Centre for Energy and
Environmental Markets

100% Renewables in Australia:

A Research Summary

by

Dr Jenny Riesz*, Dr Ben Elliston, Dr Peerapat Vithayasrichareon, Assoc. Prof. Iain MacGill

Centre for Energy and Environmental Markets
University of NSW

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*Corresponding author: Centre for Energy and Environmental Markets,
The University of New South Wales, Sydney, NSW2052, Australia.

Tel.: +61 411 042 502, Fax: +61 2 9385 5993.
E-mail: j.riesz@unsw.edu.au

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SYDNEY • AUSTRALIA

About CEEM

The UNSW Centre for Energy and Environmental Markets (CEEM) undertakes interdisciplinary research in the design, analysis and performance monitoring of energy and environmental markets and their associated policy frameworks. CEEM brings together UNSW researchers from the Australian School of Business, the Faculty of Engineering, the Institute of Environmental Studies, and the Faculty of Arts and Social Sciences and the Faculty of Law, working alongside a growing number of international partners. Its research areas include the design of spot, ancillary and forward electricity markets, market-based environmental regulation, the integration of variable renewable energy technologies into the electricity network, and the broader policy context in which all these markets operate.

This working paper aims to summarise CEEM's research on high renewable scenarios for the NEM, with reference to other relevant work, in a form that is concise and accessible for a general audience. We welcome comments and feedback, as a valuable contribution to the refinement of our ongoing work program in this field.

The corresponding author for this working paper is Dr Jenny Riesz (j.riesz@unsw.edu.au).

www.ceem.unsw.edu.au

Executive Summary

About this paper

This paper summarises the latest research on the challenges and opportunities of a future 100% renewable Australian National Electricity Market (NEM). It focuses on work undertaken at the Centre for Energy and Environmental Markets (CEEM) at UNSW Australia, but also discusses other relevant Australian studies undertaken by groups including Beyond Zero Emissions (BZE), the University of Sydney, and the Australian Energy Market Operator (AEMO).

Background

Australia has one of the most emissions-intensive electricity systems in the world, relying heavily on coal-fired generation. This means that a transition to a 100% renewable power system represents a near fundamental transition from the present system. Given the challenges experienced over the past decade by alternative low carbon options including Carbon Capture and Storage (CCS) and nuclear, and the rapid progress of key renewable technologies, a clean energy future for Australia may well hinge on whether 100% renewables is whether this is possible and, if yes, how might it best be achieved.

Is 100% renewables technically feasible?

Australia has extraordinary renewable energy potential, particularly in wind and solar. Wind and solar photovoltaics (PV) technologies are commercially available and well proven, and provide some of the most cost competitive generation options in Australia. However, wind and solar PV bring new challenges to power systems. Notably, they are:

1. ***Variable*** – The availability of wind and PV is highly variable and only somewhat predictable (particularly for PV).
2. ***Non-synchronous*** – Wind and PV are non-synchronous, meaning that they interact very differently with the power system, and do not inherently provide many of the types of grid services that we have come to rely upon from large coal and gas-fired generators.

However, wind and PV are not the only renewable technology types available for potential deployment in Australia. As shown in Table 1, there are a range of other renewable options, all of which are ‘firm’ (non-variable and fully dispatchable), and synchronous (they integrate with the grid in a very similar way to conventional coal and gas-fired technologies, and provide the same kinds of grid services). Indeed, globally, there are already a number of nations with near 100% renewable electricity, including Brazil, New Zealand and Iceland. All of these systems rely heavily upon the firm, synchronous renewables, such as hydro, geothermal and biomass.

Table 1 – Renewable technology options for deployment in Australia

Variable, non-synchronous	Firm, synchronous
Wind Photovoltaics (PV)	Hydro Concentrating solar thermal (CST) with storage Biogas turbines (and other bioenergy) Geothermal

These technologies have different challenges; for example the potential to expand hydro generation in Australia is likely to be limited, bioenergy can compete with other land and resources uses, geothermal is at an early pilot stage in Australia, and concentrating solar thermal (CST) remains very expensive compared to wind and PV.

However, by creating a generating portfolio including some *mix* of all of these types of renewables, the research suggests that these challenges can be managed to create a technically viable 100% renewable power system for Australia that is reliable and secure. The challenge for Australia will be that in order to create a *cost effective* 100% renewable grid, we will likely need to integrate much larger quantities of wind and PV, at levels beyond the experience of any grid in the world to date. Much international research is focused in this area.

Research on 100% renewables in Australia

The research into 100% renewable electricity systems in Australia has focused to date on exploring the temporal and geographical variability of renewable resources over hourly time periods, investigated under a range of assumptions regarding available renewable energy options, their costs, and future electricity demand. The non-synchronous nature of wind and PV has been minimally explored to date, but is typically managed in the models by requiring a minimum amount of synchronous generation (such as hydro, CST, biogas turbines or geothermal) to be operating at any time. There is reasonable confidence that this would address the issue, although the level of synchronous generation required is unknown at present.

Work to date by UNSW and others including the Australian Energy Market Operator (AEMO) suggests that a 100% renewable NEM can deliver the same level of reliability as the present electricity system, provided that there is sufficient:

1. ***Firm, synchronous generation*** – The modelling indicates a need for at least some firm, synchronous capacity included in the portfolio (potentially including hydro, CST with storage, biogas turbines, or geothermal). These technologies provide 'dispatchable' power at times of insufficient solar and wind, as well as other grid services.
2. ***Transmission*** – A large increase in transmission capacity is likely to be required, linking spatially diverse renewable generation and loads across the NEM. This allows wind and solar generation to be geographically dispersed and hence less variable; there are few periods when there is no sun or wind across the whole NEM.

Whilst there are a range of technical challenges for electricity industry operation that require further investigation, no insurmountable technical barriers to a 100% renewable NEM have been identified.

How much will 100% renewables cost?

There are many limitations in the modelling of future power systems, most particularly applying to estimates of cost. Given the many years that will be required to transition from Australia's present, fossil-fuel dominated system, we require forward looking estimates for the costs of renewable energy technologies. Although it is reasonable to predict that ongoing learning and innovation will mean that the costs of many of these technologies will reduce over time (based upon past experience, such as the reductions in the cost of PV over the past decade), the degree to which costs might fall for each technology is highly uncertain.

We use formal Australian government cost projections provided by the Australian Energy Technology Assessment (AETA) for 2030 and 2050 and current NEM demand in our work. Our findings highlight that the future costs of a 100% renewable NEM will depend upon many factors, including the technologies available and possible constraints on their widespread deployment, their realised future costs, and the costs of necessary additional network investment. Our lowest cost scenarios include large amounts of wind and PV (for cheap bulk energy), combined with around 40 GW of firm, synchronous renewable technologies, including hydro, concentrating solar thermal with storage, and biogas turbines. These firm renewables provide dispatchable power on demand, sufficient to reliably meet the system peak demand of 35 GW, with an additional margin, even if there are some periods with absolutely no wind and photovoltaic power available. Work by others with different assumptions has come up with broadly similar generation mixes depending on assumptions around particular technologies such as CST (BZE) and geothermal (AEMO).

Future wholesale electricity costs for 100% renewables portfolios have been estimated by UNSW and others (BZE, AEMO and the University of Sydney) to be between \$71/MWh and \$200/MWh (including transmission), weighted in the middle of this range at around **\$100-\$140/MWh**. The various cost estimates are illustrated in Figure 1, including the components attributed to transmission.

Figure 1 – Projected costs of 100% renewables for the NEM[1]. Sources: [1, 2, 3, 4, 5][2]

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[1] DR refers to the discount rate applied.

[2] [3] and [4] remain under peer review, and are not yet formally published.

To provide a basis for comparison, average annual wholesale NEM generation prices have varied in the range $30-60/MWh (or 3-6c/kWh) over the past fifteen years. This does not include transmission and distribution network costs or retail margins. The average household cost, including all these components, is currently around 29c/kWh or $290/MWh. Projections by AEMO based upon their modelling indicate that retail customer bills would need to increase by around **6-8c/kWh**, an increase of **20-30%**, to an electricity rate of around 35 - 37c/kWh, to achieve 100% renewables.

Based upon a total annual electricity cost of $1,499 for an average household [6], a 20-30% increase would equate to around $300 to $400 per year.

Importantly, a cost increase in this range is very similar to that forecast by organisations such as the CSIRO for other possible future NEM scenarios, including those involving continued significant reliance on fossil-fuels, depending on future fuel and potential carbon emission costs. This means that a transition to a 100% renewable NEM may represent a very modest cost compared to likely alternatives.

