transfer efficiency of the heat exchanger in the binary working fluid-turbine fluid circuit.
- New working reservoir fluids, such as supercritical CO_2, leading to lower heat exchange fluid circulating power requirements and higher efficiency.
- Lower cost drilling technologies, enabling drilling to greater depths and higher temperatures.

The SRG reference data set for geothermal has capital costs in 2040 varying between $6.20/W to $5.20/W and operating costs at $150/kW of capacity per year, depending on location. The proposed technology developments listed above are highly uncertain at present, but it has been estimated by the University of Melbourne that the average capital costs for geothermal could fall to $5/W (in 2009 dollars) in 2040 and that the operating costs could halve if these developments succeed. The effect of these potential improvements in net present option value and NPV is shown in Figure 22.

The results show that, under the WACC assumed in this study, the NPV of geothermal could be significantly greater than zero and the option value could double by 2040 if the proposed improvements could be achieved. The technical challenges with geothermal, however, could make this outcome difficult to achieve. Moreover, the costs of electrical transmission infrastructure from remote locations will add to the cost burden of this technology and should be taken into account in a full analysis of the prospects for geothermal in the future.

5.8.4 Coal technologies with carbon capture and storage

The coal technologies with carbon capture and storage under the base assumptions in this work have moderate net present option value but are slightly NPV negative in 2040. This is despite high electricity prices by then, according to the Treasury/Garnaut model. The key parameters in terms of accelerated technology development for these technologies are the capital cost ($/W of capacity) and the overall thermal efficiency, as well as factors such as the cost of transportation and sequestration of CO_2. The Australian Government's Carbon Storage Task Force has considered and reported on these latter factors, which remain relatively uncertain[60].

In order to examine the level of improvement needed to move these technologies into the "maybe now" part of the options space diagram with S/X>1.0 in 2040, the effect of changing the capital costs and the thermal efficiency have been examined with the present options value determination model. It has been suggested that thermal integration of the air separation unit (ASU) and CO_2 compression plants together with membrane separation of oxygen to reduce energy requirements could reduce the sent-out efficiency differential to 6 percentage points, rather than 10 points in the present study by 2030–40[61]. The base case capital cost for IGCC with CCS in the AEMO extrapolated data for 2040 (see Appendix A) is $2.70/W capacity, while the base-case thermal efficiency is 38%. Taking the suggested possible improvements into account, Figure 23 shows the effect of improving the 2040 efficiency by 4 percentage points to 42% and the capital cost by 10% to $2.40/W on both the net present options value and the NPV in terms of S/X.

It is clear from the figure that improvement in capital cost and thermal efficiency have a significant impact on the NPV and hence net present option value of the IGCC with CCS technology in 2040. These improvements, if achieved, would place the technology in the "maybe now" part of the options space diagram then.

5.9 NET PRESENT OPTION VALUE AND EXPENDITURE ON TECHNOLOGY DEVELOPMENT

There are two ways to regard option value. First, it is a measure of the potential upside in the NPV for an investor due to financial uncertainty in the future. In the context of the new power generating technologies considered here, this upside uncertainty could be caused by higher electricity prices, lower costs due to technology learning, lower fuel prices, and so on. The second way to look at option value is as a measure of the price that the investor should pay in NPV terms now to "stay in the investment game" and have the option to exercise a commercial investment in the future. The options payment could include investment in R&D, technology demonstration, infrastructure investment, purchase of tenements for CO_2 sequestration, and so on.

It is useful to undertake a "back of the envelope" calculation to see what the present results mean in terms of paying to "stay in the game". The study here has shown that the mean of the NPOVs of a range of technologies in, say, 2040 is around 25% of the commercialisation investment, with reasonable assumptions regarding the volatility of the input financial variables. Previous work by ATSE[62] for a particular power generation fleet portfolio has shown that more than $200 billion (in 2007 dollars, but invested in 2040–50) will be required to provide by 2040–50 the power generating infrastructure using new technologies. If half this investment occurred in 2030 and half in 2040, the net present present option value of this investment is around $10 billion for a present commercialisation investment NPV of $40 billion (discounting $200 billion at 7% real cost of capital). This means that Australia could be investing $10 billion now as an option price in activities such as R&D, technology demonstration and infrastructure development for new technologies for power generation under these assumptions.

Several technologies, notably brown coal drying and gasification with CCS, were not included in this analysis and it has not been determined from this study how much of the power generation fleet will comprise technologies of this type in the future. The aggregated option value today for each new technology is very dependent on this uncertain investment parameter, as well as the technology improvements that may occur, and therefore the option value today for some technologies could be higher than the simple calculation above. Therefore, it has not been possible in the present study to more accurately determine how much government support is justified now for demonstration of these and other complex technologies to make them financially viable in the future.

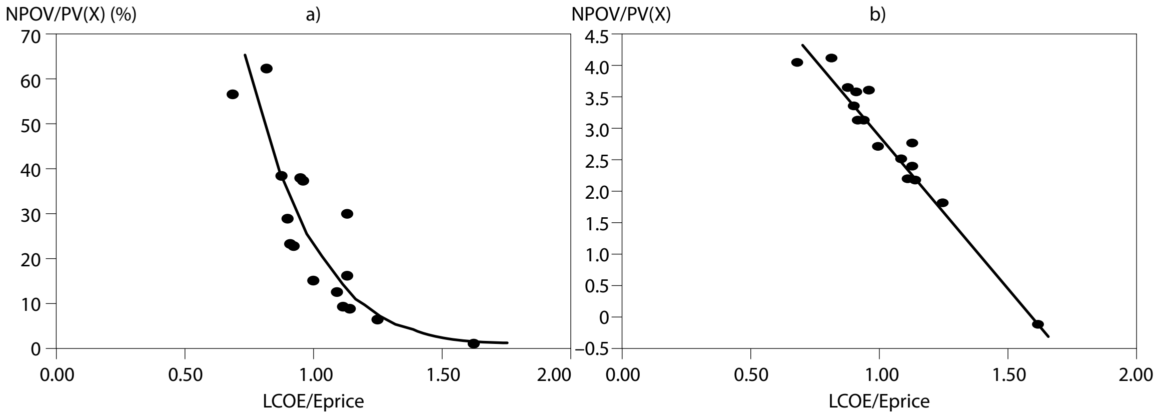
In the present study the learning curves for the new technologies have been assumed in order to calculate the net present option values. Whether "purchasing" the option for a particular technology is sufficient to achieve the assumed learning curve is a complex question that cannot be answered using this study alone. In many cases, the learning curve will depend on investment outside Australia, while in other cases investment in the option will be required to address local conditions. However, it has been shown here that net present option value is sensitive to the nature of the learning curve, and that NPOVs can be significantly increased by improved learning. This implies qualitatively that option investment in the form of RD&D is justified in some targetted situations. Further quantification of this linkage by using the present technique for RD&D strategy is warranted.

Some technologies evaluated as part of this study have lower net present option values in 2040. Even for these technologies, the NPOVs in 2040 are between 10% and 20% of the commercial investment required. Improvements in the cost and efficiency learning curves of these technologies also increase their net present option values significantly. The present study has therefore shown that current Australian Government investment of around $5 billion in the development of these technologies in the form of flagship projects and research institutes is justified. Indeed, the present work has shown that a higher investment in NPV terms could be contemplated to accelerate the process.

For some technologies, such as wind, the calculated net present option value could be higher than that needed for commercialisation of the technology. This is because this technology is now well-developed internationally, and ability to commercialise may be related to other factors such as investment in electrical transmission infrastructure. For other technologies, such as carbon capture and storage, the net present option value may be linked to investment in research, development and demonstration of the technology and in evaluation of potential geological storage sites. Thus, the nature of the purchase of the option to commercialise a given technology in the future will be different for different technologies. This is particularly important for Australia, where some technologies could be developed overseas, whereas others will require local option investment. However, for a given set of data assumptions, the present method gives an indication of how much option generation investment should be made for each technology.

A significant point that should be considered is that for an option to have value it must be ruthlessly exercised, or not, as the case may be. In other words, it is not financially prudent to pay an option price now and then exercise the option at a future time if the NPV is negative then[63]. As more information comes to hand on the technology learning curves and future CO_2 pricing regime, the net present option value of a particular technology may decrease as it traverses the "options space" diagram with time. This may lead to the rejection of an option to commercialise any particular technology and loss of the previously

Figure 24 Relationship between normalised LCOE and normalised NPOV (NPOV/PV(X)) for a range of new technologies for 2030 and 2040 – a) is the raw relationship and b) is a log-linear plot of the same data



paid option price. This outcome is to be expected in some cases for an options investment strategy. On the other hand, investment in an option now by paying the option price may lead to unforeseen "embedded" options that themselves may have further value into the future. It is for these reasons that Australia should have a portfolio of stragegic options for new technologies for power generation, and these options should be carefully managed on the "option space" over time.

5.10 COMPARISON OF NET PRESENT OPTION VALUE RESULTS WITH LEVELISED COST OF ELECTRICITY

The above net present option value analysis shows that generally the same new technologies for power generation are favoured by lower LCOE and higher NPOV. These technologies include wind, geothermal HSA, solar thermal tower, nuclear, and the gas-fired technologies. In order to determine if there is a relationship between LCOE and NPOV, the LCOE results and the NPOV results for 2030 and 2040 were compared for all the technologies under consideration.

The results of the comparison are shown in Figure 24. In this figure, the levelised costs of electricity and option values are normalised to the Treasury/Garnaut model wholesale electricity price and the exercise price (investment cost), respectively. There are two diagrams, (a) the raw relationship and (b) a plot of the two parameters as a log-linear relationship.

As can be seen from Figure 24, the option value (NPOV/PV(X)) is particularly sensitive in determining those technologies where the overall NPV is greater than that required to earn the investor the cost of capital (or in other words, when the calculated LCOE is below the prevailing wholesale electricity price). This leads to a non-linear relationship between the option value and the levelised cost of electricity, as shown in Figure 24(a). If the logarithm of the option value parameter is plotted against levelised cost of electricity, a linear relationship between the two is apparent, as in Figure 24(b). This indicates that the option value approach adopted in this work is more sensitive than levelised cost of electricity in determining the financial ranking of a particular technology, at least at the time when the technology begins to become economic and its full costs are close to the expected wholesale electricity price.

6 Conclusions

A financial model based on the analysis of free cash flows has been developed to calculate the levelised cost of electricity (LCOE) and net present option value (NPOV) of a range of new stationary power generating technologies. Data provided by a Stakeholder Reference Group (SRG) established by the Australian Energy Market Operator (AEMO) and the Australian Government Department of Resources Energy and Tourism (DRET) were used as input to this analysis. As further input to the model, the future price of carbon dioxide, and electricity, was taken from the work of Garnaut and the Australian Government Treasury. The model has been used to analyse the financial viability of the new power generating technologies from the point of view of an investor. It would also be applicable to technologies not covered here, such as electricity from integrated drying and gasification of brown coal, wave, tidal and biomass energy, to which the SRG data did not extend, and to energy efficiency projects.

It is important to emphasise that the analyses and conclusions described here apply strictly speaking to the various individual power generating technologies specified. When it comes to their combined application in a portfolio of technologies in real power systems and networks, a new set of issues arises to do with size of generating units, intermittent availability of outputs from some renewable energy sources, and additional transmission costs due to the remote locations expected for renewable technologies such as wind, solar and geothermal. Supply-demand economics also come into play in terms of electricity and natural gas prices. Ongoing security and stability of the power system comprising different technologies will also be of primary concern when intermittent renewable technologies are involved. Investment policy and strategy to achieve those aims will depend on more than the individual technology financial analyses presented here, though these should prove very helpful in arriving at future investment decisions.

