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Achieving cost-effective abatement from Australian electricity generation

A Measure for the Australian Renewable Energy Agency

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Introduction

The purpose of this study has been to address three key questions:

a) What combination of generation, transmission and storage technologies will achieve the least cost transition from existing infrastructure to a low carbon economy by 2050, and
b) How effectively will the National Energy Market (NEM) function under this new mix of technologies, and is a re-design on the market going to be required.
c) What is the value of distributed generation and storage technologies?

The project is a collaboration between the University of Melbourne and the University of New South Wales, along with the Australian Energy market Operator (AMEO), Bureau of Meteorology, Victorian Department of Treasury and Finance, GE and Market Reform. The project has been led by Dr Roger Dargaville[1] and Prof Michael Brear from the University of Melbourne, and Assoc. Prof. Iain MacGill from UNSW.

A suite of modelling tools have been developed, with the first group simulating the function of the NEM, and second group examining the market behaviour of the NEM under the least cost generation mix determined by the first set of models. The key deliverables of this work have been several peer-reviewed papers in the academic literature along with the source code of the models being made publically available. The research team has made several public presentations of the project work. The papers contain significant detail describing the models and results, and the purpose of this report is to summarise the key outcomes.

Key Outcomes

The key outcomes of the study are:

a) Modelling tools designed to assess the performance of future energy systems under different levels of renewable energy penetration.
b) Descriptions of pathways to least cost combinations of generation and transmission technologies that achieve a range of carbon abatement trajectories
c) Improved collaboration between research community, government and renewable energy industry.

Three different technology mix models have been developed, and the code for each is available online. See below for more details. The models have been used to find least cost combinations of RE technologies, and the results have been written up in peer-reviewed articles. Engagement between the University researchers and government and industry have been enhanced during the course of the project with project meetings facilitating detailed discussions between the partners, and public events to present key results to a broad range of stakeholders.

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Main Findings

The key results have been written up in the peer-reviewed literature (see list below) and are highlighted in a Powerpoint presentation available on the ARENA website. The results show that:

a) A low carbon energy system for the NEM is technically and economically feasible, and under certain circumstances may be cheaper than a business as usual scenario energy system with mostly fossil generation.
b) The model configuration and the cost assumptions that go into the simulations are very important and strongly affect the results. The results from Jeppesen et al. and Elliston et al. show that assuming the emission abatement target for 2050 is set at 80% of 2000 levels, the least cost combination of technologies is approximately 5% biomass, 20% onshore wind, 10% utility scale PV, 35% combined cycle gas turbines, 25% concentrating solar thermal, and 6% hydro power (Jeppesen, see figure 1), or 5% biomass, 60% onshore wind, 10% PV, 20% CCGT and 5% hydro (Elliston et al., figure 2).
c) The transition from today's infrastructure to a low carbon energy system involves a rapid decline in capacity for black and brown coal over the period 2015-2030 while wind capacity ramps up, then an increase in combined cycle gas turbines and concentrating solar thermal from around 2030 onwards while the remaining coal capacity is retired.
d) A scenario with nuclear power and carbon capture and storage (CCS) included in the generation mix shows that at the Australian Energy Technology Assessment report (AETA, published by BREE) cost estimates, nuclear power is an attractive option, however CCS is not cost competitive. In none of the scenarios is geothermal power selected as cost competitive.