How can we achieve lower cost 100% renewable systems?

UNSW's modelling suggests that achieving 100% renewable portfolios at the lower end of the projected cost range will likely require the following measures:

- ***Enable significant wind generation*** – The lowest cost portfolios consistently include significant quantities of wind generation (supplying up to 80% of energy). Portfolios with lower proportions of wind are feasible, but generally more expensive. Enabling wind deployment in this range may require measures to establish and maintain a broader societal consensus around the benefits associated with this technology.
- ***Address wind and PV integration challenges*** – Achieving such high proportions of wind and PV generation brings many technical integration challenges which will need to be addressed, including in adjustments to the NEM Rules, and in AEMO's operational procedures. UNSW's modelling suggests particular importance in maximising the amount of energy that can come from non-synchronous sources, by minimising the application of unnecessarily conservative constraints[3].
- ***Some bioenergy*** – The availability of at least a small amount of flexible bioenergy (or other peaking capacity, such as demand side participation) is important to assist with periods of low wind and solar generation, at a reasonable cost. Portfolios without any bioenergy are feasible (as long as other firm synchronous technologies such as CST can be deployed), but are generally more expensive.
- ***Minimise uncertainty*** – The cost of capital is very important for renewables, and financiers will adjust this rate depending upon their judgement of the risks

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[3] In the Irish system, they have implemented an "NSP" limit, which defines the maximum amount of "non-synchronous penetration" that can be managed by the system in any dispatch interval. If the NSP is limited to 50%, for example, then half of the energy generated in any period must come from synchronous sources, such as CST, geothermal or (bio)gas turbines. If the NSP is increased to 90%, then only 10% of energy in any period needs to come from synchronous sources (and up to 90% can come from wind and PV). Relaxing the NSP limit is found to reduce system costs considerably. Research is required to determine the appropriate level for this limit, and how to minimise it.

associated with investing in a project. Policy frameworks and stable market environments that minimise uncertainty over project returns will minimise the cost of capital, and can reduce the costs of renewable generation considerably.

It is also clear that new policies, market rules and regulatory frameworks will be required to facilitate the major renewable investment involved, with suitable regard to appropriate patterns of technology, location and timing. More generally, Australia will need to establish and maintain a broader societal consensus around this profound electricity industry transformation.

Transmission requirements and costs

Many of the best solar and wind sites in Australia are in remote locations that will require significant transmission investment. Furthermore, balancing wind and PV generation around the NEM requires strong interconnections to take advantage of geographical diversity.

Some preliminary and high level estimates suggest transmission costs in the range of **$6 – 20/MWh** (from studies by UNSW and AEMO), to enable 100% renewable scenarios. This equates to around 10% of the total cost of a 100% renewable system, suggesting that transmission expenditure is important, but not a dominating contributor to costs.

These costings only include a high level representation of the major interconnections; further investment is likely to be required intra-regionally. For comparison, current transmission expenditure in the NEM is around $2.7b/year or around $14/MWh. Much of this investment is "sunk", so a proportion of the transmission investment required to enable 100% renewable scenarios is likely to be additional to these costs. For this analysis, all new transmission investment has been considered as additional to present (included in the total system costs quoted).

The impact of a 100% renewable NEM on distribution network costs will depend on many factors including, critically, the role that distributed renewables such as residential, commercial and industrial PV plays. There has been very little Australian work to date on the overall costs of distributed scenarios of this nature.

Is 90% renewables likely to be significantly less expensive?

UNSW's analysis suggests that there is not a significant escalation in costs to go from 80-90% renewables to 100% renewables. This is largely due to the availability of a range of firm, synchronous renewable technologies (such as biogas turbines and concentrating solar thermal with storage) that can cost effectively and reliably meet the last 10-20% of energy that would otherwise be supplied by fossil fuels. Biogas turbines, in particular, have a low capital cost, and therefore are cost effective for operating rarely but providing the required level of reliability.

Mitigation of cost risk

UNSW's modelling also highlights explicit co-benefits in moving to high renewable scenarios, through the mitigation of cost risk associated with uncertain gas and carbon prices in future. Renewables are shown to be very effective at mitigating this cost risk, which consumers are exposed to in high fossil fuel scenarios (particularly high gas scenarios). For this reason, a "gas transition" to renewables has been shown to be high cost, and high risk, compared with a direct transition to renewables.

Nuclear and Carbon Capture and Storage

UNSW's modelling highlights that nuclear energy and carbon capture and storage are both likely to be higher cost than renewables (in some cases, significantly higher cost). These technologies also carry a significantly higher cost risk profile than renewables.

What next?

The technical feasibility and quite likely relatively attractive economics for a 100% renewable NEM, naturally gives rise to possible next steps.

Given Australia's pressing clean energy challenges, there are excellent reasons to set higher and more ambitious renewable generation targets than those established at present. While there are significant opportunities to reduce the costs of renewable options through judicious R&D and demonstration, major deployment has proven a key driver of reducing cost and improved expertise.

As renewable penetrations climb, we should not underestimate the challenges in effectively and efficiently integrating these technologies into the NEM. Current NEM arrangements have proven remarkably resilient to regionally significant wind and PV penetrations to date (by comparison with some other electricity industries around the world). However, a 100% renewable NEM will inevitably operate very differently to the present, and significant resources will be required for all electricity industry stakeholders to understand, drive and adapt to these changes.

Such profound electricity industry transition will also require societal consensus on the importance of addressing our clean energy challenges and renewable energy's role in addressing them. Beyond these challenges lie the opportunity for Australian leadership and innovation in creating a clean energy future for Australia and others around the world.

Contents

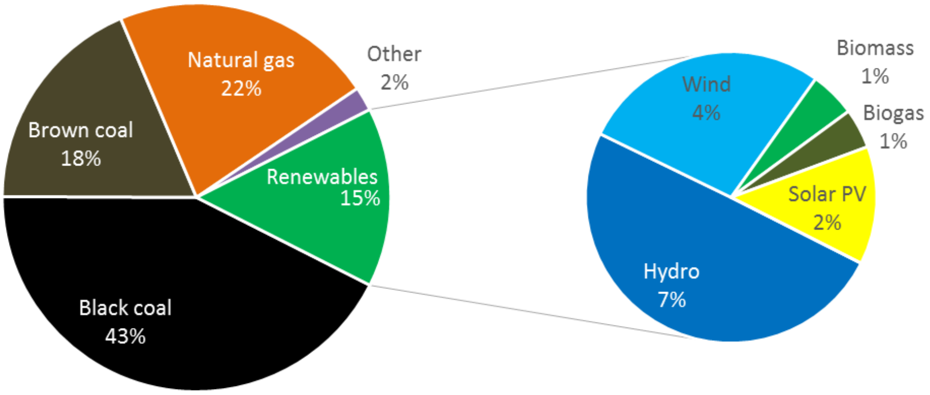
1 Introduction

This paper discusses the potential for a 100% renewable Australian National Electricity Market (NEM), reviewing the latest research on the technical feasibility and potential costs. It summarises the work conducted by the Centre for Energy and Environmental Markets (CEEM) and associated researchers at UNSW Australia, but also discusses other significant NEM related studies where they provide additional insights.