LEVELISED COST OF ELECTRICITY

The LCOE is the constant price in today's dollars received by the generator into the future that enables a return equal to the cost of capital. In this work, results for LCOE are compared with previous studies by the International Energy Agency (IEA), the Electrical Power Research Institute (EPRI), and Australian consultants McLennan Magasanik Associates (MMA). In general, it is shown that the financial model used in the present work yields trend results similar to the previous results when the same/similar input data are used.

New results from the model for LCOE, taking into account the price of CO_2 into the future as well as other variables such as the price of Renewable Energy Certificates (RECs) in Australia, show that:

- The LCOE varies significantly with the year of the investment and the type of new technology deployed.
- In 2020, with RECs priced at $50/MWh, only a few technologies have LCOEs below the Treasury projection (for 2020) of a $72/MWh wholesale electricity price and a US$43/t CO_2 price. Those technologies include geothermal in favourable regions, wind turbines at good wind locations, and combined cycle gas turbine (CCGT).
- In 2030, when RECs disappear and wholesale electricity price is forecast by Treasury to reach $96/MWh, with a US$US/t CO_2 price, the same situation with regard to technologies as 2020 is found to apply. That is, geothermal, wind and CCGT technologies are predicted to have the lowest LCOE. However, gas-fired CCGT with carbon capture and storage (CCS) is also found to have a LCOE near to the 2030 electricity price for a gas price escalation of 2% per year. Other technologies, such as solar

and coal-based CCS, are predicted to have a significantly higher LCOE than the prevailing wholesale electricity price in 2030.

- By 2040, the learning curves of the new technologies have reduced their LCOEs to between $75 and $150/MWh. By then, the Treasury predicted wholesale electricity price is $112/MWh, with a CO_2 price of US$90/t in 2009 dollars. Under these conditions, many technologies have LCOEs lower than the wholesale electricity price and would be thus earning their cost of capital. These include wind, geothermal in favourable regions, CCGT with CCS, nuclear generation III, CCGT, and solar thermal central receiver technologies (with and without energy storage). Technologies such as geothermal in less favourable regions, coal with CCS and solar PV with twin axis tracking are predicted to have LCOEs close to the then wholesale price of electricity and are thus becoming economic. So, the results show that by 2040 there will be a wide choice of economic technologies to create a power generating portfolio, provided sufficient learning occurs and the CO_2 and electricity prices have risen to adequate levels.

Because the LCOE modelling in this work assumes the prices of electricity and CO_2 to remain constant after the investment is made, the LCOE results are relatively lower (better) for technologies that have a rising CO_2 cost impost during their operating lifetimes.

NET PRESENT OPTION VALUES OF NEW POWER GENERATING TECHNOLOGIES

An approach to analysing new power generating technologies based on the concept of net present option value has been evaluated. Simply explained, the net present option value is the potential upside to an investor due to the probabilistic nature of the NPV distribution. A project can have some net present option value even though its NPV based on the mean values of the distribution is negative, provided there is sufficient variance in the distribution of NPV in the future.

Net present option values are calculated here using the Direct Monte Carlo method to determine a future probabilistic NPV distribution. Most of the input data are treated as distributed, probabilistic variables (see Appendix A.7 for details). This technique generates the appropriate financial probability distributions of NPV and then calculates the net present option value numerically. Comparisons are made with a simple European call option calculating the different "real option value", and it is found that the Monte Carlo method reproduces the results for analytical methods such as the Black-Scholes equation (see Appendix D). It is concluded that the Monte Carlo method is suitable for the calculation of net present option values for the new power generating technologies in this study.

The main inputs to the model for calculation option values are:

- the SRG reference data set for different technologies;
- the mean CO_2 price trajectory suggested by the Australian Government Treasury and Garnaut models and electricity price trajectories; and
- probability distributions associated with these data.

These inputs provide revenue and cost streams for the financial model for calculating net present option values.

The results show that:

- Net present option value can be correlated with LCOE in a non-linear relationship that indicates that option value is a more sensitive indicator than LCOE as to the financial viability of a technology.
- Only a few technologies have any net present option value in 2020. These include wind, geothermal in favourable regions and gas-fired CCGT.
- By 2030, the net present option values are predicted to increase. Gas-fired technologies, including

CCGT with CCS, and geothermal, have the highest net present option values. Wind and nuclear technologies also have moderately high net present option values in 2030. However, it is predicted that coal-fired technologies and the solar technologies have low net present option value and negative NPVs in 2030.

- In 2040 virtually all technologies (except coal-fired without CCS) have some net present option value. This means that there could be a wide technology choice by then for a power generation portfolio.
- The highest net present option value technologies in 2040 are CCGT with CCS, wind, nuclear and geothermal in favourable regions, all with positive NPV. The least-cost solar thermal technology, solar central receiver (with or without storage), also has moderately high net present option value and a positive NPV in 2040. Although CCGT has high net present option value in 2040, it has negative NPV for investment then, compared with positive NPV in 2030. This is due to the increasing cost of its CO_2 emissions. Coal-based CCS, solar PV and geothermal in less favourable regions have moderate net present option values, but are predicted to have NPVs close to or less than zero in 2040. Sensitivity analysis shows that through further technology development these technologies could move to a situation where they are all NPV positive with small changes in their financial and efficiency inputs. Coal-based technologies without carbon capture have essentially zero net present option value in any of the years 2020–40 under the Treasury/Garnaut carbon pricing scenario.
- The net present option values calculated in this study agree qualitatively for the fossil fuel technologies with previous work by the CRC for Coal in Sustainable Development using a different real option value calculation methodology.

SENSITIVITY ANALYSIS OF NET PRESENT OPTION VALUE

Several sensitivity analyses on net present option value of the new technologies for power generation have been undertaken. It is shown that net present option value is sensitive to many of the input parameters:

- The change of CO_2 price into the future is an important parameter governing the new technology net present option value. A rate of increase in CO_2 price half that of the Treasury/Garnaut models gives net present option values only one quarter of those at the full model rate. The work here clearly shows that the price of CO_2 must rise at a rate close to or exceeding the Treasury/Garnaut model in order that most of the new technologies have reasonable net present option values and NPVs in the years beyond 2030. This is an important conclusion for policy development by government.
- The escalation of natural gas prices in the future is an important parameter for the gas-fired technologies. AEMO has published a number of gas price scenarios indicating that prices could rise between +1% per year to +5% per year. The lower rate leads to high net present option values for the gas-fired technologies in 2030 and 2040, but the higher rate leads to virtually no net present option value for these technologies then. It is concluded that investment in gas-fired technologies in the medium to long term has relatively high gas price risk. This risk may need to be mitigated to enable investment in these technologies in the medium term.
- The cost of capital of the generating company has a significant influence on net present option value, especially for those technologies with high capital intensity.
- The net present option value is sensitive to the capital cost per unit of installed capacity, and the thermal efficiency and operating costs of the new power generating technologies. In order to make the net present option value more attractive by 2040, the financial position of solar PV, some geothermal, and the coal-based carbon capture and storage technologies will need to improve relative to the SRG reference data, through further technology development.
- The net present option values of solar thermal technologies with local storage of energy for increasing capacity factor have been predicted to be slightly higher than the same technologies without storage. It is concluded that RD&D into solar thermal energy storage should be a priority, especially for the lower-cost solar central receiver technology.

NET PRESENT OPTION VALUE AND TECHNOLOGY DEVELOPMENT

An approach to presenting the net present option values for new power generating technologies on a two-dimensional "Options Space" (after Luehrman[64]) appears to be a very useful tool for displaying where a particular technology sits with regard to investor value. The diagram should find application in future analysis of power generating options since it allows decoupling of the NPV and volatility components of value. It should also allow technologies to be "tracked" on the options space over time towards commercialisation as more information becomes available. It will also prove useful in the analysis of different scenarios in the future and the strategic development of any "embedded" options that arise during the course of technology development.

A simple analysis of the overall option values of the new power generating technologies shows that the present option value of the portfolio of new technology options for investment in 2030–40 is around $10 billion. This result shows that present Australian Government investment in RD&D in this area is justified and could possibly be increased, especially if such investment is likely to accelerate progress along the various technology learning curves.

7 Acronyms and Glossary of Terms

ABARE	Australian Bureau of Agricultural and Resource Economics; see www.abare.gov.au
AEMO	Australian Energy Market Operator; see http://www.aemo.com.au
ASU	Air separation unit; facility for separating nitrogen and oxygen from the air to provide an oxygen supply for fuel combustion in future coal-fired plants.
ATSE	Australian Academy of Technological Sciences and Engineering; see http://www.atse.org.au/
ARC	Australian Research Council; see http://www.arc.gov.au/
biphasic	Having two distinct phases, liquid and vapour.
capacity factor	Ratio of the actual power of a power plant over a period of time to its output if it had operated at its full capacity for the entire time.
CCGT	Combined cycle gas turbine; a gas turbine generator where the hot exhaust gases are used to generate steam and then, for added efficiency, drive a second steam turbine before release into the atmosphere.
CCS	Carbon capture and storage: a process whereby the CO_2 produced from a fossil fuel-fired facility is captured, compressed to a supercritical state, transported by pipeline to a suitable site, and sequestered underground in deep porous strata over-capped by impervious rock.
Central receiver	A form of solar thermal technology where the sun's rays are focused by an array of tracking reflectors onto a central heating point on top of a tower, where a fluid is heated and then fed to a generator.
Class of wind	A measure of average wind velocity in a location: Class 3 = 6.7 ms^{-1}; Class 4 = 7.3 ms^{-1}; Class 5 = 7.8 ms^{-1}; Class 6 = 8.4 ms^{-1}.
CO_2	Carbon dioxide, a colourless gas, denser than air, formed in the combustion of carbon-containing fuels.
cost of capital	See WACC, defined by eq. (2)
cost of debt	The average corporate interest rate paid by a firm for funds borrowed as a debtor.
cost of equity	The cost of equity of a firm as seen by shareholders; related to the perceived risk of a company in terms of its share price volatility.
CRC	Cooperative Research Centre
debt, D	Amount of debt on a company balance sheet
daf	Dry ash free; a specification for a solid fuel.
DNI	Direct normal irradiance, a measure of the intensity of solar energy reaching the earth's surface, in units of $kWh/m^2/day$. In terms of megajoules, DNI = 5 equates to 18.0 $MJ/m^2/day$, DNI = 6 to 21.6 $MJ/m^2/day$ and DNI = 7 to 25.2 $MJ/m^2/day$
DRET	Australian Government Department of Resources Energy and Tourism; see http://www.ret.gov.au/Pages/default.aspx
equity, E	Amount of shareholders' equity in a company's balance sheet
EBIT	Earnings before interest and taxation