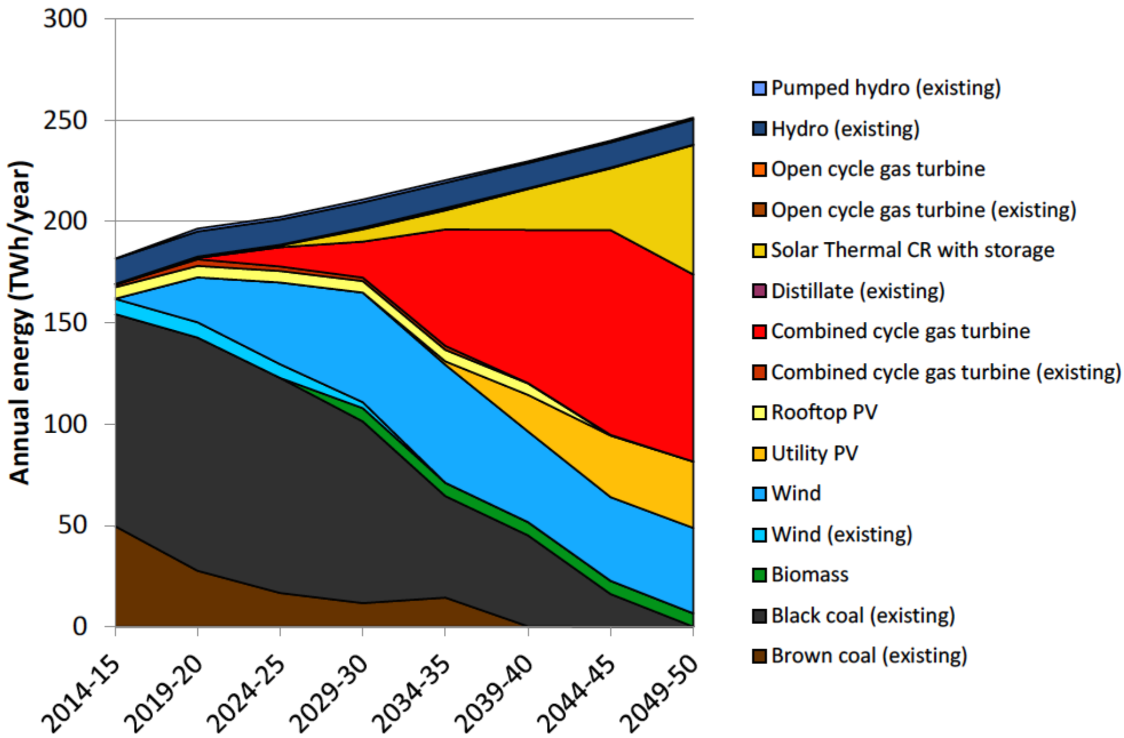

Figure 1: Least cost transition pathway for an 80% emission reduction target (from Jeppesen et al.)

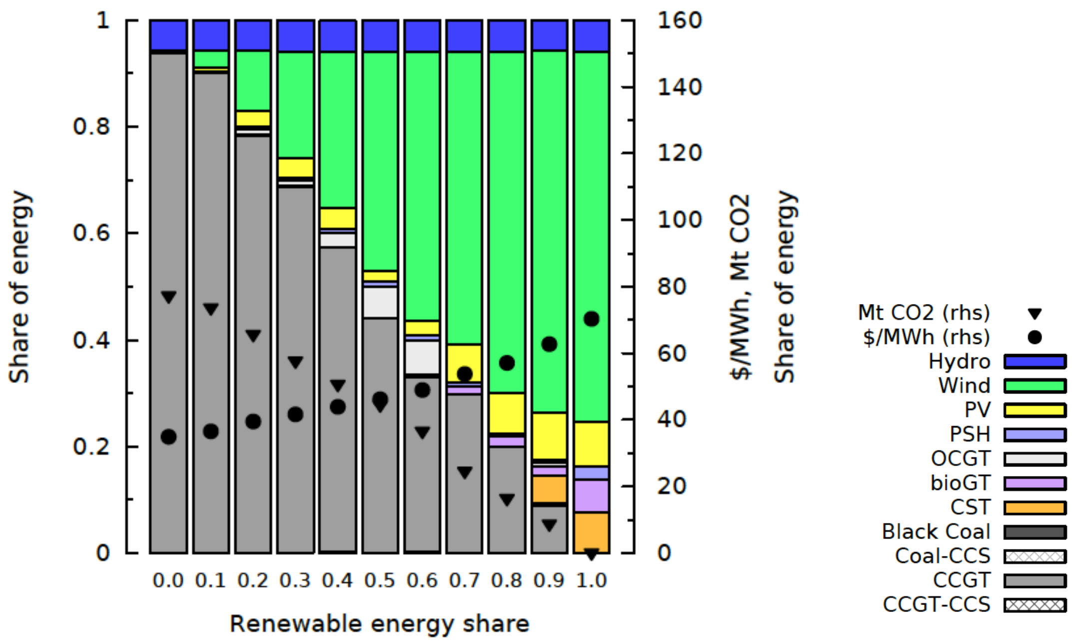

Figure 2: Generation mix for decreasing fossil fuel emissions from Elliston et al. (2015).