1.1 Electricity in Australia

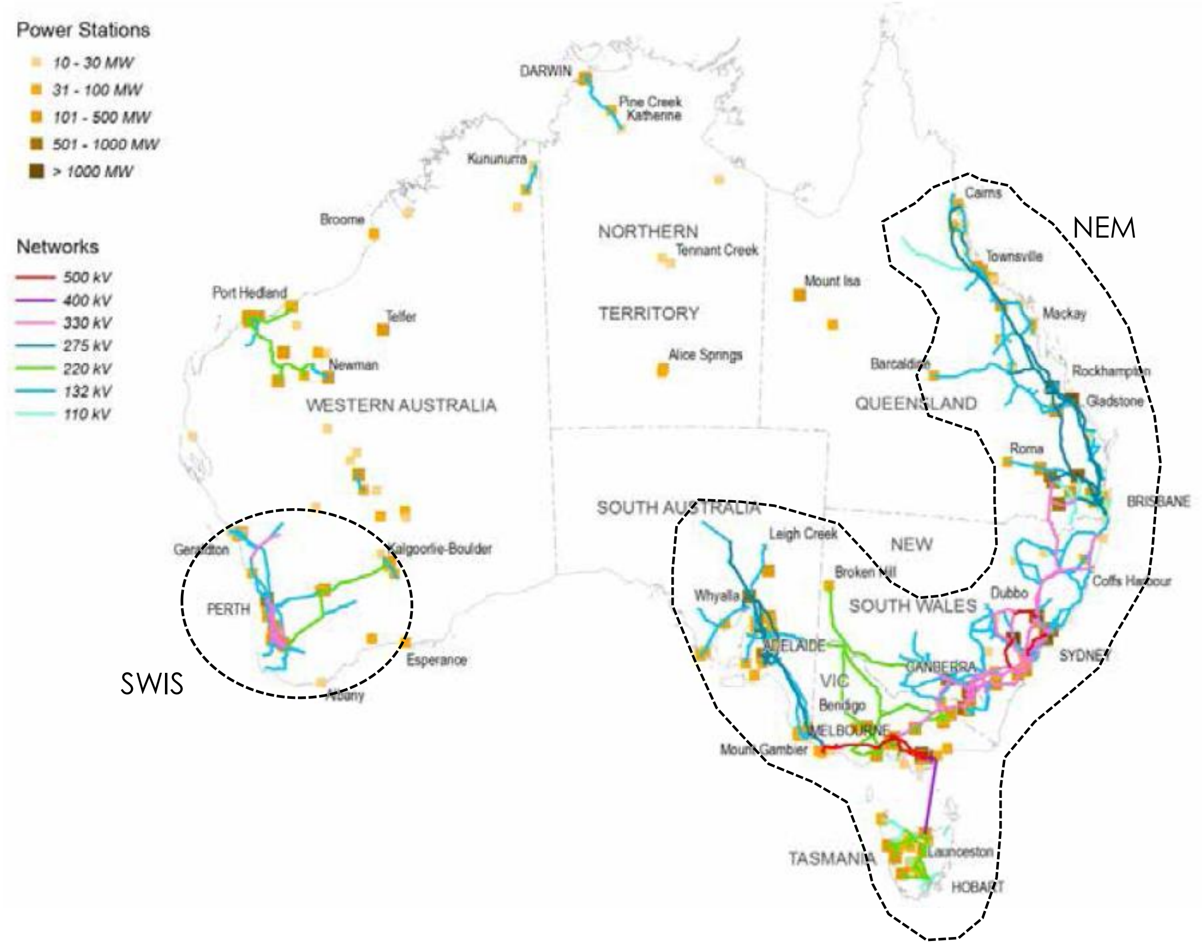
As illustrated in Figure 2, Australia's present electricity mix is dominated by fossil fuels, with more than 60% of electricity generated from coal, and more than 20% from natural gas. By contrast, renewables provided only 15% of Australian electricity in 2013-14. Of this renewable generation in Australia, almost half is hydro-electricity, with only 6% of electricity being sourced from wind and photovoltaics at present. A transition to 100% renewable electricity will require a very significant change.

Figure 2 – Australian electricity generation by fuel type (2013-14). Source: [7]



There are a number of distinct electric power systems in Australia. The two largest are the National Electricity Market (NEM), and the South-West Interconnected System (SWIS), as illustrated in Figure 3 [8]. There are other smaller grids in the Northern Territory, Mt Isa, the Pilbara and small rural communities. Due to the relatively low loads served by these smaller grids and the high costs of transmission lines over long distances, these systems are not all physically connected at present.

Figure 3 – Australia's electricity infrastructure. Source: [8]



The National Electricity Market (NEM)

The NEM is the largest power system in Australia, supplying approximately 200 TWh of energy per year, with a peak demand of around 35 GW, and a minimum demand of around 15 GW [9]. In 2012–13, the states and territories in the NEM (QLD, NSW, VIC, SA and TAS) accounted for 85% of Australian electricity consumption [8].

Most published analysis on Australia's electricity supply looks at the NEM only, since this greatly simplifies the modelling, and captures a large majority of the electrical load in Australia. A transition to 100% renewables would also require a transition of the other electricity systems in Australia. The technical feasibility of renewable mini-grids has been demonstrated in pilot studies, and in many cases, these remote locations can be economically suitable for significant photovoltaics installations to offset costly diesel imports [10]. However, this document doesn't directly discuss the transition of these other systems to renewable energy.

1.2 Terminology

Wind and photovoltaics aren't "intermittent", they're "variable"

The term "intermittent" is commonly used to describe renewable technologies with variable availability, such as wind and photovoltaics (PV). In normal usage, "intermittent" is usually used to refer to things that suddenly switch on and off, with a 'flickering' characteristic.

This is not a good description of how wind and PV generation varies over time [11]. Each wind turbine has some degree of physical inertia, meaning that in usual operation it doesn't suddenly cut in and out[4]. This is then aggregated over the whole wind farm with many turbines, such that the total wind farm output will show a much more gentle variability over time. Similarly, cloud cover moving over a PV installation will take time to progress over the land area covered by the panels; the larger the farm, the longer it will take, smoothing the generation produced by that installation.

When this is then aggregated over the whole power system, summing the output of many wind and solar farms, geographical diversity means that the total wind and solar output supplied to the system shows something that varies gradually hour to hour, rather than cutting in and out in seconds.

The pervasive use of the term "intermittent" to describe wind and solar generation is perhaps a part of the reason why the general public is so susceptible to the idea that wind and solar generation can't provide reliable power. Therefore, we use the term 'variable generation'[5]. This more accurately describes the changing nature of wind and solar generation over time, but avoids the association with rapid flickering.

The difference between local and whole-system renewable targets

It's important to note that there is a significant difference between a 100% renewable target for a local jurisdiction (such as a city or state), and a 100% renewable target for a whole electricity grid (such as the NEM or the SWIS). For example, South Australia could implement a 100% renewable target, and achieve this by importing and exporting to the rest of the NEM. The NEM offers significant grid support and "balancing" of renewable variability. Therefore, it is technically much easier to achieve a renewables target in a local area (such as the ACT or South Australia) than it is to transition the whole NEM to that target.

If desired, a city or state could also 'achieve' 100% renewables simply through the purchase of Greenpower certificates for all electricity consumed. Many city councils already do this for their own electricity purchases. The renewable generation would not necessarily occur locally, and could be produced anywhere in Australia. This is environmentally sound, and does support real growth in renewable generation in locations with good renewable resources. However, it is technically different to constructing sufficient renewable generation (and storage) to directly supply that city or state, and it is extremely different to aiming for complete self-sufficiency on renewables, disconnecting from the local grid, and self-supplying with a mini-grid and storage. These options are illustrated in Figure 4.

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[4] With the exception of high speed cut outs in some older designs. Modern wind turbines typically ramp down gradually at extreme wind speeds to avoid sudden cut out effects.

[5] This term was proposed by, and is generally used by the US National Renewable Energy Laboratory (NREL) in Golden, Colorado.

Figure 4 – Spectrum of options for Australian states and local government areas to implement renewable energy targets

From a technical perspective, it is important to clarify what is meant by a local target. Note that none of these should be considered universally superior; different approaches will suit different communities. Some may be satisfied with the ease and low cost of Greenpower. Others may prefer to invest in local renewables for the co-benefits in local economic stimulation. Still other communities may find complete disconnection preferable or necessary, especially where there is no pre-existing grid (such as in remote rural communities), or in fringe-of-grid locations where the main grid connection is expensive or unreliable.

The rest of this document discusses the prospects for transitioning the whole NEM to 100% renewables. By definition, this system must be managed with complete self-sufficiency, since the NEM (and Australia) does not have any physical grid connections to other nations at present.

2 Is 100% renewables technically feasible?

When discussing a 100% renewable power system, most people immediately think of a system operating on wind and photovoltaics (PV). These technologies are very different to those operating in Australia's power system today. In particular, they have variable and uncertain availability, and they are non-synchronous (meaning that they interact with the power system in a very different way, and don't inherently provide many of the types of grid services supplied by conventional coal and gas-fired generators)[6].

However, there are a suite of other renewable technologies available, many of which would likely be a part of the mix in a 100% renewable power system in Australia. Hydro,

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[6] Non-synchronous generation includes wind and photovoltaics, which connect to the system via an inverter. Synchronous generation includes coal, gas, concentrating solar thermal, geothermal, biogas, and hydro generation. Synchronous generators provide a range of important system services such as inertia (to assist with managing system frequency), and fault level for riding through power system disturbances [54]. Non-synchronous generators do not naturally provide these services, which must then be sourced elsewhere (or managed in a different way).

concentrating solar thermal (CST) with thermal storage, geothermal and biomass technologies are all firm (non-variable), and synchronous (meaning that they interact with the grid in a very similar way to existing coal and gas-fired units, and provide the required types of grid services)[7].