EGS	Enhanced geothermal system: a geothermal technology where fluid is circulated down through hot deep fractured dry rock strata, taken to the surface, and used to produce steam (or other fluid) to drive a turbine.
EPRI	Electric Power Research Institute, an American energy consulting company; see www.epri.com
FCF	Free cash flow, defined by Eq. (1)
GA	Geoscience Australia; see http://www.ga.gov.au/
geological sequestration	Injection of supercritical CO_2 into deep, porous geological strata over-capped by impervious rock.
GJ	gigajoule: a measure of energy, 1000 million (10^9) joules.
HHV	Higher heating value of a fuel, the heat released with a final product temperature of 25ºC.
HSA	Hot sedimentary aquifer, sometimes called 'conventional hydrothermal': a geothermal technology where pressurised hot water present underground in an aquifer is extracted and sent to generating equipment where it is flashed to make steam and drive a turbine, or used indirectly to heat a fluid to drive a turbine.
IEA	International Energy Agency; see http://iea.org
IGCC	Integrated gasification combined cycle: a process for gasification of coal followed by use of the gas in a combined cycle gas turbine generator (see CCGT).
joule	The derived unit of energy in the International System of Units (SI).
KD	Cost of debt of a company (%)
KE	Cost of equity of a company (%)
kW	kilowatt; a measure of power, 1000 watts.
LASP	Linkage Learned Academy Special Project, a funding scheme of the ARC; see http://www.arc.gov.au/ncgp/lasp/lasp_default.htm
LCOE	Levelised cost of electricity, usually expressed as $/MWh; cost of electricity that allows a generating company to earn its cost of capital.
Learning curve	Change in cost of a technology over time due to development.
MMA	McLennan Magasanik Associates, an Australian energy consulting company.
MOHC	Metal-organic heat carrier; component of a working fluid designed to increase efficiency of heat recovery, especially from geothermal sources.
MWh	megawatt hour; a measure of energy; one million watt hours or 3.6 gigajoules.
n	Number of years since the start of an investment.
Nm^3	Normal cubic metre, a unit of gas volume at specified pressure and temperature.
NPV	Net present value; calculated by discounting net future after-tax cash flows at the firm's cost of capital.
NPOV	Net present option value calculated from the probabilistic distribution of the net present value of "S-X", where both "S" and "X" are discounted to today's value at the company's cost of capital. It is that part of the S-X probability distribution where S-X is greater than zero.
Nuclear Gen III	3rd Generation nuclear generator; an evolutionary design based on improved efficiency, fuel technology and safety.
OCGT	Open cycle gas turbine; a gas turbine generator where the hot exhaust gases are released directly to the atmosphere via a flue.
Parabolic Trough	A form of solar thermal technology where the sun's rays are focused by a long parabolic-shaped reflector onto a central pipe at the reflector's focus point through which a fluid is circulated and heated.
PV	photovoltaic; an electrical effect produced when radiation strikes certain materials, usually solar radiation striking a particular kind of semiconductor junction; generally refers to the method of generating electricity from solar energy using photovoltaic devices.

PV(z)	Present value of financial parameter z, obtained by discounting z at the designated costs of capital of the firm from the year when z was expended or received to today.
RD&D	Research, development and demonstration.
REC	Renewable Energy Certificate; a tradable market instrument to ensure Australia achieves 20% renewables in its electricity supply by 2020.
R_y	Relative cumulative volatility, defined by eq. (B.2) in Appendix B.5.
σ	Standard deviation; or standard deviation per year
σ^2	Variance
σ^2_s	Variance of financial parameter "S".
σ^2_x	Variance of financial parameter "X"
$\sigma^2_{s,x}$	Co-variance of financial parameters S and X, defined by eq. (B.1) in Appendix B.
$\sigma\sqrt{t}$	Cumulative volatility, equal to standard deviation per year times the square root of time; assumes that the variance of a financial parameter increases linearly with time.
S	Net present value of future annual free cash flows from an investment for time > t, not including the investment required in years 1 to t to secure these cash flows.
SC	Supercritical; a state of matter of a fluid; in electricity generating technologies, a coal-fired boiler where the steam is produced at sufficiently high temperature to produce supercritical steam conditions.
SE	Specific energy; the energy content per unit (weight or volume) of fuel.
SRG	Stakeholder Reference Group, formed by the Australian Energy Market Operator and the Australian Government Department of Resources, Energy and Tourism.
SRG reference data (set)	The set of stationary energy sector modelling reference data compiled and moderated by the Stakeholder Reference Group.
storage	A process whereby the capacity factor for solar thermal technologies can be increased by storing some of the energy for later use when the sun is not shining.
supercritical	A fluid in a state where the temperature and pressure conditions are above the thermodynamic critical point.
t	Time into the future (years)
tCO_2	Tonnes of CO_2
tax	Taxation rate.
thermal efficiency	For a generating plant, the ratio of the electrical energy produced to the thermal energy supplied.
transmission	Transfer of electrical energy from the point of generation to the point of use, generally using electrically conducting cable transmission lines.
twin tracking	A method of tracking the sun to improve efficiency of solar PV generators, involving mechanically moving the solar arrays in two directions simultaneously.
turbine	A rotating engine driven by a high velocity fluid striking blades mounted on its axis.
WACC	Weighted average cost of capital, comprising the weighted average of the after-tax cost of debt and the cost of equity of a firm, defined by Eq. (2)
watt	A measure of power, the rate at which energy is generated or consumed; equals one joule per second.
X	The net present value of the investment required in years 1 to t to secure the free cash flows that make up "S".

Appendix A – Financial Data and Calculation Model Assumptions

A.1 Capital and operating cost learning curves, construction profiles and facility life assumptions

Unless otherwise noted, capital and operating costs used in the study were taken from the SRG reference data set[65]. Figures A.1 and A.2 show the capital costs ($/kW capacity) used in the study, with the error bars representing the range in values for the five AEMO scenarios for 2015 and 2030. For nuclear Gen III the error bars are derived from data in the EPRI report referred to earlier (reference 4). Values for 2020 were taken from a linear interpolation of the data between 2015 and 2030. Values for 2040 obtained by continuing the reference data linear extrapolation from 2030 to 2040 are shown in Figure A.3, together with the standard deviation error bars assumed in the options calculation model for 2040. Geothermal costs were taken from recent confidential data on a regional basis provided to the SRG by the Australian Geothermal Energy Association.

Figure A.4 shows the variable operating and maintenance costs (VOM), in $/MWh sent out, for 2015 and 2030 for the same technologies as in Figures A.1 and A.2, where applicable. For VOM, the costs are the same for all years. In the case of nuclear, the VOM cost includes a $3/MWh remediation and fuel disposal cost[66].

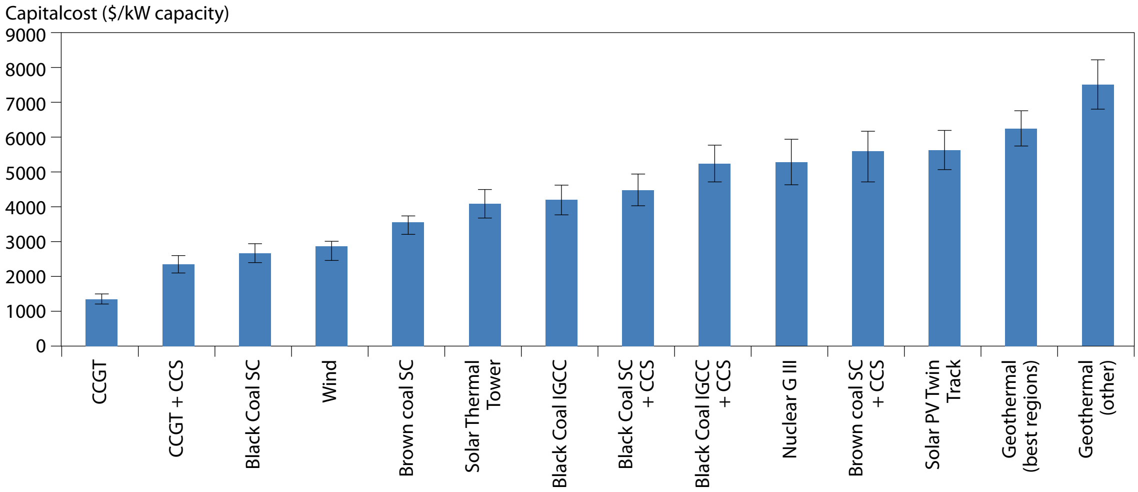
Figure A.5 shows the fixed operating and maintenance costs (FOM), in $/kW capacity per year, for 2015 and 2030 for the same technologies as in Figures A.1 and A.2. Values of FOM for 2040 were obtained by continuing the linear extrapolation from 2030 to 2040.

Table A.1 shows the construction profiles assumed for the new technologies from the SRG reference data set, plus an assumption for nuclear technology. Percentages in the Table represent proportions of total capital expenditure in each of the construction years. For the calculation of NPV, the negative cash flows associated with the capital expenditure profile were inserted into the model for each technology and discounted at the cost of capital during the construction years, followed by 30 years of free cash flow associated with the revenue and operating cost streams discounted by the same cost of capital. In the case of nuclear technology, these cash flows were calculated and discounted over 50 years following a six-year construction phase.

Table A.1 Construction profile assumptions for the new technologies

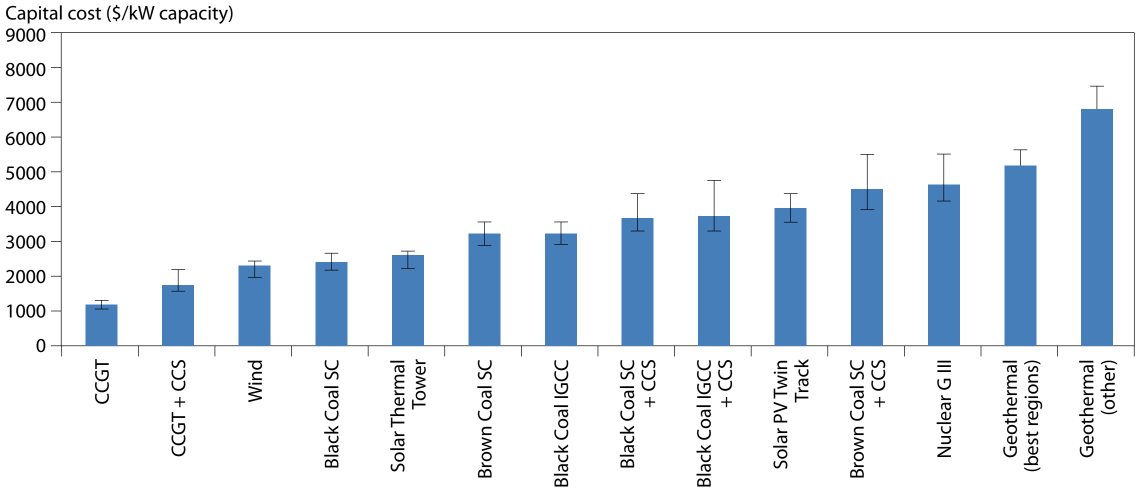
Technology	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
CCGT	60%	40%	–	–	–	–
CCGT with CCS	60%	40%	–	–	–	–
Solar Thermal	50%	50%	–	–	–	–
Wind	75%	25%	–	–	–	–
Solar PV	100%	–	–	–	–	–
Geothermal	40%	20%	20%	20%	–	–
Black Coal IGCC	30%	40%	20%	10%	–	–
Black Coal SC	35%	35%	20%	10%	–	–
Brown Coal SC	35%	35%	20%	10%		
Nuclear	20%	30%	20%	15%	10%	5%

Figure A.1 Capital costs ($/kW capacity) for new power generating technologies in 2015



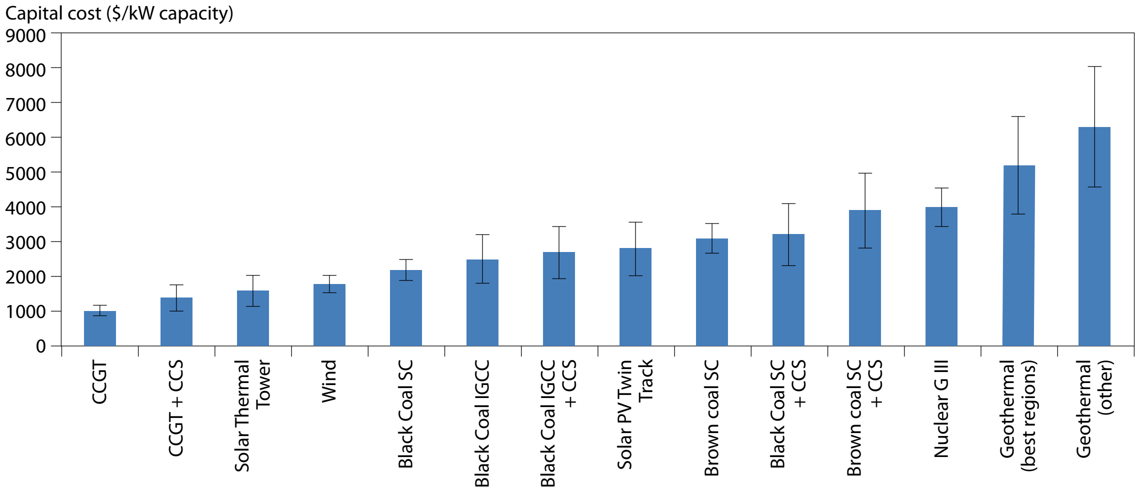
Error bars represent one standard deviation volatility estimates for the net present options value model.