e) The cost implications (fig 3) for the average wholesale price of electricity are modest for an 80% emission abatement, but again the results depend on the modelling study: for the Jeppesen et al. model results show an increase from $70/MWh for no abatement in 2050 to $105/MWh for 80% reduction. However to get to 100% emission reduction would cost $160/MWh without nuclear, or $110/MWh with nuclear. For the 80% target, nuclear is slightly cheaper at just under $100/MWh. For Elliston et al., prices increase from $40/MWh to $55/MWh for 80% emission reduction, and then to $70/MWh for 100%.

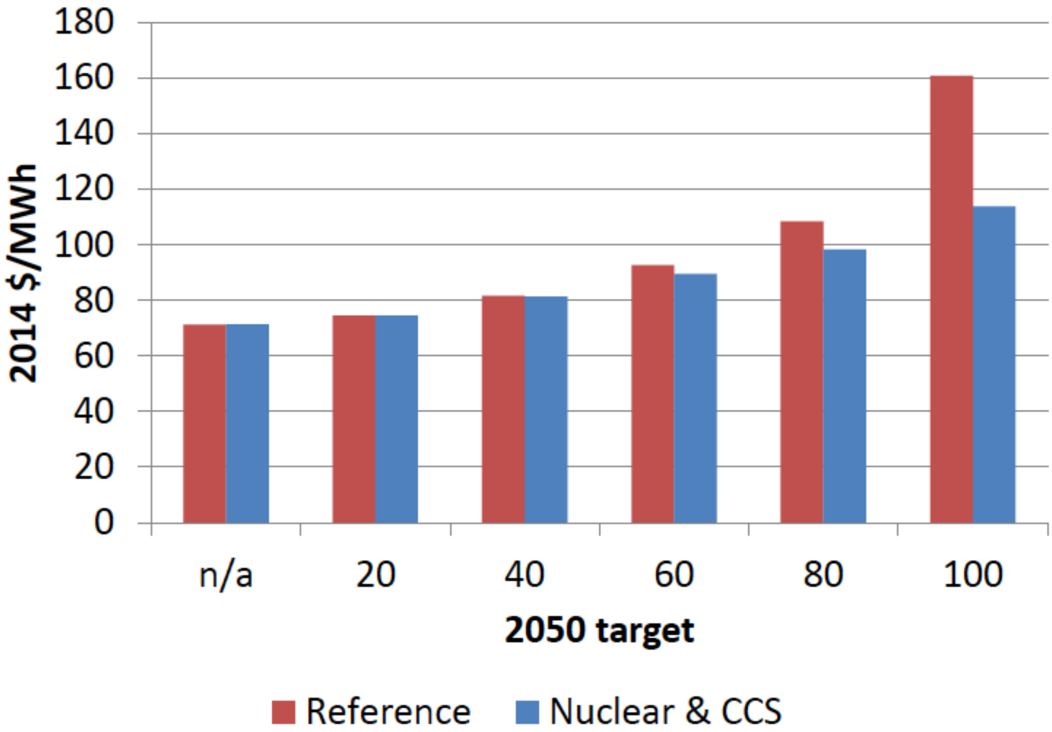

Figure 3: wholesale electricity prices for the reference case, and case with nuclear and CCS allowed (Jeppesen et al.)

f) The implications for the design of the energy only market are significant, but there is not yet a clear consensus on whether the current market design is suitable or not for high penetration renewable energy cases. Using Cournot game theory modelling, the spot market price volatility was simulated firstly using the current energy-only market (EOM), and secondly with a hybrid capacity and energy market (CEM). The increase in market volatility for the EOM case is notable – for the highest 5% of price events the price increases from $100 to $500/MWh in the EOM, but for the CEM the increase is only $80 to around $150/MWh (Chattopadhyay and Alpcan, 2016, Chattopadhyay D., T. Alpcan, M. Jeppesen and M. J. Brear, 2015). The study by Reisz at Mulligan (2015) suggested that a much higher market cap would be required, while the Jeppesen et al. (2016) and Brear et al. (2016) showed that the market would function up to 80% emission reduction with the current market design and cap.