Table 2 shows that the overall potential for renewable generation in Australia is around 500 times greater than forecast NEM demand, in terms of both energy and capacity. Moreover, around half of that potential is in firm, synchronous technologies. In particular, there is vast potential for CST, which is a proven, commercially available technology that could be installed in Australia immediately, if desired. Therefore, if we wanted to, Australia could meet its entire electricity demand (many times over) entirely with CST with storage, and the system could potentially operate very similarly to today. This would be very expensive (CST is a more expensive technology compared with wind and PV), but there is little doubt that it is technically feasible.

Since a system based entirely on CST would be a very expensive option, it would be more sensible to use a mix of technologies, including some proportion of the variable and much less expensive wind and PV. The exact proportion of wind and PV that is lowest cost remains an active area of research, and will continue to evolve as technology costs change over time.

Table 2 – Renewable potential in Australia. Source: [1]

		Maximum installable generation capacity (GW)	**Maximum recoverable electricity (TWh/yr)**
Variable and non-synchronous	Wind – onshore (capacity factor greater than 35%)	880	3,100
	Wind – offshore (capacity factor greater than 35%)	660	3,100
	Photovoltaics (PV)	24,100	71,700
	Wave	133	275
	Total variable potential:	***25,773 GW***	***78,175 TWh***
Firm and synchronous	Concentrating Solar Thermal (CST)	18,500	41,600
	Geothermal (EGS)	5,140	36,040
	Geothermal (HSA)	360	2,530
	Biomass	16	108
	Hydro	8	12
	Total firm potential:	***24,024 GW***	***80,290 TWh***
Current NEM		***50 GW***	***200 TWh***

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[7] International research is underway focused on enabling wind and PV plants to eventually provide some of these services (for example, frequency control, fault ride-through capabilities, and synthetic inertia).

Figure 5 shows the lowest cost generation mix (by energy) for the NEM calculated by CEEM, based upon recent technology cost assumptions. In this system, the lowest cost wind and PV provide more than three quarters of the energy. A significant capacity of biogas turbines are also installed; these operate only rarely (when wind and PV output are insufficient to meet demand), but their low capital cost and firm dispatchability means they provide cost effective reliability. These turbines play a role very similar to gas peaking plant in the present NEM, which are installed to operate only rarely when demand hits the highest peaks.

Figure 5 – Lowest cost generation mix for 100% renewables in the NEM. Source: UNSW's modelling[8]

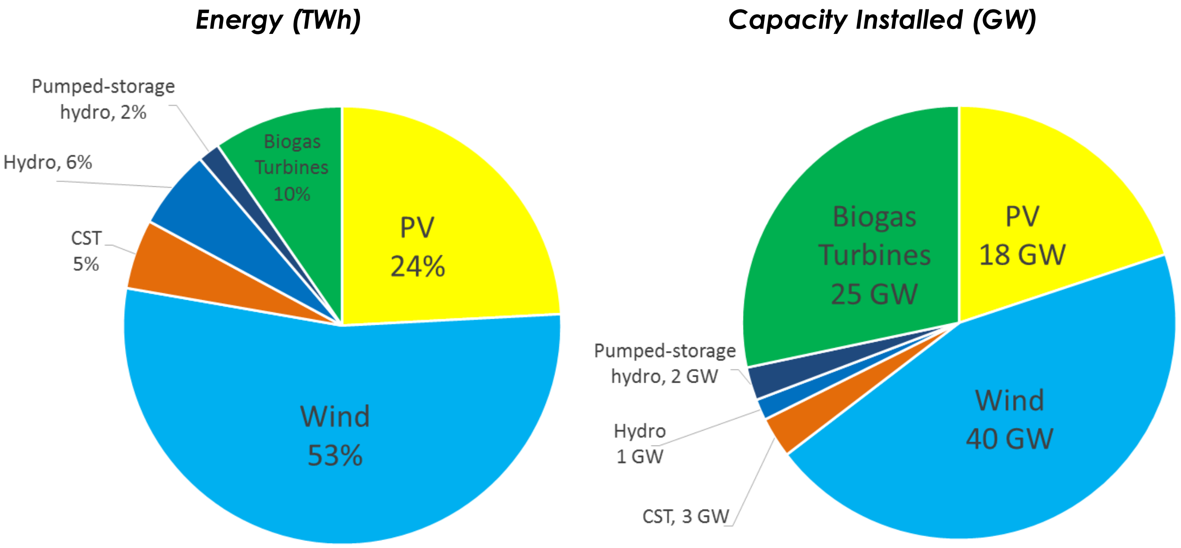

Figure 6 provides a comparison of the firm capacity installed in a 100% renewable system, with the capacity installed in the present NEM. In the present system, there is around 50 GW of capacity, mostly composed of coal-fired and gas-fired generation. This capacity meets a demand that varies from a minimum of 15 GW to a maximum of 35 GW. A low cost, reliable 100% renewable system has far more capacity installed (almost 200 GW), with most of that being in wind and PV. However, the 100% renewable system maintains almost 40 GW in firm technologies (CST, biogas turbines and hydro). This amount of firm capacity is sufficient to meet peak demand, even if there is absolutely no wind and PV available when that peak in demand occurs. In this way, the high reliability standard of the present system can be maintained, even

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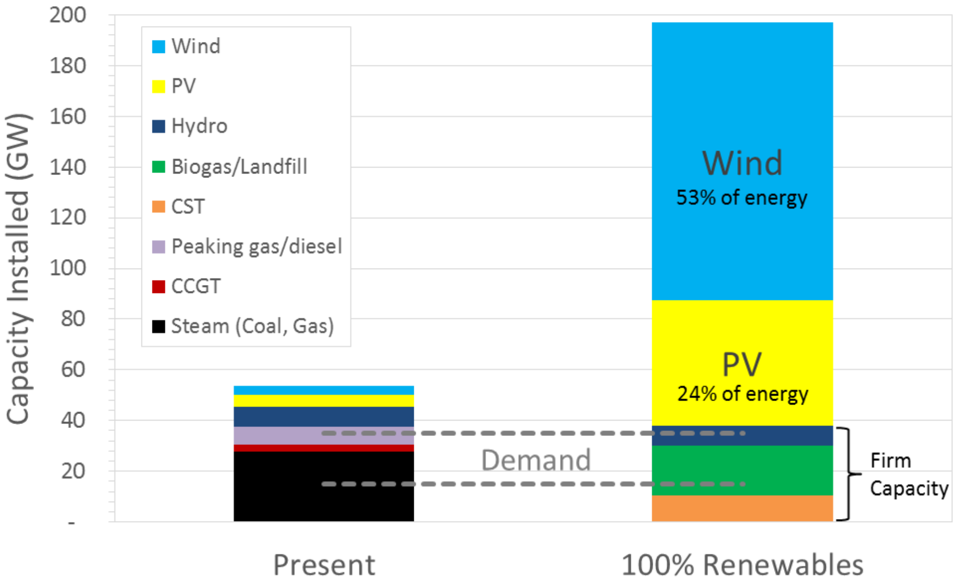
[8] Modelling using the NEMO model, by Dr Ben Elliston. NEMO uses an evolutionary algorithm to search for a least-cost technology mix, based upon hourly generation profiles for each technology, to meet an hourly demand profile for 2010 [20]. Technology costs for 2030 were sourced from a comprehensive Bureau of Resources and Energy Economics 2013 study [25], with PV costs updated based upon 2015 analysis by the CO2CRC, for utility scale single-axis tracking technology [5]. This analysis assumes continuation of centralised electricity supply, and does not include consideration of transmission costs. No batteries or demand side participation are included.

though wind and PV have variable availability. Wind and PV provide low cost bulk energy most of the time, but the lights don't go out just because the wind isn't blowing, and the sun isn't shining.

Figure 6 - Comparing installed firm capacity[9] [12, 13]



The concept of "back-up" generation

It's tempting to think of the biogas turbines (and other types of firm renewables) as "backing up" the variable renewables. When the variable renewables aren't available, the biogas turbines start up to supply power, and maintain reliability. However, this conceptually leads to the idea that the variable renewables "lack" something that they should be supplying, and even (in some international jurisdictions) to the idea that the variable renewables should be paying an "integration cost" which includes the cost of "back-up" generation.

A more appropriate conceptual framework notes that it is *customers* that require a reliable electricity supply, and therefore should pay for the various aspects required to provide it. Providing cost effective reliable electricity requires low cost bulk energy (supplied by variable renewables), and firm capacity on-demand (supplied by biogas turbines and other firm renewables). These are both "services" required by customers, and therefore should be paid for by customers (not by other renewable generators) [14].