Figure A.2 Capital costs ($/kW capacity) for new power generating technologies in 2030



Error bars represent one standard deviation volatility estimates for the net present options value model.

Figure A.3 Capital costs ($/kW capacity) for new power generating technologies in 2040



Error bars represent one standard deviation volatility estimates for the net present options value model.

Figure A.4 Variable operating and maintenance costs ($/MWh) sent out for new power generating technologies

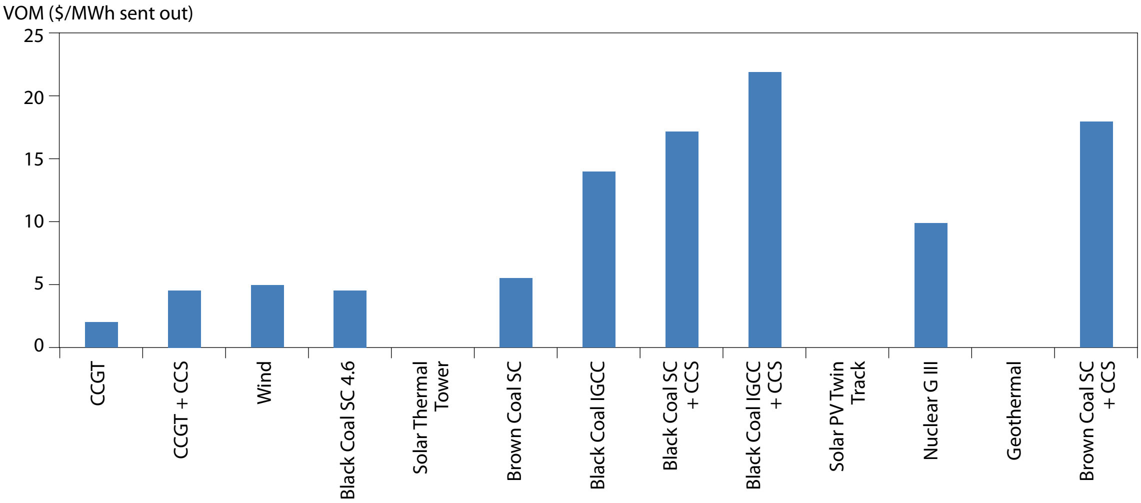
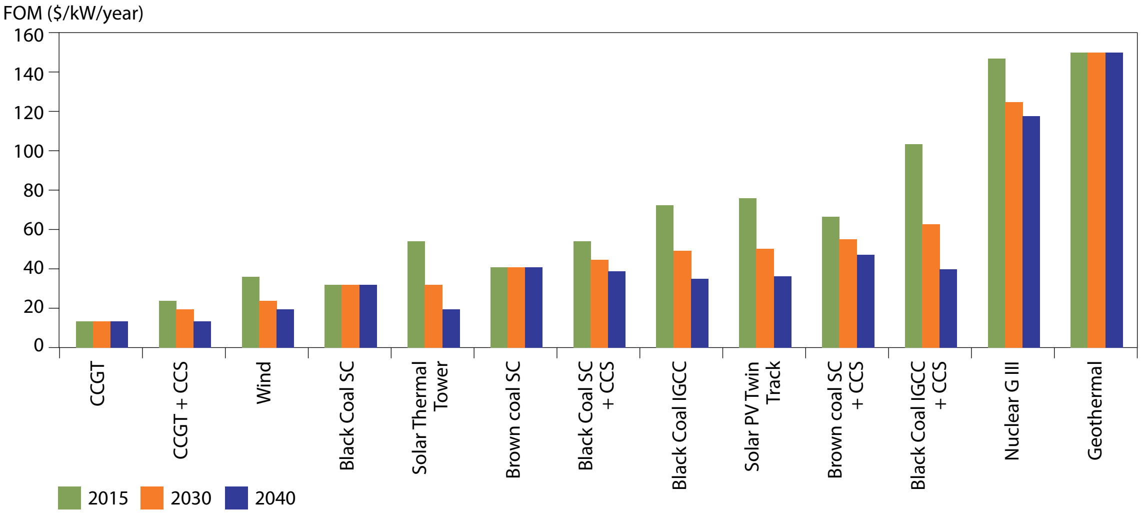


Figure A.5 Fixed operating and maintenance costs ($/kW capacity per year) for new power generating technologies



A.2 THERMAL EFFICIENCY LEARNING CURVE ASSUMPTIONS

Figures A.6 to A.8 show the assumptions used for the thermal efficiencies of the fossil fuel technologies, where thermal efficiency is on a "power sent out – HHV" basis. Figure A.6 is for the gas-fired technologies, Figure A.7 is for the black coal-fired technologies and Figure A.8 is for the brown coal-fired technologies. The thermal efficiencies from 2015 and 2030 shown in the figures are from the SRG reference data set[67]. The thermal efficiencies for 2040 were estimated in the study by extrapolation from 2030 at 67% (two-thirds) of the AEMO linear rate between 2030 and 2040 to account for a reduced rate of learning over 2030–40 and to ensure the thermal efficiencies assumed in 2040 are realistic.

Figure A.6 Assumed thermal efficiencies of gas-fired technologies (power sent out – HHV basis)

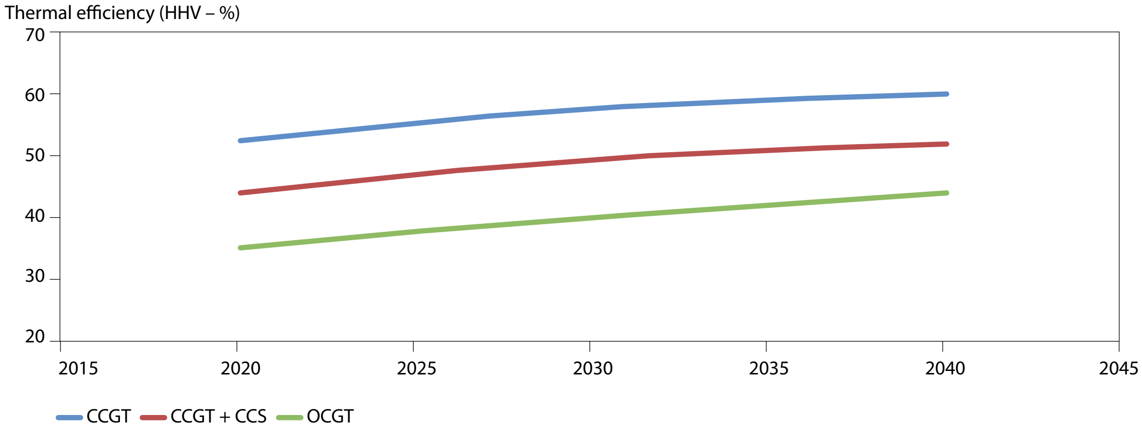


Figure A.7 Assumed thermal efficiencies of black coal-fired technologies (power sent out – HHV basis)

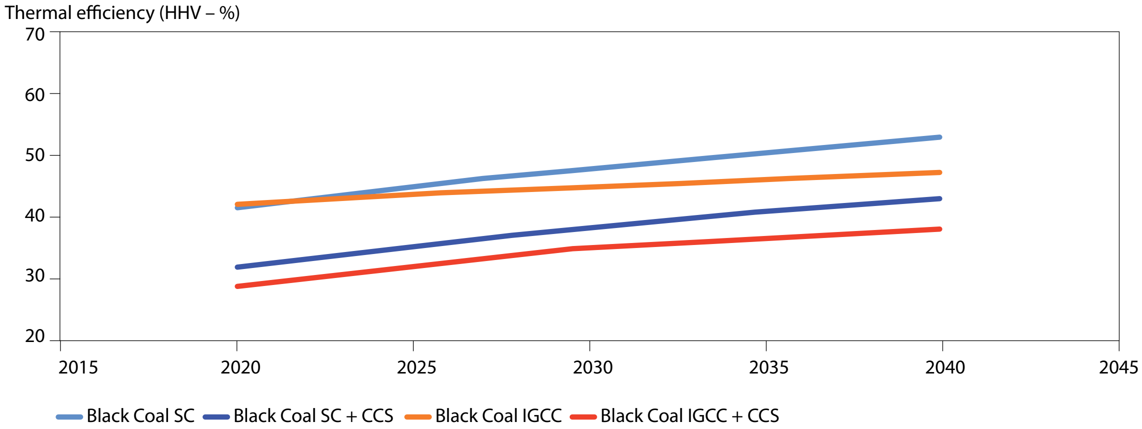
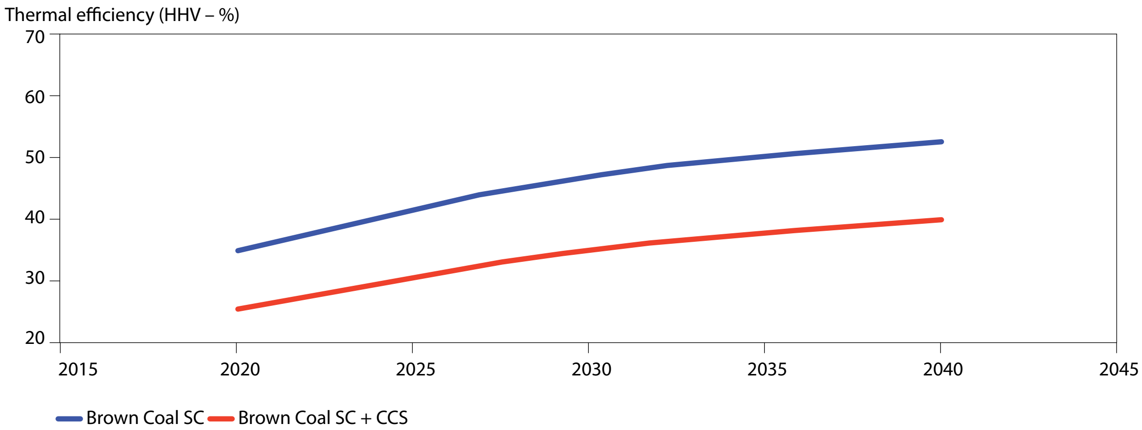


Figure A.8 Assumed thermal efficiencies of brown coal-fired technologies (power sent out – HHV basis)



A.3 CAPACITY FACTOR ASSUMPTIONS

Table A.2 shows the capacity factors from the SRG reference data set assumed in the study. The wind capacity factors as a function of wind class were taken from the EPRI report referred to above (reference 4)

Table A.2 Capacity factors for a range of new technologies from the SRG reference data set

Technology	Capacity Factor (%)
Fossil fuels and nuclear	85.0%
Geothermal	85.0%
Solar PV (twin axis tracking)	30.0%
Solar thermal central receiver (DNI=6)	24.2%
Solar thermal parabolic trough (DNI=6)	24.1%
Solar thermal central receiver + 6 hours storage (DNI=6)	39.7%
Solar thermal parabolic trough + 6 hours storage (DNI=6)	39.5%
Wind (Class 4)	33.2%
Wind (Class 6)	40.6%

A.4 CO_2 AND ELECTRICITY PRICE TRAJECTORY ASSUMPTIONS

The CO_2 price trajectory used in the major part of the study on net present option value was based on a linear model with intercept US$20/t$CO_2$ and slope 2.33 US$/t$CO_2$/year (refer Figure 4); see Section 5.5. Several different trajectory models for CO_2 price were also examined in terms of their effect on net present option values. The results of this sensitivity analysis are presented in Appendix C. The net present option values were calculated by treating the defined CO_2 price trajectory as the mean value in conjunction with a probabilistic distribution; details of the statistical distribution are given in Section A.7.