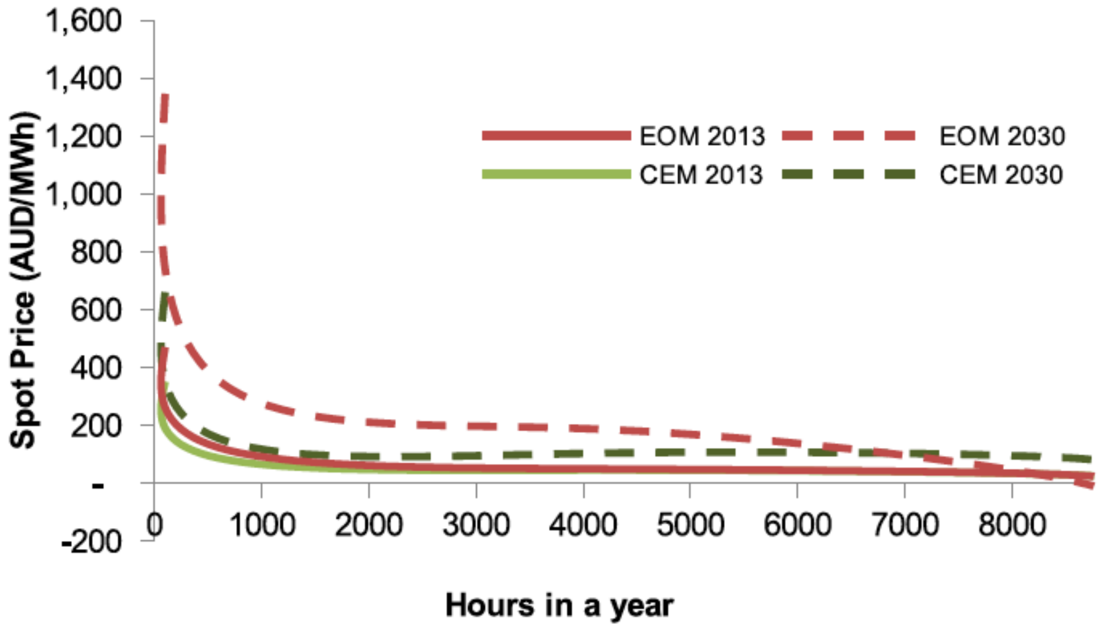

Figure 4. Spot price duration curves for South Australia under current and high renewable scenarios (Chattopadhyay and Alpcan, 2016)

g) Using the developed models, the implications of distributed battery storage have been examined. Using the assumption that uptake of rooftop PV and batteries will result in savings in network costs, the modelling study shows that in an optimal generation mix, the role of batteries and rooftop PV is sensitive to the assumptions regarding how much the network savings will be. Using three scenarios with low, medium and high network costs, the uptake of rooftop PV and batteries only occurs when the network costs are high (figure 5). By 2050, in the high network cost scenario, there is around 16GW of rooftop PV and 12GW of storage. These technologies provide a significant portion of the capacity, but produce a relatively small amount of the total energy as the capacity factor of the PV is low compared to other generation technologies.