A new power system paradigm

Figure 7 illustrates the new power system paradigm for a 100% renewable system. The present system includes a large capacity of "baseload" generation that operates most of the time, with peaking and intermediate plant ramping up and down to meet variations in demand. In a renewable system, the variable renewables will provide the

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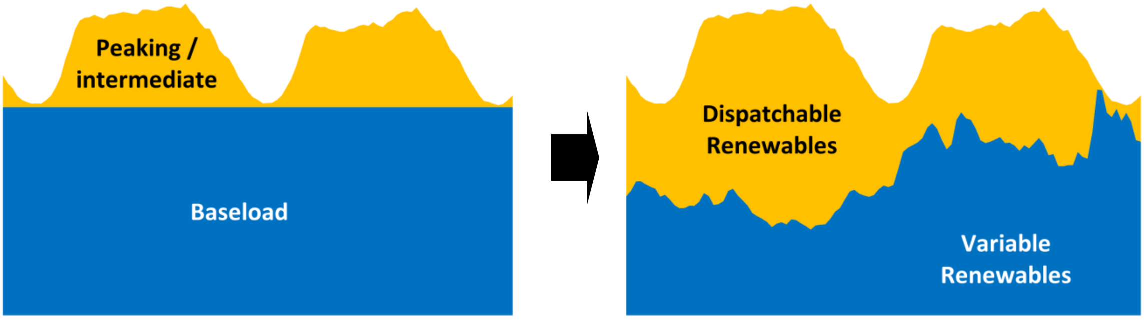
[9] CCGT refers to "Combined Cycle Gas Turbine", a type of natural gas generator.

bulk of the energy, and firm, flexible renewables will ramp as required to fill the gap and meet the demand. CEEM's modelling has demonstrated that variable renewables act primarily to displace baseload generation in the system, and partner ideally with larger amounts of intermediate and peaking plant (such as biogas turbines) [14]. Conceptually, the operational practice is similar: the generators with the lowest operating cost are dispatched first.

Figure 7 – A new power system paradigm [15]



Beyond Zero Emissions (with the University of Melbourne's Energy Research Institute) were the first to publish modelling illustrating how a 100% renewable power system could operate reliably in Australia [5]. This has since been supported by modelling at UNSW, which further optimised the technology mix, and demonstrated that costs could be lower if more wind and PV were integrated [16, 2, 17]. The University of Sydney also recently released a study (still under review) demonstrating that Australian electricity demand can be met with renewable technologies, "without using fossil fuels, and at current stringent loss-of-load and reserve requirements, provided a contribution is made by a flexible renewable technology featuring high capacity credit, such as biofuels" [3].

In 2013, the Australian Energy Market Operator (AEMO) published a detailed report on modelling of a 100% renewable electricity system in Australia [1]. AEMO is the organisation responsible for operating the NEM, ensuring it operates reliably and securely day to day, and over longer term horizons. As the operator of the NEM, they are a very important electricity industry organisation, which makes their report particularly important as a reference on the feasibility and cost of 100% renewables.

AEMO's report concluded that the present reliability standard could be maintained, and that the operational issues associated with a 100% renewable system "appear manageable". They state [1]:

> *"High penetrations of semi-scheduled and non-synchronous generation would constitute a system that may be at or beyond the limits of known capability and experience anywhere in the world to date…"*

But:

> *"There are no fundamental technical limitations to operating the given 100 per cent renewable NEM power system generation portfolios that have been identified."*

And:

> *"Many issues remain to be determined without doubt, but it is valuable to note that this operational review has uncovered no fundamental limits to 100% renewables that can definitely be foreseen at this time."*

They also note that the transition to renewables will occur dynamically over time, allowing proper scope for learning and evolution, with the additional experience gained.

Therefore, even though the sun doesn't always shine, and the wind doesn't always blow, the research is now clear that it is technically possible to build a 100% renewable power system in the NEM, providing the same levels of reliability that we enjoy today.

Do we need novel energy storage systems such as batteries?

Modelling to date consistently suggests that novel battery energy storage are not required to reliably operate a 100% renewable electricity system. There is sufficient geographical diversity in the wind and PV generation in Australia, sufficient firm renewable capacity available, and a host of other lower cost means for achieving system flexibility, that an affordable, reliable electricity system can be constructed without any need for electrochemical batteries at all.

However, if battery costs continue to fall, it may become cost effective to install some battery storage, particularly in cases where this can defer investment in distribution networks.

Batteries are likely to be important for facilitating larger quantities of PV generation (beyond those illustrated in Figure 5), since PV only generates during a relatively narrow window of time during the middle of the day [18]. This means that PV generation can tend to "saturate" at a level of 8-15 GW in the NEM, if batteries are not present [19, 20, 21, 22].

3 How much would 100% renewables cost?

If it is technically feasible to operate the NEM on 100% renewables, it comes down to a question of cost. How much will it cost to build and operate this system?

There are many limitations in the modelling of future power systems, most particularly applying to estimates of cost. Given the many years that will be required to transition from Australia's present, fossil-fuel dominated system, we require forward looking estimates for the costs of renewable energy technologies. Although it is reasonable to predict that ongoing learning and innovation will mean that the costs of many of these technologies will reduce over time (based upon past experience, such as the reductions in the cost of PV over the past decade), the degree to which costs might fall for each technology is highly uncertain.

3.1 Wholesale costs

The wholesale cost of electricity is the cost of electricity purchased in bulk through the NEM "pool"[10]. Residential customers typically purchase electricity through a retailer, and pay a range of other costs in their electricity bill, as discussed in section 3.4. This section outlines the modelling outcomes for wholesale costs, which are then put into the context of average customer electricity bills in section 3.4.

The modelling presented here assumes that the centralised supply of electricity will continue into the future. This assumes that most customers will continue to purchase electricity from the main grid, and will not choose to self-supply the majority of their electricity from rooftop photovoltaics, or other forms of distributed energy. A more distributed (or even disconnected) scenario will lead to very different outcomes, and has been minimally studied in Australia to date [23, 24].

Each of the relevant studies that projects costs for a 100% renewable electricity system in the NEM are discussed below.

Beyond Zero Emissions

Beyond Zero Emissions (BZE) modelled a 100% renewable electricity system in 2020 in the NEM, based upon a somewhat arbitrarily selected portfolio of 42.5 GW of CST with up to 17 hours of molten salt thermal storage capacity (providing 60% of energy), and 48 GW of wind (providing the remaining 40% of energy). Their intention was to demonstrate the potential reliability of such a system, rather than to optimise the technology mix.

This system was costed at **$120/MWh**, including transmission augmentation [5]. Although this system relies heavily upon the relatively expensive CST technology, BZE used a relatively low estimate for the cost of CST, and applied a very low discount rate of 1.4%. The discount rate indicates the value placed on future costs or benefits, and is of critical importance when evaluating the costs of capital intensive infrastructure, such as renewable generation. This low discount rate was selected by BZE as a representative measure for long term societal costs. However, a discount rate of 5-10% is more standard for industry analysis.

UNSW (2013)

UNSW's modelling of 100% renewables applied an evolutionary algorithm (in the NEMO model) to optimise the mix of technologies in the generating portfolio, based upon hourly generating profiles, to minimise total system costs. Widely accepted technology cost estimates published by the Australian Government Bureau of Resources and Energy Economics (BREE) in 2012 [25] were applied. Only technologies that are commercially available today were included in the mix (for example, geothermal and wave technologies were excluded), to demonstrate that 100%

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[10] There is a difference between "costs" and "prices". In most studies on 100% renewables to date, wholesale costs have been projected based upon the average total cost of the system (to install and operate). This is similar to assuming that the electricity spot market will be competitive, such that spot market prices will trend towards long run marginal costs. In reality, there are many influences on spot market prices, and market participants often exercise market power. These effects are not taken into account in these long term projections, but can be important, particularly where the market isn't operating competitively, or when investigating short term effects.

renewables is feasible and affordable, even if these emerging technologies never become commercially available.

Based upon this analysis, the resulting 100% renewable portfolios modelled in 2030 sourced 30-40% of energy from wind, and 15-30% of energy from PV. Firm capacity was provided by existing hydro, 8-13 GW of CST and 23 GW of biogas turbines. Costs for 2030 were found to be in the range **$96 - $108/MWh,** not including transmission augmentation, with a 5% discount rate[11] [2], or $104-$119/MWh including long distance transmission.