For the LCOE calculations, the CO_2 price was taken from the above relationship at the time of investment, held constant for the life of the facility, and the electricity price iteratively adjusted to yield a zero NPV. For the LCOE calculations there was therefore no linkage between CO_2 and electricity prices.

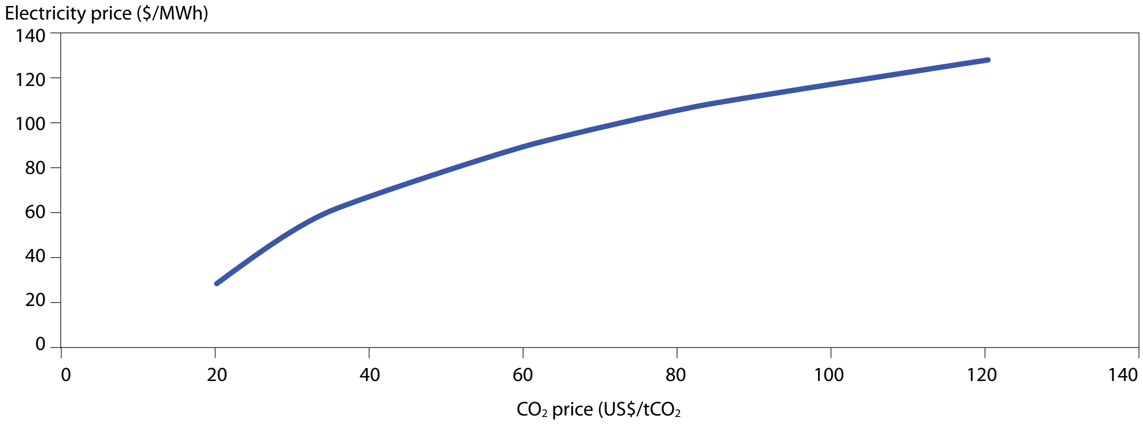
For the purposes of the net present option value calculations used in this study, the CO_2 and electricity prices were linked. Treasury modelling[68] of a global CO_2 trading scheme showed a range of wholesale electricity prices for Australia depending on the target for atmospheric CO_2 concentration proposed by Garnaut[69]. The CO_2 trajectory into the future under these model conditions and the technology mix deployed (influenced by assumptions of future technology costs) governs the electricity price. The relationship published by Treasury is non-linear, with electricity prices higher than CO_2 price early in the period 2010–50, tending to similar prices later in the period. For the purposes of this study, the relationship in Figure A.9 between the two parameters was assumed from curve fitting of the mean values of the Treasury model results. The variation in electricity price was also related to the volatility in the CO_2 price, so that the CO_2 price trajectory in any given iteration of the Monte Carlo method was used to calculate the electricity price in that iteration.

The electricity-CO_2 price relationship in Figure A.9 is, in analytical form,

$$\text{Electricity price (AUD)} = 55\ \ln(CO_2\ \text{price}) - 135 \qquad (5)$$

This equation is applicable for CO_2 prices in the range greater than US$20/t$CO_2$.

Figure A.9 Relationship between CO_2 price and electricity price used in the study



It should be noted that in this study there was no optimisation of NPV or cost to build a portfolio of technologies to satisfy the supply-demand requirements of electricity in Australia. If this was done, the price of electricity for any given CO_2 price could change as a function of the chosen portfolio. In this work the electricity-CO_2 price relationship was assumed to be given by the Treasury relationship for CO_2 price and Eq. A.1.

A.5 FUEL PRICE ASSUMPTIONS

Fuel price assumptions for the base conditions in this study were as shown below in Table A.3:

Table A.3 Fuel price assumptions used in the study.

Fuel	2015 price (2009 dollars) ($/GJ)	Price escalator (% per year)
Natural gas	$5.20	+2%
Black coal	$1.33	-0.6%
Brown coal	$0.56	0%
Nuclear	$0.94	0%

The above fuel prices were taken from new entrants for AEMO scenarios 1-5[70] and, in the case of nuclear, from the EPRI report referred to earlier (reference 4). Sensitivities to the gas price escalation factor in terms of option values and NPV are presented in the main body of the report

A.6 FUEL CHEMISTRY AND SPECIFIC ENERGY ASSUMPTIONS

Fuel property assumptions (from reference 4)

Table A.4 Fuel property assumptions used in the study

Gas	Value
Density	0.75 kg/Nm^3
Specific energy (SE)	38.6 MJ/Nm^3 (HHV[71])
Specific energy (SE)	51.4 MJ/kg (HHV)
Carbon content	75% by weight
Black Coal	**Value**
Moisture (as delivered)	7.5%
Ash (ash delivered)	21.2%
Specific energy (SE) (as delivered)	24.8 MJ/kg (HHV)
Specific energy (SE) (dry ash free (daf))	34.0 MJ/kg (HHV)
Carbon content (as delivered)	60.2% by weight
Carbon content (dry ash free)	82.6% by weight
Brown Coal	**Value**
Moisture (as delivered)	60%
Ash (ash delivered)	2%
Specific energy (SE) (as delivered)	9.9 MJ/kg (HHV)
Specific energy (SE) (dry ash free)	25.3 MJ/kg (HHV)
Carbon content (as delivered)	26% by weight
Carbon content (dry ash free)	66.3% by weight

Mass and Energy Balance Calculations (basis = one year)

Net plant electricity output = (Plant capacity) x (capacity Factor) [MWh]

Thermal input from fuel = Net plant generation / thermal efficiency[72] (HHV) [MWh]

Fuel consumption (daf) = (thermal input from fuel x 3600) / (SE (HHV) x 1000) [tonne]

CO_2 generation = (Fuel consumption (daf)) x (carbon content (daf)) x 44/12 [tonne]

Fuel cost = (fuel price ($/GJ) x (SE (HHV) (GJ/t) x (fuel consumption (t))

For CCS facilities, fuel consumption is assumed to be the same as the technology without CCS and the net plant output is calculated from the SRG reference data thermal efficiency of the combined plant.

A.7 PROBABILITY DISTRIBUTION ASSUMPTIONS

In order to calculate net present option value, assumptions must be made about the probability distribution of each of the financial parameters as a function of time.

Winsen has shown that electricity prices in the short term (hours and weeks) tend to mean revert – that is, they trend towards the current price over time. Winsen found that the volatility of price grew very slowly over time, and that the appropriate relationship was that the volatility term $\sigma\sqrt{t}$ used in the Black-Scholes relationship varied as $\sigma t^{0.1}$ for these short-term electricity price changes (see Winsen[73]). In the present work, over much longer time scales (decades) and with increasing electricity prices, the uncertainty (volatility) in electricity price should clearly increase with time. The same argument applies to the costs and efficiencies associated with the new technologies. It was therefore assumed in the present study for all the parameters given below that the standard deviation of the relevant parameters increased linearly with the square root of time (that is, the variance of the probability distribution increased linearly with time). This is also the assumption in the Black-Scholes relationship and that assumed by Luehrman[74] for real options. There are few data on this for new power generating technologies, but the uncertainty level of many of the financial parameters is high. For the purposes of this study, the following were therefore assumed[75]:

Probability Distributions

The following parameters were described by a normal probability distribution in the Monte Carlo net present option value calculations (where applicable), with defined standard deviations (see below) calculated at the time of investment:

- capital cost ($/kW capacity);
- operating costs (FOM [$/kW/year] and VOM [$/MWh out]);
- fuel prices ($/GJ);
- CO_2 transport and sequestering costs ($/t$CO_2$);
- Renewable Energy Certificate price ($/MWh).

The following parameter was described by a triangular distribution with upper and lower limits defined by the standard deviation (see below) at the time of investment:

- thermal efficiency [sent out – HHV].

There is greater uncertainty surrounding the learning curves of technologies that have not yet been commercialised. Similarly, there is considerable uncertainty regarding future CO_2 and gas prices. The following parameters were therefore assumed to have a variance of σ^2=0.0025 per year for the net present option value calculation. The standard deviation at any given year was then given by the product of σ=0.05 and $\sqrt{t}$ for the investment year in question for the following parameters:

- coal prices
- gas price (see below)
- capital and operating costs for new technologies not yet commercialised:
  - solar technologies
  - fossil fuel technologies using carbon capture and storage
  - geothermal technologies
- CO_2 price (see below)
- electricity price (see below)
- thermal efficiency (sent out – HHV) of the fossil fuel technologies with CCS not yet commercialised, with a triangular distribution for the thermal efficiency as described above.

Technologies that have already been commercialised theoretically have a lower uncertainty than those still under development. The following parameters were therefore assumed to have a volatility of half the developing technologies, or σ^2=0.000625 per year (σ=0.025):

- capital and operating costs for technologies already commercialised:
  - wind
  - nuclear
  - fossil fuel technologies without CCS
- thermal efficiencies of technologies (sent out – HHV) for nuclear and fossil fuel technologies without CCS already commercialised, with a triangular distribution for thermal efficiency as described above.

The proportion of CO_2 captured for CCS technologies was assumed to be described by a triangular distribution between 85% and 95%, with a mean of 90%.

The transport and sequestering costs of CO_2 were assumed to be described by a triangular distribution between \$20/tCO_2 and \$40/tCO_2 for those cases with a mean value of \$30/tCO_2 (i.e. black coal), and \$5/tCO_2 and \$20/tCO_2 for those cases with a mean of \$10/tCO_2 (i.e. brown coal and gas).

Time Distributed Variables following Investment

In the cash flow model for the study, the CO_2 price is required each year during the economic life of the facility. The mean CO_2 price trajectory was computed for the life of the facility after investment according to the linear price escalation model described in Appendix A.4. For each year in the trajectory, the CO_2 price was modified through multiplication by a random variable taken from a normal distribution with a mean of unity and a variance calculated from σ^2=0.0025 per year times the number of years into the future in the trajectory model. This method created a separate trajectory of CO_2 price, for each Monte Carlo iteration, with volatility increasing over time. In this way, a probability distribution of CO_2 prices was created for each year in the life of the facility over thousands of iterations in the Monte Carlo simulation. This process created, in turn, a probability distribution of electricity prices for use in determining the distribution of parameter "S" according to the relationship described in Appendix A.4 above. The standard deviation of CO_2 prices was calculated to increase over time using this calculation method, with the standard deviation approximately matching the range in values reported by the Treasury/Garnaut model results.

The same method as that described in the paragraph above was used to calculate the distribution of gas price as a function of year, given the defined gas price escalation factor (generally +2% per year).