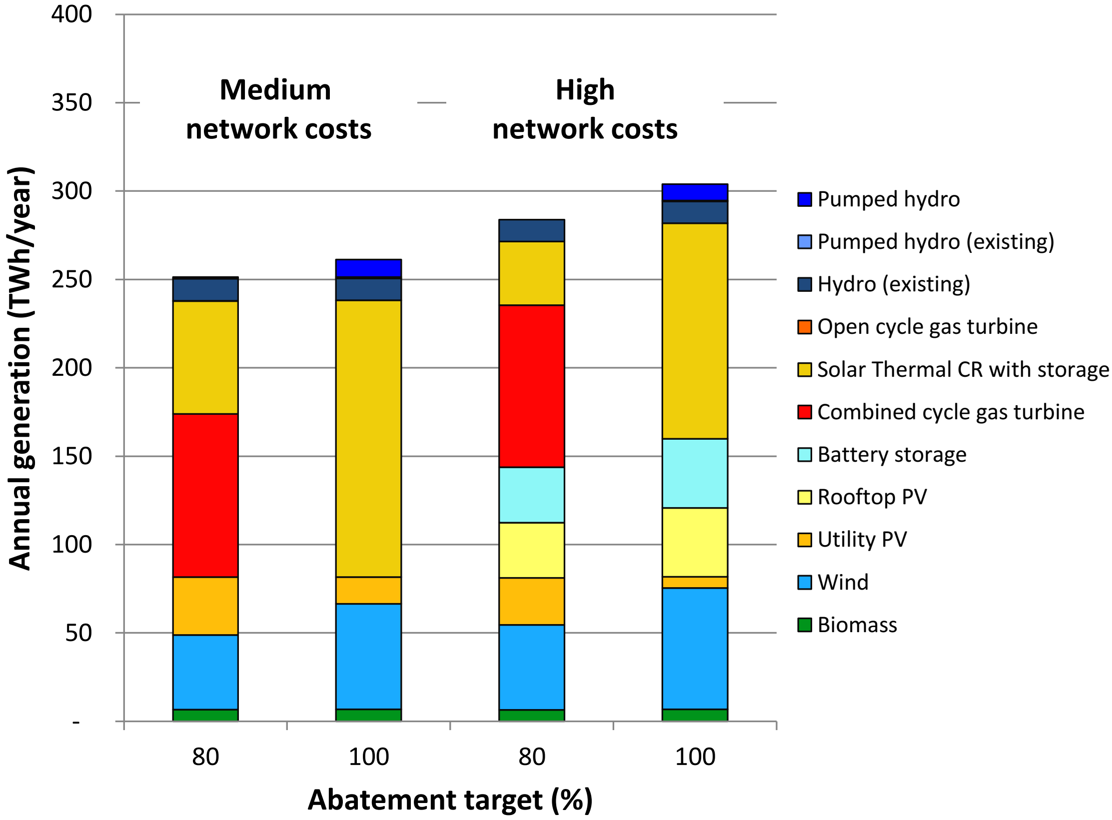

Figure 5: Technology mix for 80 and 100% abatement targets with medium and high network cost assumptions.

Model descriptions and publications

Three optimisation models of NEM have been developed. University of Melbourne has produced two models, one that utilises a genetic algorithm and one with a linear programming approach to the optimisation. UNSW has developed a model with a genetic algorithm. The logic behind developing multiple models is that model output can be sensitive to the modelling approach and configuration, and so even with the same input assumptions regarding technology and fuel costs, models can produce different results. By using different models, we can assess what aspects of the results are robust, and what might be due to peculiarities of the modelling tools.

The three models all share a common basic structure. The models simulate output for no-dispatchable renewables (wind, solar PV etc.) and then balance demand with dispatchable generations such as hydro, concentrating solar thermal and conventional thermal generation. The dispatchable generation is dispatched in merit order unless transmission and ramping constraints require out of merit order dispatch. The models then use their different optimisation techniques to vary the amounts of the different technologies in the system such that targets (emission reductions) are met while keeping the overall system costs (capital, fuel, operation and maintenance) to a minimum.

Two of the models developed have been written up and submitted to peer-reviewed journals. The third model will be written up in the future, but an early paper (Huva et al.) describes the early version of the model.

- Huva, R., R. J. Dargaville and S. Caine. Prototype large-scale renewable energy system optimisation for Victoria, Australia, *J. Energy*, **41**, 326-334, 2012.
- Elliston, B., I. MacGill, M. Diesendorf, "Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market", *Renewable Energy*, **66**, 196-204, 2014.
- Jeppesen, M., M.J. Brear, D. Chattopadhyay, C.G. Manzie, , R. Dargaville and T. Alpcan Least cost, utility scale abatement from Australia's National Electricity Market (NEM). Part 1: problem formulation and modelling. *J. Energy*. doi:10.1016/j.energy.2016.02.017, 2016.
- Brear, M. J., M. Jeppesen, D. Chattopadhyay, C.G. Manzie, T. Alpcan and R. Dargaville. Least cost, utility scale abatement from Australia's National Electricity Market (NEM). Part 2: scenarios and policy implications. *J. Energy*. doi:10.1016/j.energy.2016.02.017, 2016.
- Elliston, B., J. Riesz, I MacGill. "What cost for more renewables? The incremental cost of renewable generation - an Australian National Electricity Market case study". *Renewable Energy*, **95**, 127-139, 2016.