Australian Energy Market Operator (AEMO)

As discussed above, AEMO is a conservative organisation, highly trusted and respected in the electricity industry, which makes their analysis particularly important. Unlike UNSW's modelling, AEMO's portfolio did include emerging technologies (such as geothermal and wave) in some scenarios. AEMO's 2013 report projected total system costs of **$111 - $128/MWh** for 2030, not including transmission (or $121 - $139/MWh, including transmission) [1].

University of Sydney

The University of Sydney's analysis (published as a working paper, still under review) found costs of around **$200/MWh**, for 100% renewables in Australia[12] [3]. Unlike the other studies described here, this study included the SWIS and the Northern Territory markets, as well as the NEM. The study explores a wide range of possible portfolios, calculated by varying the costs of the technologies in the range ±25%.

There appear to be a range of conservative assumptions implemented in this modelling, which lead to costs being higher than previous studies.

Firstly, the model includes a requirement that wind generation supplies no more than 30% of total generation, due to "integration issues". As a result, almost half of energy is supplied by the much more expensive CST technology. A wind integration limit of 30% could be considered conservative, given that other nations have already achieved wind levels approaching this; for example, Ireland (a small, island power system with all the associated integration challenges) is already operating at a wind penetration level of 23%, and aiming to increase that level [26].

Secondly, wind generation in the study is limited to a capacity factor of only 20%. This appears very low, compared with widely accepted datasets, and the operational behaviour of existing wind farms. For example, the sixteen wind farms operating in South Australia achieved average capacity factors between 27% and 42% over the past five years [27]. Similarly, the Australian Government "Australian Energy Technology Assessment" projected average on-shore wind capacity factors of 38% [28]. The capacity factor has a strong influence over the levelised cost of electricity sourced from this technology, and therefore this assumption could escalate costs considerably.

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[11] UNSW's analysis also included calculations applying a 10% discount rate, which led to wholesale costs of $135 - $154/MWh (not including transmission augmentation), or $153-$173/MWh including long distance transmission costs [13].

[12] The discount rate used for this calculation was not provided, but could be a significant reason why this cost is higher than other estimates.

Thirdly, the model limits "spilled" generation to no more than 20% of the total. Although spilling could be considered "wasted" energy, it is not directly problematic in of itself, so it is difficult to see why a more expensive power system should be selected, simply on the basis of minimising spilling.

For these reasons, the University of Sydney estimate could be considered a conservative estimate of costs.

UNSW (2016)

UNSW has recently conducted further modelling (still under review) with a number of important model improvements which have reduced total system cost estimates to **\$71/MWh**[13] (not including transmission) [4]. These updates include:

1. ***Updated cost data*** – using a more recent technology cost dataset, released by BREE in 2013 [28]. This dataset reduced the variable operations and maintenance cost of wind from \$12/MWh to \$10/MWh; when applied to the very large proportion of wind generation in these portfolios, this makes a significant difference in total system cost. The levelised cost of PV was also reduced from a NEM average of around \$143/MWh (in 2030), to around \$129/MWh, on the basis of observed rapid cost reductions for that technology.
2. ***Better representation of wind diversity*** – This more recent modelling also improved the representation of wind diversity. In UNSW's earlier study [2], wind diversity and variability was based upon observed historical operation of existing wind farms. Due to the very limited number of operating wind farms in Australia at the time, this limited the diversity in the wind profiles. For this reason, the least cost portfolios included only 30-40% of energy from wind generation. In contrast, UNSW's more recent modelling utilised extensive datasets produced by ROAM Consulting as an input to the AEMO 100% Renewables Study [1]. These datasets provided hourly estimates of wind and solar generation over six historical years, from 43 "polygon" areas across the NEM. This dramatically increased the diversity of wind generation available to the model. In response, the model includes far more wind generation (supplying up to 70% of energy) in the latest portfolio calculations. This was found to reduce the costs of 100% renewable scenarios considerably.

A wide range of different renewable portfolios were explored, illustrating the robustness of reliable 100% renewable portfolios, even with various technologies excluded from the mix. This modelling highlighted number of factors which are found to be important for maintaining relatively low system costs:

1. ***Include significant quantities of wind –*** Including significant quantities of wind generation brings costs down considerably. This suggests the importance of policy mechanisms and research to enable significant wind deployment in the NEM, to enable low cost 100% renewable scenarios. Although wind generation is commercially relatively mature, there remain a range of barriers to widespread deployment of this technology, such as community acceptance and integration challenges. Addressing these barriers is important for enabling low cost renewable portfolios.

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[13] With a 5% discount rate.

2. ***Include at least a small amount of bioenergy –*** Proponents of renewable energy are often cautious about bioenergy, because some types can compete with other uses of land and water resources (such as food production). However, the inclusion of at least a small amount of energy from peaking biogas turbines reduces system costs considerably. The amount of bioenergy required is far less than the amount estimated conservatively to be feasible under drought conditions (20 TWh pa) [2]. This means that enabling biofuels and other technologies that can provide peaking capacity (such as demand side participation) provides significant value. Alternatively, allowing a small proportion of natural gas generation (in a peaking capacity only) would bring down power system costs considerably, without adding significant greenhouse emissions.
3. ***Minimise the "Non-Synchronous Penetration" limit*** – The "NSP" limit is the maximum amount of "non-synchronous penetration" that can be managed by the system in any dispatch interval. If the NSP is limited to 50%, for example, then half of the energy generated in any period must come from synchronous sources, such as CST, geothermal or (bio)gas turbines. If the NSP is increased to 90%, then only 10% of energy in any period needs to come from synchronous sources (and up to 90% can come from wind and PV). This is found to reduce system costs considerably [4, 22, 29]. Research is required to determine the appropriate level for this limit, and how to minimise it. This is a specific aspect of wind and PV integration that needs to be explored.
4. ***Minimise uncertainty*** – Most renewable technologies (and transmission) are very capital intensive, meaning they have high upfront costs to install, but low operating costs. This means that the cost of capital (the rate at which they can secure financing) is extremely important to overall costs. Financiers will carefully consider the risk associated with a project, and provide lower financing rates to those that are judged to have a more certain return. The policy environment, and the nature of the policies implemented to support renewable technologies play a significant role in this risk assessment. The importance of this factor is illustrated in Figure 10, in the significantly higher costs associated with a 10% discount rate, compared with a 5% discount rate[14]. This might be associated with policies that create a riskier investment environment for renewables.

Despite a wide range of alternative assumptions, wholesale costs for 100% renewable portfolios from this study were found to be in the range of $65/MWh to $106/MWh (not including transmission costs), maintaining a minimum of 15% synchronous generation operating at all times.

3.2 Transmission requirements

UNSW's modelling costed transmission augmentation in a relatively simplistic manner, based upon average $/MW/km costs for transmission, and the distances and maximum flows calculated between the five NEM regions, as illustrated in Figure 8 [2]. This provides a high level estimate of the cost of transmission, but is clearly limited by the simplicity of the network modelled; further investment is likely to be required intra-

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[14] The discount rate is analogous to the Weighted Average Cost of Capital (WACC).

regionally. Transmission costs were calculated via this method to be in the range **$8 - $11/MWh** (with a 5% discount rate)[15].

Figure 8 – Transmission options in UNSW's 2013 study. Source: [2]

AEMO's 2013 study [1] included a more bespoke analysis of transmission requirements to support their 100% renewable portfolios, as illustrated in Figure 9. This study includes transmission upgrades within regions (as well as between regions), although it does remain high level. As with the UNSW analysis, further investment is likely to be required intra-regionally. AEMO's analysis calculated transmission costs of **$6 - $10/MWh**.