Coal prices were assumed to follow a normal distribution with a defined variance of 0.0025 per year multiplied by the years to the commercial investment (σ=0.05) and then held constant, given the small variation in coal prices over time in the AEMO data.

Parameters that did not have probabilistic distributions for the NPOV calculations were:

- plant capacity (MW);
- capacity factor (%);
- auxiliary power consumption (%);
- fuel chemistry, moisture, ash and specific energy (MJ/kg); and
- financial parameters (tax, depreciation, cost of debt, cost of equity, financial leverage (%)).

Appendix B – Option Valuation

An introduction to option values was given in Section 4. Further details follow below.

B.1 A SIMPLE ILLUSTRATION OF OPTION VALUE

The simple illustration below demonstrates how option value may be calculated from a set of probabilities associated with a game of chance. It is not an endorsement of such games.

Imagine a simple dice game, with a croupier rolling the dice. In the rules of this game, you will be paid:

- $60 if the (unbiased) dice comes up "6",
- $40 if it comes up "5", or
- $4 if it comes up "4".

On the other hand, you will have to pay the croupier:

- $5 if it comes up "3",
- $40 if it comes up "2", or
- $60 if it comes up "1".

Question: What is the value to you of playing in this game?
Answer: The probabilistic value to you of each throw is given by:

Value = 1/6 x ($60+$40+$4-$5-$40-$60) (6)

That is, the value to you is –$0.167. That is, you should expect *the croupier to pay you* more than $0.16 per throw of the dice for you to come out ahead in the long run for this game.

Now imagine that you had the option to retire from the game, with no penalty, after the dice is thrown. In this case you would know the number before you had to make the call to proceed. Clearly you would make the decision to retire from that throw if the dice came up with a "3", "2", or "1", these being negative outcomes for you. How much would you be prepared to pay each time the dice is thrown to play in this second game?

The calculation is much the same as eq. (6), except there are no negative outcomes:

Value = 1/6 x ($60+$40+$4) (7)

or, value = $17.33. This is the value to you of having the option not to play the game if you know that you will suffer financially. You should therefore *pay the croupier* up to $17.33 to play for each throw of the dice to secure this option.

There are a few things to note from this simple game:

- There is no option value unless the result is uncertain. It is the potential upside for you in the uncertainty that creates the option value.
- You have to make a management decision to proceed or not as the facts emerge. If you do not make this decision in an appropriate way after paying the $17.33 for the privilege, you will lose money.

- The $17.33 is a measure of how much you should be willing to pay to participate in the game, given the option not to proceed as you learn more.
- In this game there was no "exercise price", i.e. you did not have to make a payment to proceed with the game, only an option price before the dice is thrown. In share market or other options, there is normally a payment to proceed that has to be deducted against the upside benefit, in addition to the option price, when the decision to invest is made.
- The loss of $0.167 you would make on average for each throw in the first game (where you did not have the option to proceed or not) is analogous to the Net Present Value (NPV) of a project. The difference here is that it is the result of a probabilistic calculation of the range of possible values that the project could generate. Of course, you might be lucky if the dice comes up a "6", but on average you would make a loss.
- The option value can be very different from the NPV (in this case the NPV is negative, but the option value is positive). Clearly, the NPV and option value are very dependent on the "volatility", or range of possible financial outcomes for the game (or project).

B.2 VALUATION CONCEPTS

Net present ption value in terms of probability distribution

Net present option value is calculated from the probability distribution of the net present value (NPV). It is that part of the distribution where NPV is greater than zero. The rationale for this is that if the NPV is below zero at the investment date in the future, then an investor will abandon the strategy to commercialise the technology. Viewed from today, there may be some probability of a favourable financial outcome in the future and it is this that provides the option value.

Net present option value is a function of two parameters:

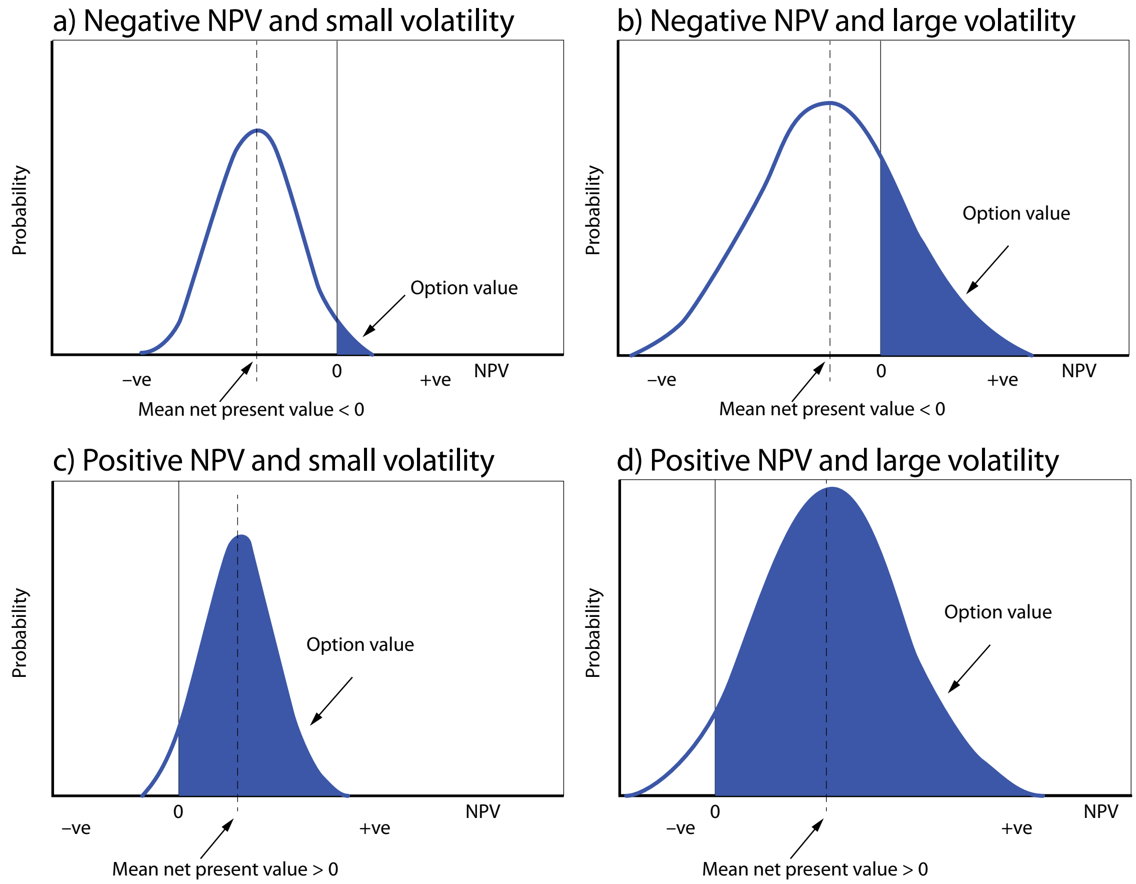
- the mean value of the NPV distribution; and
- the variance in the NPV distribution.

Figure B.1 shows four NPV distributions with different means and variances. Also shown is the position of zero NPV and the part of the distribution that contributes to option value. As can be clearly seen, option value is increased by both an increase in NPV and an increase in the variance of the probability distribution.

Option values have historically been calculated in order to price options for share market investors. For example, a share market investor can purchase a call option to purchase shares at a certain date in the future at the current share price . The investor is paying to "participate in the game" in an analogous way to the player in the dice game described in Section B.1. If the share price at the future date is above the "exercise price" then the investor should buy the shares at the lower price, sell them at the market price, and make a profit. Hopefully, the profit will then be above the originally paid option price. If the exercise price at the future date is now lower than the market price, then the investor would decide not to take up the option and lose the option price paid.

The area of investments in real assets, such as new technologies for power generation, provides an analogy with the financial options discussed above. Here, the investor could pay to be "in the game" while waiting to see what situation emerges. This options payment could be for R&D, pilot facilities or demonstration plants, or orders for spare parts, for "capture-ready" CCS facilities, for land or sub-sea tenements or for potential pipeline infrastructure, and so on. In the event that the R&D succeeds or that the infrastructure is in place, the investor could "exercise the option" by going ahead with the commercial investment. This application of options theory is termed "Real Options".

Figure B.1 Probability distributions showing NPV and variance in NPV, illustrating option value



B.3 OPTION VALUE CALCULATION METHODS

Four key methods are available for calculating option values: the Black-Scholes method[77]; the Binomial method[78]; the McDonald-Siegel[79] method, and the Monte Carlo method. In the financial industry there are many more methods than these, but for the purposes here these are sufficient for comparisons to be made. ATSE has commissioned a separate research paper on these approaches, which is available for interested readers[80].

Option valuation methods normally do not assume any probability distributions. Options are valued by arbitrage arguments, and in the case of the binomial methods the size of the binomial fluctuations determines the resulting valuation parameters, which behave as if they were discrete "risk-neutral" binomial probabilities. As the number of steps in the binomial calculation is increased, the implied binomial distribution approaches a lognormal and the binomial valuation becomes identical to the Black-Scholes value[81].

The Black-Scholes method is an analytical method based on a random walk of stock prices. A constant exercise price is assumed, and the volatility in the form of variance in market price is assumed to vary linearly with time into the future. The Binomial method uses a numerical approach based on analytical analysis of the market volatility to calculate the option value in a forwards-backwards calculation technique with bifurcation at each time step. It is computationally intensive and the calculation increases exponentially with more time steps. The analytical McDonald-Siegel method, unlike the first two approaches, includes the possibility for variation in the exercise price with time. All these techniques use the risk-free rate to discount the exercise price to today's value.

The Monte Carlo method used in this study directly computes the actual probability distribution of the NPV and then calculates the net present option value based on this probability distribution for that part of the distribution where NPV>0. It builds up the distributions numerically and iteratively. For a complex problem with varying input data like the option value analysis of the new power generating technologies, the Monte Carlo method has inherent data flexibility advantages relative to the analytical methods. In the present study, the Monte Carlo method was used to create the NPV probabilistic distribution, with both the commercialisation investment X and the future free cash flows S discounted to today at the firm's cost of capital to calculate the NPV. The option value determined from this approach was termed "net present option value, NPOV" in the work herein. The NPOV is not the same as the "real option value" calculated from the other analytical methods discussed in this Appendix.

In order to compare the two major analytical methods with the Monte Carlo method, to ensure that the more flexible Monte Carlo method was calculating the same results for a "real option value", a simple European call option was simulated in this work to calculate a real option value, as opposed to a NPOV. In this case X was discounted to present value using the risk-free rate and a lognormal distribution was assumed in the Monte Carlo simulation. The Black-Scholes, Binomial and Monte Carlo methods were programmed into an Excel spreadsheet. Important parameters (volatility, exercise price and time) were varied as part of this analysis. The work demonstrated agreement, within a small numerical error at large volatility, between all three methods for a simple European call option[82] with constant S and a wide variety of values of X, T, volatility (σ) and parameters such as the risk-free interest rate and the cost of capital. The results are presented in Appendix D.

B.4 RELATIVE CUMULATIVE VOLATILITY FOR CHANGING S AND X

For the case here, when calculating the NPOV there are two sources of volatility (namely, S and X), and it is more appropriate to calculate the co-variance, $\sigma^2_{s,x}$, between S and X and define the relative cumulative volatility term[83], R_v, as follows:

$$\sigma^2_{s,x} = \sigma^2_s + \sigma^2_x \tag{B.1}$$

$$R_v = 2\sqrt{(\sigma^2_{s,x})}/(S+X) \tag{B.2}$$

where: (S+X)/2 is the mean of the modulus of S and X and S and X are assumed to have a correlation coefficient of zero[84].