Renewable Generation Technologies:
There are two categories of renewable generation – non-dispatchable and dispatchable. The non-dispatchable technologies are wind, solar PV and wave energy, while dispatchable renewables include hydro, concentrating solar thermal with storage, bioenergy and geothermal.

The non-dispatchable generation technologies are described in the models using weather data derived from weather models or observations. The weather model data is either accessed directly from the Bureau of Meteorology, or via a product generated by Roam Consulting for the AEMO 100% study. In both cases, the data is wind speed and solar irradiance from ACCESS-A, the same model used for weather forecasting for Australia. The Bureau's model assimilates observations from in situ weather stations and satellite observations into a numerical model of the physical system to create an internally consistent, physically realistic distribution of weather variables that also agree with the observations. As a result, it is possible to use the BoM data where there are currently no in situ observations of the weather and be comfortable that they are representative of reality.

The wind and solar PV technologies use either a simple conversion from incoming short wave radiation or wind speed to power output. For wind power this is a non-linear relationship described using a "power curve" specific for a turbine type. These technologies are always dispatched first unless system constraints require curtailment due to either transmission constraints or synchronous generation constraints.

The dispatchable renewables are dispatched in exactly the same way that the conventional thermal generators are dispatched with the exception that hydro and solar thermal with storage have limits on the fuel available (water or heat in molten salt storage) and so these need to be dispatch strategically to match peak demand. Geothermal and biomass energy are assumed to have unlimited fuel stock, although, again biomass energy is capped based on the reasonable limits of biomass feedstock that is available in a typical year.

Thermal technologies
Black and brown coal and open and combined cycle gas technologies are dispatched based on simple merit order combined with ramping constraints. Without emission constraints brown coal is the cheapest, and also have the strongest ramp rate constraints. Black coal is dispatched next, and then the gas generators are used last to match demand. With increasing emission reduction targets, the model dispatches less carbon intensive generation by retiring existing plant either when its normal lifetime is reached, or prematurely if required to meet emission trajectories.

Transmission
In each of the models, transmission is considered as different levels. In the most basic case, transmission constraints are ignored, resulting in unrealistic distribution of renewable generation technologies. In the next order of complexity, the inter-connectors between the states are considered, and cost effective augmentation of those connectors. Figure 6 shows the increase in interconnector capacity required to move power around the NEM, mainly to enable enough synchronous generation to be available to each state to keep the grid stable during times of high output from non-synchronous renewable generators.

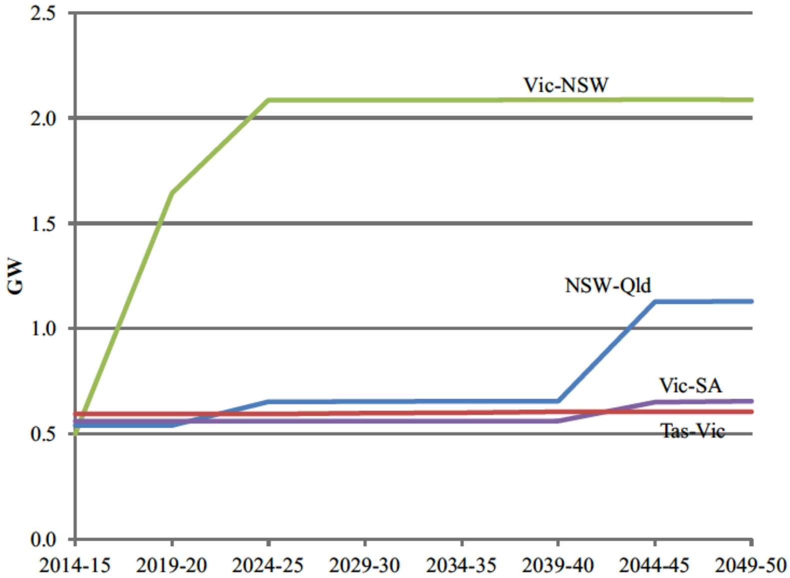

Figure 6: Transmission upgrades (Jeppesen et al.,)