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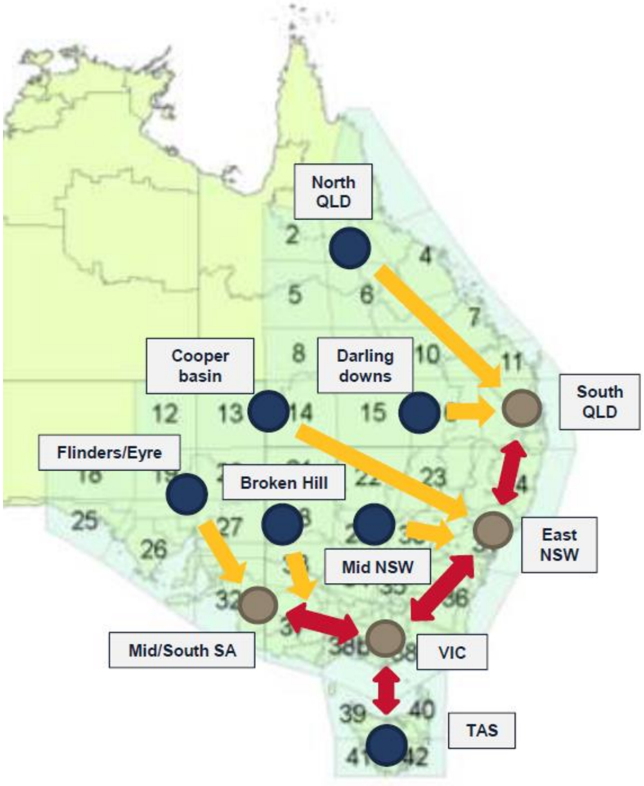
[15] Transmission costs were calculated to be $18-$19/MWh with a 10% discount rate [13], highlighting again the importance of the cost of capital for high renewable scenarios requiring a significant capital investment.

Figure 9 – Transmission options in AEMO's 2013 study. Source: [1]



Both studies found that transmission costs are around 10% of the cost of the electricity generation technologies themselves, as illustrated in Figure 10. This suggests that transmission costs are important, but they are not the dominant contributor to total costs for a 100% renewable electricity system.

These costings only include a high level representation of the major interconnections; further investment is likely to be required intra-regionally. For comparison, current transmission expenditure in the NEM is around \$2.7b/year or around \$14/MWh. Much of this investment is "sunk", so a proportion of the transmission investment required to enable 100% renewable scenarios is likely to be additional to these costs. The total system costs quoted above included all new transmission investment as additional to sunk transmission investment.

3.3 Costs summary

Estimates from studies by BZE [5], UNSW [2, 4], University of Sydney [3] and AEMO [1] for the cost of a 100% renewable power system in the NEM are calculated to be in the range of **\$81** to around **\$200/MWh** (including transmission costs)[16]. The various cost estimates, with proportions attributed to transmission, are illustrated in Figure 10.

Achieving the costs at the low end of this range will require:

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[16] Costs may be slightly lower (around \$75/MWh) if geothermal technologies advance significantly and can be included in the portfolio, as projected by BREE [25].

- Installing very significant quantities of wind generation (supplying around 80% of energy);
- Addressing wind integration technical challenges, such that the system can operate with up to 85% of energy at any time coming from non-synchronous sources;
- Production of around 6TWh of biogas fuel per annum;
- Cost reductions over time for the relevant technologies, as projected by BREE (particularly for technologies such as CST).

If these conditions are not met, or other system limitations apply, then costs may be more similar to estimates at the top of this range.

AEMO's estimate of **$121 - $139/MWh**, including transmission, could be considered a reasonable estimate in the middle of this range, suitable for most purposes.

Figure 10 – Projected costs of 100% renewables for the NEM. Sources: [1, 2, 3, 4, 5]

Note that an important limitations of these studies is that they all assume the entire system is constructed at the technology costs applying in the relevant year of analysis (2030). In reality, much of the generating capacity will be installed prior to 2030 (or the relevant year), and will therefore be installed at a higher cost [1]. UNSW has estimated that these additional "trajectory costs" are around 10-20% [30].

3.4 Putting the costs in context

Present costs

Historical average wholesale prices in the NEM have varied significantly from year to year, and also from state to state. Since the commencement of the NEM, prices have averaged around $44/MWh [31]. In the most recent three year period, average prices have been somewhat higher due to the carbon price.

AEMO projects an increase in retail prices of **6-8c/kWh** to support a 100% renewable power system, based upon their modelled wholesale costs, transmission costs, and compared with recent historical prices [1]. This provides a reasonable central estimate. However, based upon the other modelling studies discussed, retail price increases from long term average NEM prices could be as low as 4c/kWh, or as high as 16c/kWh.

What does this mean for an average household?

Retail electricity prices vary state by state, but average around 29c/kWh in Australia at present [6], or a total annual cost of $1,499 for an average household[17] [6].

As outlined above, AEMO estimates that a move to 100% renewables would involve an increase in the range of 6- 8c/kWh (including transmission). This is an increase of between 20% and 30%, to an electricity rate of 35 - 37c/kWh. The impact on household bills would be an increase of around $300 to $400 per year (20% to 30%).

Given that this is associated with moving to a 100% renewable power system, these costs could be considered moderate. The moderate increase in cost is because only around 20-30% of household electricity bills are related to the wholesale cost of electricity, as illustrated in Figure 11. Around a third of the bill is related to the cost of electricity distribution (the low voltage "poles and wires" that distribute electricity to individual households). A further 10-30% of the bill is related to retailer's costs and margins. These components could be reasonably assumed to remain relatively unchanged in a transition to 100% renewables[18]. Thus, it is only the wholesale cost component (20-30% of the bill) that increases, along with a small increase in the transmission component (included in the c/kWh increase estimates above). This is the same reason that 100% Greenpower typically only costs 20-30% more than "black" (non-renewable) electricity at present.

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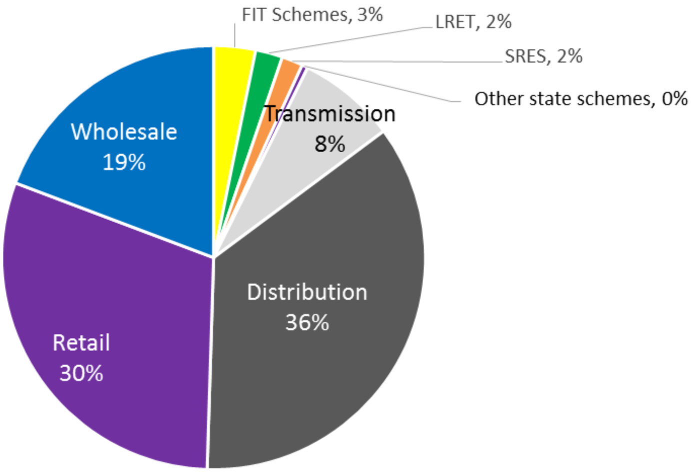
[17] For 2015-16, based upon a national weighted average consumption level of 5,248 kWh per year.

[18] This assumes that the 100% renewable power system remains relatively centralised, with no transition to distributed energy. The costs for the distribution network in such a transition have not been analysed.

Figure 11 - Components of retail electricity bills[19]. Source: [6]



What does this mean for industry?

It is important to bear in mind that less than a quarter of Australia's electricity is consumed by residential households, as illustrated in Figure 12. Each sector will need to be considered individually, because they face different electricity cost structures. For example, large industrial customers (such as aluminium and zinc smelters) are often connected directly to the transmission network, and therefore avoid distribution network charges. This means that an increase of 1.5 - 8.4c/kWh in wholesale and transmission costs causes a more significant proportional increase in overall electricity costs for those industries. This could have significant implications for industries for whom electricity is a significant proportion of costs.

Similarly, commercial customers are often bulk purchasers, and can therefore negotiate lower wholesale and retail rates. They may also have individually negotiated distribution network charges.

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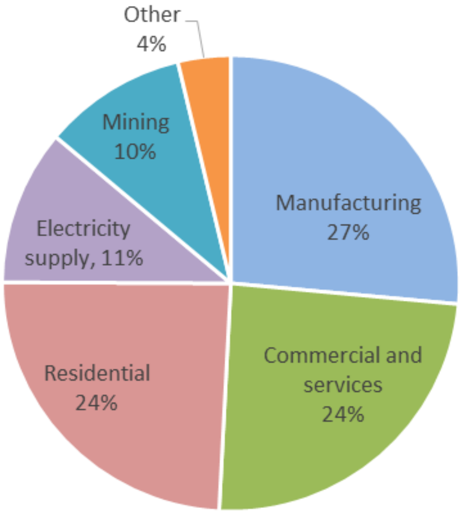
[19] Figure shown for national average in 2015-16. The "retail" component is not provided by the AEMC. A wholesale cost of 5.5c/kWh has been assumed (based upon historical average wholesale prices), leaving the remainder of the "wholesale and retail" component as retail costs. This split is acknowledged to be approximate.