The values of σ^2_s and σ^2_x are determined in the present work by analysing the distributions of S and X produced by the Monte Carlo simulation.

Appendix C – Net Present Option Value Sensitivity to CO_2 Price Trajectory Assumptions

In the main report the option values were calculated from a linear fit to the Treasury CO_2 price trajectory as a function of time. The relationship used, commencing in 2010, was:

CO_2 price (\$US/t) = 20.0 + 2.33 x (time in years), where the price is exclusive of inflation.

To evaluate the sensitivity of net present option value to the shape of the CO_2 price trajectory, three alternative models are tested here in addition to the linear model:

- A sigmoidal-shaped curve, where the CO_2 price increases exponentially to 2050, and then decreases exponentially thereafter. This model more closely approximates the Treasury model results in the period 2020–50.
- A step-shaped curve, where the CO_2 price increases linearly until 2050 and then remains constant for the remaining life of the facility.
- A constant-price CO_2 model, where the price rises linearly until the option exercise date, and then remains constant for the full life of the facility after commercialisation.

Figure C.1 shows the trajectories of these different models. The constant price model is not shown, since the constant CO_2 price depends on the year of commercial investment. In the comparative results in Figure C.2 the constant CO_2 price applies from 2040, the investment date.

Figure C.1 CO_2 price trajectory models.

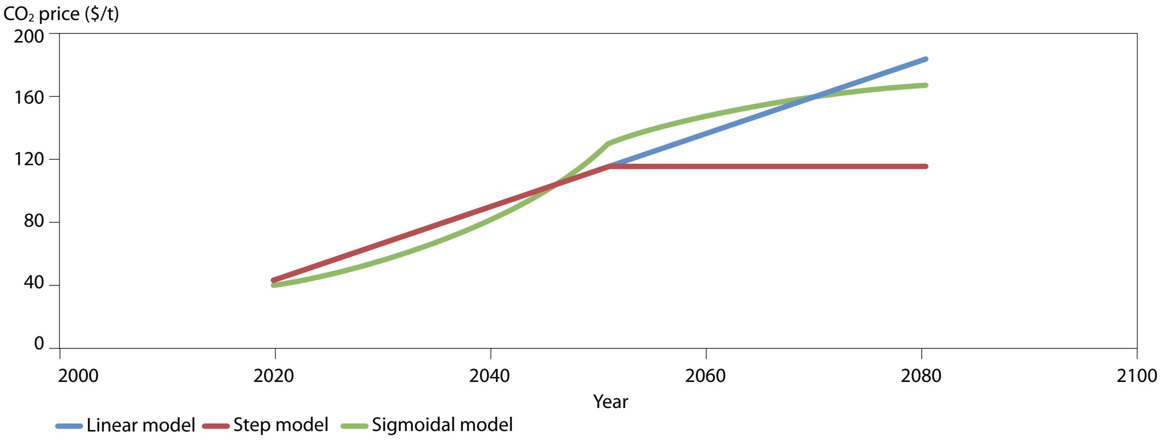
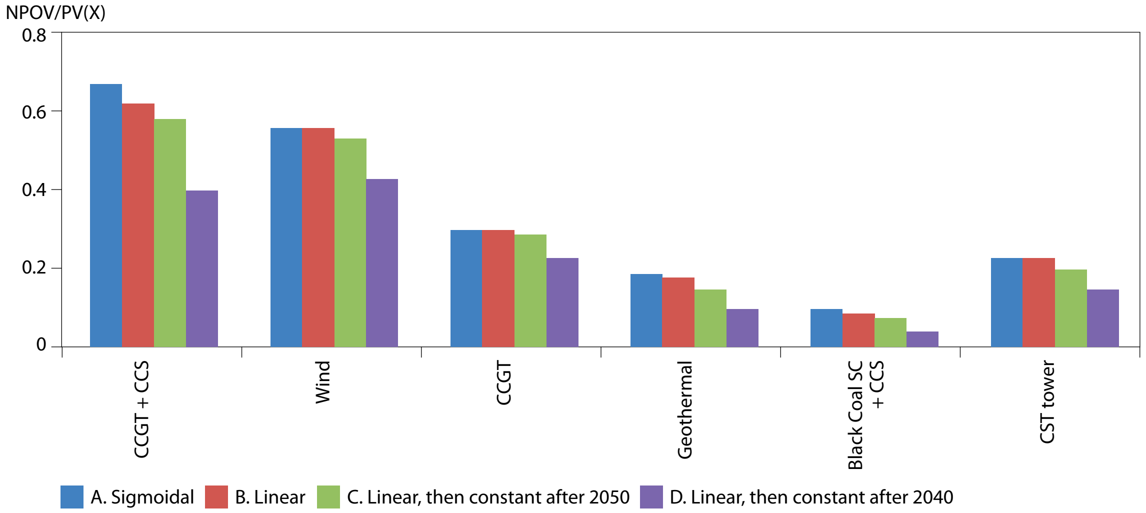


Figure C.2 shows the net present option values calculated by the for CO_2 trajectory models for commercialisation of selected new technologies in 2040. As can be seen from the figure, option value is sensitive to the assumed shape of the CO_2 trajectory. However, the sigmoidal and linear trajectories are very similar in terms of the net present option value calculated. As expected, the constant price CO_2 model, which is similar to the model assumed in the levelised cost of electricity calculations, gives the lowest net present option values and some differences in relativities. This is mainly due to the unrealistic assumption of constant CO_2 and electricity prices in all years after the investment for the LCOE case. Overall, the relativities between technologies in terms of net present option value are similar for all models except the constant price model. As shown in the main body of the report, the rate of change of CO_2 price is an important parameter in determining the absolute net present option value and can have an influence on the relative NPOVs, and this is confirmed for the different trajectory shapes shown here.

Figure C.2 Sensitivity of net present option values in 2040 to CO_2 price trajectory model for selected new technologies



Appendix D – Comparison of Analytical and the Direct Monte Carlo Method for Option Value Calculation

As part of this project Professor Michael Hasofer was commissioned to undertake a review of the various methods of calculating option value[85]. His report is available from ATSE for interested readers. In summary, the review concluded that the Direct Monte Carlo Method for option value calculation was the most applicable to the analysis, given the complexities involved.

In order to calculate the probabilistic parameters for the Direct Monte Carlo method, a procedure is required to iterate many times using values extracted from defined probabilistic distributions. The ATSE model uses Oracle "Crystal Ball" software to undertake this task. The software is a plug-in to Microsoft Excel and it enables appropriate parameters in the spreadsheet to have defined probabilistic distributions. The model then takes random values of the parameters of interest defined by the distributions and calculates the financial parameters. Thus, each NPOV calculation yields a different set of cash flows and NPV, but over time the distribution of NPV is built up, typically with thousands of iterations.

This Appendix compares some of the different calculation methods for the calculation of "real option value", as opposed to the parameter NPOV introduced in the main body of the report.

As noted previously in Appendix B, four key relatively straightforward methods are available for calculating the option value: the Black-Scholes method; the Binomial method; the McDonald-Siegel method, and the Monte Carlo method. The analytical McDonald-Siegel method, unlike the first two approaches, includes the possibility for variation in the exercise price with time. The first two methods are also analytical, with constant exercise price, and practical methods for their calculation are provided elsewhere in standard texts, e.g.[86]. These two latter methodologies were programmed into an Excel spreadsheet in this study to compare the methods.

The relevant parameters for determining the option value are the present value of future positive cash flows, S, and the present value of the exercise price (commercialisation investment), PV(X)[87]. When the exercise price is fixed, as in a European option, S is discounted at the firm's cost of capital and X is discounted at the risk-free interest rate. The ratio of these parameters, S/PV(X), is used to determine the Black-Scholes option price in look-up tables[88] or using the analytical equation[89]. The relevant "volatility" parameter is the standard deviation per year in S, times the square root of the time into the future when the option can be exercised, $\sigma\sqrt{t}$. This implies that the variance in the distribution of S increases linearly with time into the future.

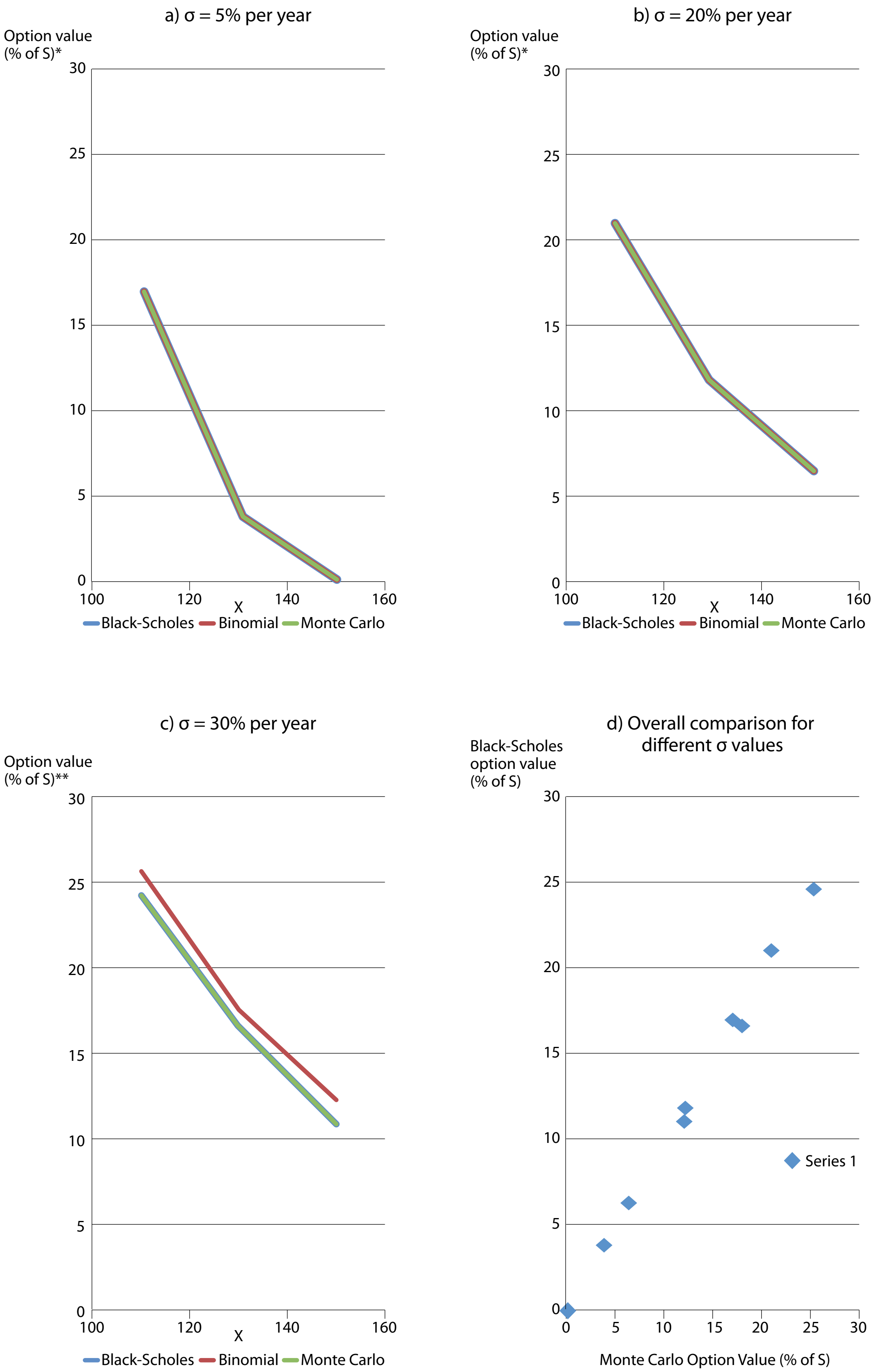
A binomial method for calculation of the option value was also developed for comparison purposes. The method is described fully elsewhere, where details are given on relationships to relate the binomial method parameters and σ[90]. In the results below, 40 forward and backward steps were used to compute the option value by this method. As the number of steps in the binomial method is increased, the implied binomial distribution approaches the lognormal and the binomial valuation becomes identical to the Black-Scholes value.