The second tier of questions (impact on the market) have been explored in four papers

- Chattopadhyay D. and T. Alpcan. "A game-theoretic analysis of wind generation variability on electricity markets". *IEEE Trans. on Power Systems*, **29** (5), 2069-2077.
- Chattopadhyay D., T. Alpcan, M. Jeppesen and M. J. Brear. "Electricity Market Implications of a Least-Cost Carbon Abatement Plan: An Australian Perspective". *The Electricity Journal*, **27** (8), 105-115, 2015.
- Chattopadhyay D. and T. Alpcan. "Capacity and Energy-Only Markets under High Renewable Penetration" *IEEE Trans on Power Systems*, **31**, 1692-1702, 2016
- Riesz, J. and M. Milligan "Designing electricity markets for a high penetration of variable renewables". *Wiley Interdisciplinary Reviews: Energy and Environment,* **4(3),** p. 279-289. doi: 10.1002/wene.137, 2015.

Each of these papers find that the current energy only market in the NEM will not support the increased price volatility that will result from significant increases in the penetration of non-dispatchable renewable energy technologies, in particular wind energy. The increase in volatility will discourage investment in the market to provide the technologies required to balance the variability in wind generation output. The current structure of the market, with only a few large vertically integrated companies holding a majority of the market power means that sub-optimal outcomes for energy customers is likely unless a capacity market is developed.

The Chattopadhyay series of papers describe a Cournot Game-Theory model that simulates the market behaviour for a given set of generation capacity. The model takes into account the ability of large generators to control the market price by using their market share. The model is run under two different scenarios – one with an energy only market, and one where generators receive payment for being available to generate, such that even if they are not deployed they receive an income stream. The model suggests that the capacity and energy market results in a better outcome for energy consumers.

The problem with the capacity market is to know exactly how much generation is required. The simulations presented here use perfect foresight to calculate the generation mix. In the absence of perfect foresight, there is a risk that if an oversupply of generation is supported with capacity payments, then the outcome for energy customers could be worse.