In the Direct Monte Carlo method for the calculation of real option value (not NPOV), for comparative purposes, the parameters S, X and $\sigma\sqrt{t}$ were used to construct a lognormal probabilistic distribution of values of [S-PV(X)] using Excel and Crystal Ball, given the value of σ and the investment date, which provides the length of time for the option before expiry, t. For the purposes of comparison with the other methods, the output distribution of the Monte Carlo method was fitted to a log-normal distribution[91] with 2000 subdivisions for [S-PV(X)]. For cases where [S-PV(X)] <= 0, it is assumed that a rational investor will not invest in the future. For cases where [S-PV(X)] > 0, it is assumed that the investor will pay the exercise price for the investment, since the value under these conditions will be positive. Thus, the option value is given by the sum of all values of [(S-PV(X)] greater than zero in the log-normal distribution. In this way, the Monte Carlo method can be used to approximate the other methods for the calculation of real option value, as opposed to NPOV.

Using the same values of S, X and $\sigma\sqrt{t}$, the results from the Black-Scholes, Binomial and Direct Monte Carlo calculation methods were compared in terms of calculated option value. The work showed agreement, within a small numerical error at large σ, between all three methods for a simple European call option[92] with constant S and a wide variety of values of X, T, σ and parameters such as the risk-free interest rate and the cost of capital. Some of these results are shown in Figures D.1 and D.2, below.

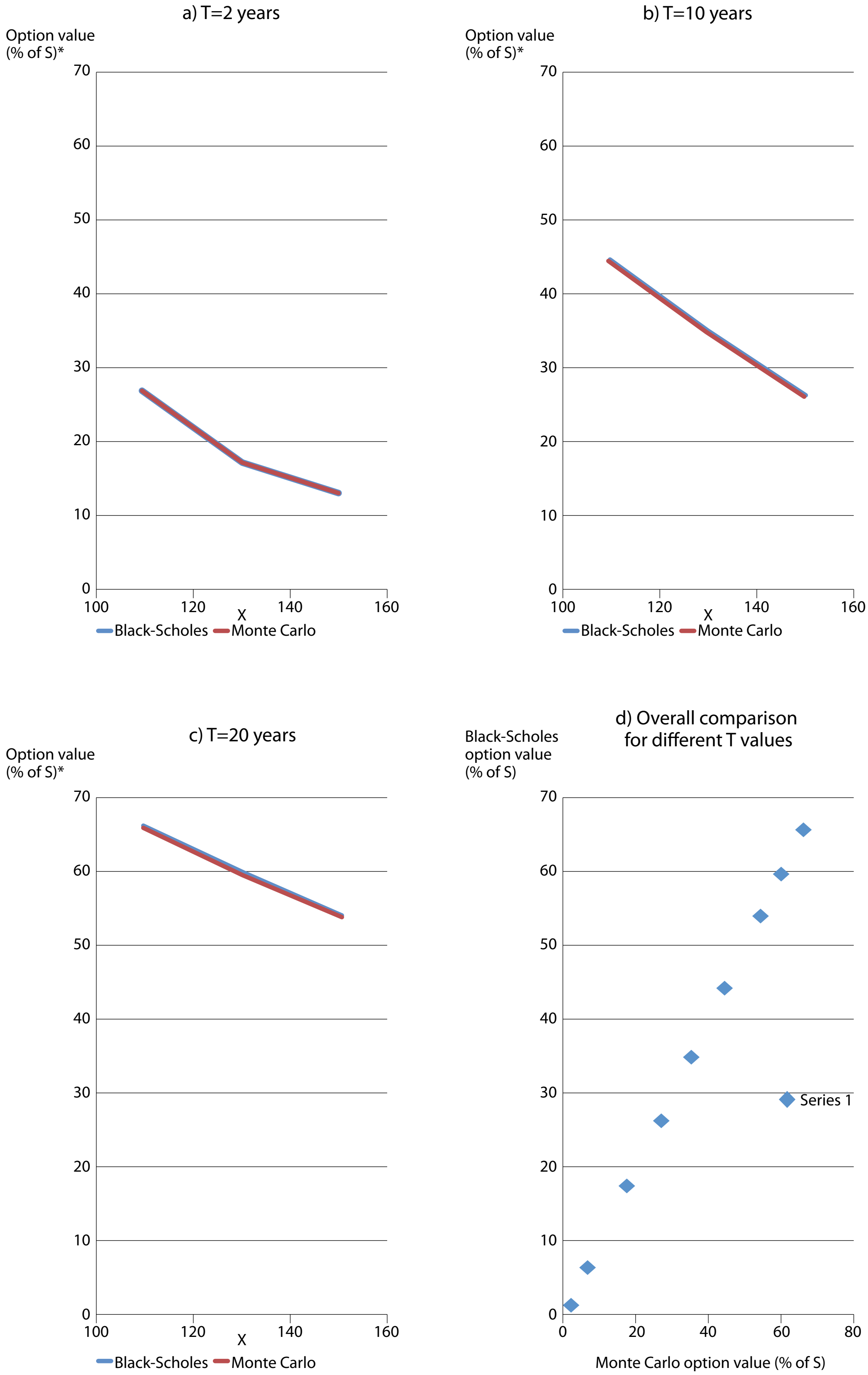
The agreement shown in Figures D.1 and D.2 is deemed sufficient to use the Direct Monte Carlo method for the net present option value calculation with new power generating technologies where both drift and volatility occur in the discounted free cash flows S and the investment X.

Figure D.1 Comparison of Black-Scholes method, Binomial method, and Monte Carlo Direct method of calculating the value of a European Call option [S=$120M, T=2 years]



* All three lines are effectively co-incident in these two graphs.
** The Black-Scholes and the Binomial lines are effectively co-incident in this graph.

Figure D.2 Comparison of Black-Scholes method and Monte Carlo Direct method of calculating the value of a European Call option [S=$120M, σ=10% per year]



* The Black-Scholes and the Monte Carlo lines are effectively co-incident in these three graphs.

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2 http://www.arc.gov.au/ncgp/lasp/lasp_default.htm

3 This electricity cost variable is the constant real wholesale electricity price that yields a zero NPV for the investor. That is, the investor is earning the cost of capital from the investment in the technology at that LCOE price.

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12 *Analysis for Financial Management*, 6th Edition, Higgins R C, Irwin McGraw-Hill, Boston, 2001, pp. 326.

13 *Ibid*, pp. 280.

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15 *National Transmission Network Development Plan: Consultation Paper*, AEMO, http://www.aemo.com.au/planning/0418-0002.pdf.

16 *Modelling Assumptions – Supply Input Spreadsheets*. See: http://www.aemo.com.au/planning/ntndp.html

17 Capacity Factor: The ratio of time, on average, that a generator is operating at full capacity to the total time available.

18 Class 6 and Class 4 wind conditions are average wind speeds of 8.4 ms^{-1} and 7.3 ms^{-1} respectively.

19 DNI 5, 6 and 7 conditions are sunlight Direct Normal Irradiance at levels of 5, 6 and 7 $kWh/m^2/$ day respectively.

20 Dalton S M, Director Generation, and Phillips J N, Senior Program Manager Advanced Coal Generation, Electrical Power Research Institute (EPRI), California and New Carolina respectively, USA, Personal Communication, April 2010.

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27 *Comparative Costs of Electricity generation Technologies*, Report to Australian Geothermal Energy Association Inc, McLennan Magasanik Associates, February 2009.

28 The ranges shown are taken from EPRI modelled LCOEs with upper and lower case scenarios.

29 A real before-tax cost of capital of 8.4% is equivalent to an after-tax weighted average cost of capital (WACC) of 7% when calculated by eq. (2), assuming a debt to total capital leverage ratio of 70%, a cost of debt of 6.3%, a cost of equity of 13.2% and a tax rate of 30%, as proposed by EPRI and used throughout for the results in this report. After tax WACC is used to discount cash flows that do not include a tax-deductible interest charge, eq. (1). (see *Analysis for Financial Management*, Higgins R C, Irwin/McGraw-Hill, 2001, 6th Ed., pp.280-295.)

30 For nuclear, a remediation and waste disposal cost of $3/MWh was added to the cost, as discussed in the earlier ATSE report *Energy Technology for Climate Change – Accelerating the Technology Response*, ATSE, January 2009. For geothermal, operating and maintenance costs similar to coal firing were assumed, but the SRG reference data for capital costs and auxiliary power load were retained.

31 The Treasury relationship from the mean values of the electricity price and CO_2 price shown in Figures 4 and 5 was used in the option values calculation following later in the report.

32 The most favourable geothermal cases are geothermal EGS in northern South Australia, and geothermal HSA in south-east South Australia and some locations in Victoria. These cases have similar LCOEs.

33 *Australia's Low Pollution Future: The Economics of Climate Change Mitigation*, Australian Government Treasury, October 2008.

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37 *Options for Electricity Generation in Australia*, Graham P, Dave N, Coombes P, Vincent D, Duffy G, CRC for Coal in Sustainable Development, Technology Assessment Report 31, Sept. 2003.

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43 *National Transmission Network Development Plan - Consultation Paper*, 29 Jan, 2010. See http://www.aemo.com.au/planning/ntndp.html

44 *Investment Opportunities as Real Options: Getting Started on the Numbers*, Luehrman T A, Harvard Business Review, July-August, 1998. Also, Strategy as a Portfolio of Real Options, Luehrman T A, Harvard Business Review, Sept-Oct 1998.

45 DNI: Direct Normal Irradiation. A value of DNI=6 $kWh/m^2/day$ is equivalent to a location in northern South Australia.

46 *National Carbon Mapping and Infrastructure Plan – Australia*, Concise Report, Carbon Storage Taskforce, September 2009, Department of Resources, Energy and Tourism, Canberra, pp. 21. http://www.ret.gov.au/resources/Documents/Programs/CS%20Taskforce.pdf

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51 The favourable geothermal locations are EGS in northern South Australia and HSA in some locations in Victoria and south-east South Australia. The less favourable geothermal bubble is for other locations in Australia.

52 *NTNDP Modelling Assumptions - Supply Input Spreadsheets*, 15 Feb 2010; and worksheet Fuel Costs for new CCGT facilities for scenarios 1-5. See: http://www.aemo.com.au/planning/ntndp.html

53 *Energy Technology for Climate Change – Accelerating the Technology Response*, ATSE, January 2009.

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61 Professor T. Wall FTSE AM, University of Newcastle, NSW, Personal Communication

62 *Energy Technology for Climate Change – Accelerating the Technology Response*, ATSE, January 2009.

63 The analogy is to proceed with the previously mentioned dice game if the dice comes up a "3", "2", or "1".

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82 In a European call, the date for exercising the option is fixed by contract.

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84 The co-variance of (S-X) is $\sigma^2_{s,x} = \sigma^2_s + \sigma^2_x - 2\sigma_s \sigma_x \rho_{s,x}$, where $\rho_{s,x}$ is the correlation coefficient between S and X.

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91 A log-normal distribution describes the distribution in values of S in the case of the Black-Scholes and Binomial methods based on random-walk theory.

92 In a European call, the date for exercising the option is fixed by contract.

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