Distributed generation and storage

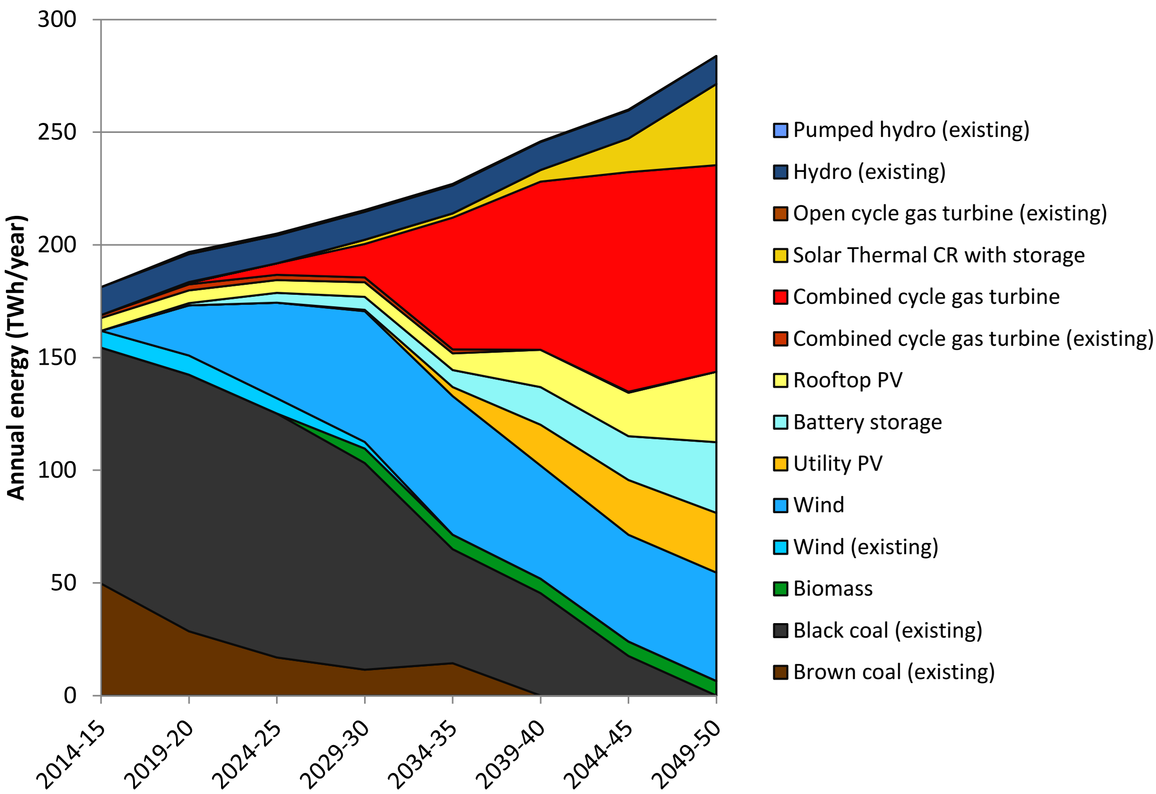

Figure 7: Example annual energy trajectory for the distributed generation and storage study (High network cost and low storage cost scenario.

An extension to this ARENA study considered the potential benefits of distributed storage, in particular when considering the potential avoided costs of distribution network upgrades. This work considered several scenarios for distribution network costs based on reported costs by distributors to the AER, and scenarios for storage costs based on recent engineering studies. The report also considered the different possible benefits of distributed rooftop PV and utility PV. More detail is available in the extension, but in summary it appears that in some areas distributed generation and storage are already a competitive form of greenhouse gas abatement. Figure 7 shows an example of the results for the scenario with high network costs and low battery storage costs.

Model Code

A key component of this study has been to make the source code for the models available. Each of the models, along with the documentation required to run the code has been made available.

Melbourne Uni Genetic Algorithm model:
Code: https://github.com/Melbourne-Energy-Institute/ARENA-MUREIL/tree/master/ARENA_MUREIL

Project website: http://www.energy.unimelb.edu.au/achieving-cost-effective-abatement-australian-electricity-generation

Melbourne Uni Linear Programming version:
https://github.com/centre-for-energy-systems/least-cost-australian-electricity-emissions-abatement

UNSW NEMO model:
Code and documentation: http://nemo.ozlabs.org

Future work

This section describes a non-exhaustive list of possible applications of the developed modelling suite:

- Sensitivities to future cost curves for the different technologies – the models could be run with more or less optimistic curves to test the sensitivities of the different technology costs.
- More detailed assessment of the role of storage. Some storage work had been done in this study, but extensions to explore the role of different storage options (small scale batteries, i.e. Tesla Powerwall, larger scale batteries within the distribution network, and large scale storage, i.e. pumped hydro).
- Impact of demand-side management. This is an area that is has had very little research done. Understanding how different industrial, commercial and residential scale processes could be modified to respond to pricing signals and thereby allow greater penetration of variable renewables is poorly understood.
- Large scale transmission extensions. This study has only considered augmentation of the existing transmission network. However additional network capacity to remote areas or even connecting the currently separate grids within Australia has not been considered. These options are generally considered to be expensive, but under high penetration renewable energy systems, the potential benefits might outweigh the costs.
- Application of the models to other regions. The models could be used to investigate optimal pathways for other established networks, or even for emerging economies in the developing world. Initial work looking at Chile and Brazil is currently being undertaken.
- Extension of the models to include the natural gas system so that interactions between demand for gas for residential heating, industrial processes, electricity generation and international export can be studied.

This ARENA funded project has produced state of the art modelling tools to be used to examine the pathway to a low carbon electrical energy system. The models have demonstrated that the pathway to large carbon abatement is technically feasible and unviable from an economic point of view. The implications for the incumbent generators however are very significant, with large-scale retirement of all the existing coal fired generators. Managing this transition will be complex. This study has not considered the policy framework that will be required to achieve the abatement goals, but there is little doubt that incentives via carbon pricing, emission restrictions or renewable energy targets are required to achieve the system restructuring required.