Figure 12 - Australia's electricity consumption by sector (2012-13). Source: [8]



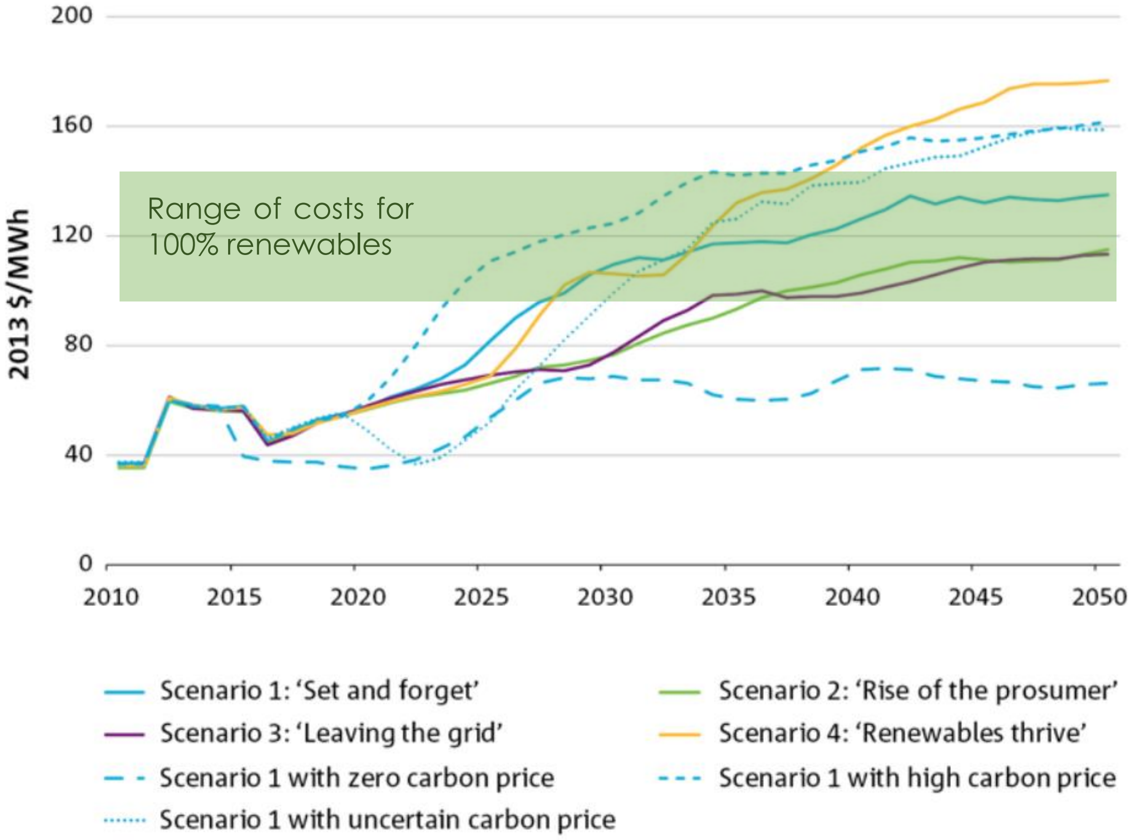
For these reasons, mechanisms such as the Renewable Energy Target have previously included exemptions for certain types of industrial customers. This reduces the risk of placing overly onerous costs on these industries (particularly where they are trade exposed), potentially harming their international competitiveness. However, it is important to realise that this increases the cost burden on residential customers, who must make up the difference in order to achieve a total renewable percentage for Australia. As the renewable target grows, it is likely to become increasingly difficult for the residential sector to bear these costs alone; alternative mechanisms will be required.

"Reference" scenarios

Even in the absence of policies to promote renewable energy, it is unlikely that the electricity system in Australia will remain static. Therefore, a perhaps more appropriate frame of reference is to compare the cost of a 100% renewable power system to the costs for alternative "reference" scenarios in 2030, representing the other options for how the power system might evolve. The choice of an appropriate reference scenario is challenging. For example, "business as usual" might be interpreted as continuing investment in coal and gas-fired plant. However, there is general consensus that new investment in coal-fired plant in Australia is very unlikely, making this an unrealistic reference case [32]. Ultimately, the choice of reference will depend upon the nature of the insights sought.

However, there is general consensus that under most future scenarios, wholesale costs are going to increase. For example, Figure 13 shows the projected wholesale costs in a range of scenarios, modelled by the CSIRO. The range of costs for 100% renewable portfolios is superimposed, showing that from 2030, these costs are very similar to those of other forecast scenarios.

Figure 13 – Projected average wholesale electricity costs from the CSIRO. Source: [33]



3.5 Would 90% renewables be significantly cheaper?

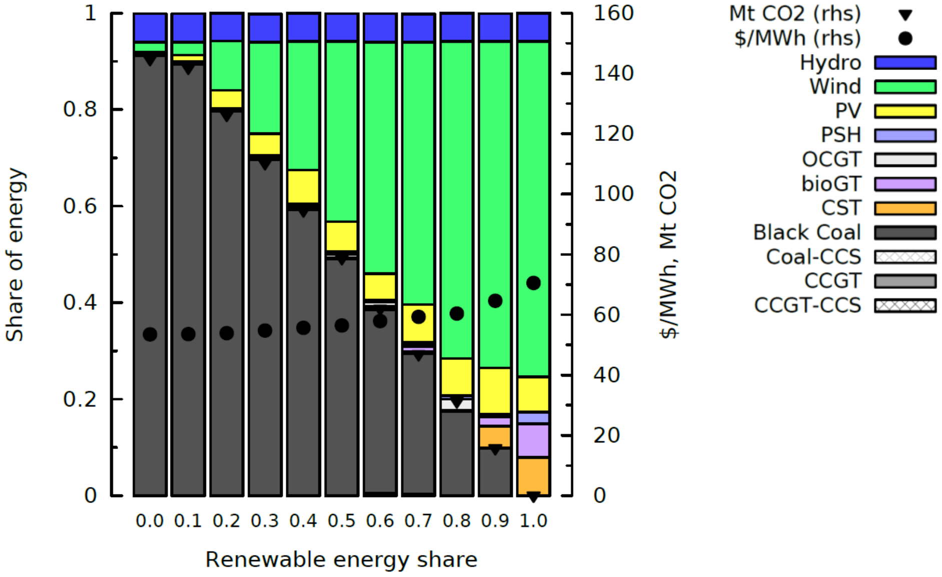
It has been suggested that a 90% renewable system might be significantly less expensive than a 100% renewable system, and therefore would make a more suitable long-term target. As discussed above, UNSW's modelled 100% renewable portfolios include a significant capacity of biogas turbines that operate as peaking capacity. UNSW's model limits the use of biogas to 20TWh pa, which is 10% of the total annual generation in the NEM. Therefore, a 90% renewable target would allow those biogas turbines to operate on natural gas (instead of renewable sources).

To explore the implications of a lower renewable target level, CEEM modelled the incremental increase in the renewable energy target, as illustrated in Figure 14. This figure demonstrates that total system costs escalate approximately linearly as the proportion of renewable energy increases, until renewables generate around 80% of annual energy. At renewable energy levels below 80%, the model prefers to use only wind and PV to meet the renewable energy target, and doesn't find it necessary to include any of the firm and synchronous renewable generation types.

To move beyond 80% renewables, the model finds it is lower cost to include some of the more expensive firm renewables (biogas turbines and CST). This means that costs escalate non-linearly beyond 80% renewables. However, the escalation remains minimal; CST and biogas turbines provide cost effective firm and synchronous capacity, allowing the model to achieve 100% renewables with only minor cost escalation to the average cost per megawatt hour.

This modelling suggests that if the aim is to get the greatest "bang for buck", the most appropriate renewable target might be around 80% renewables (or around the level when synchronous renewables start to become required). However, this modelling suggests that a 100% renewable power system is possible at only a moderate cost escalation beyond that level, and is technically and economically achievable.

Figure 14 – Generation mix and escalation in power system cost as the renewable proportion grows[20]. Source: [34]



3.6 Mitigating cost risk

Moving to a 100% renewable system also has advantages in mitigating the *cost risk* or *uncertainty* in cost associated with fossil fuel systems. Fossil fuel generation is exposed to a number of factors that create uncertainty over future generation costs, such as uncertainty around future gas prices, and uncertainty over future carbon prices (or equivalent incentives to rapidly reduce greenhouse emissions). The *uncertainty* over future costs needs to be taken into account when considering future generation portfolio options, in addition to the central estimate of cost.

CEEM modelled a range of portfolios, from 15% renewables to 85% renewables, looking at the uncertainty in future generation costs. The results are shown in Figure 15, illustrating the probability distributions of cost for each portfolio. The higher renewable proportions have significantly narrower distributions, meaning that renewables can effectively mitigate the cost risk associated with gas and carbon price uncertainty in Australia. This result was found to be robust to a wide range of assumptions around carbon pricing [35].

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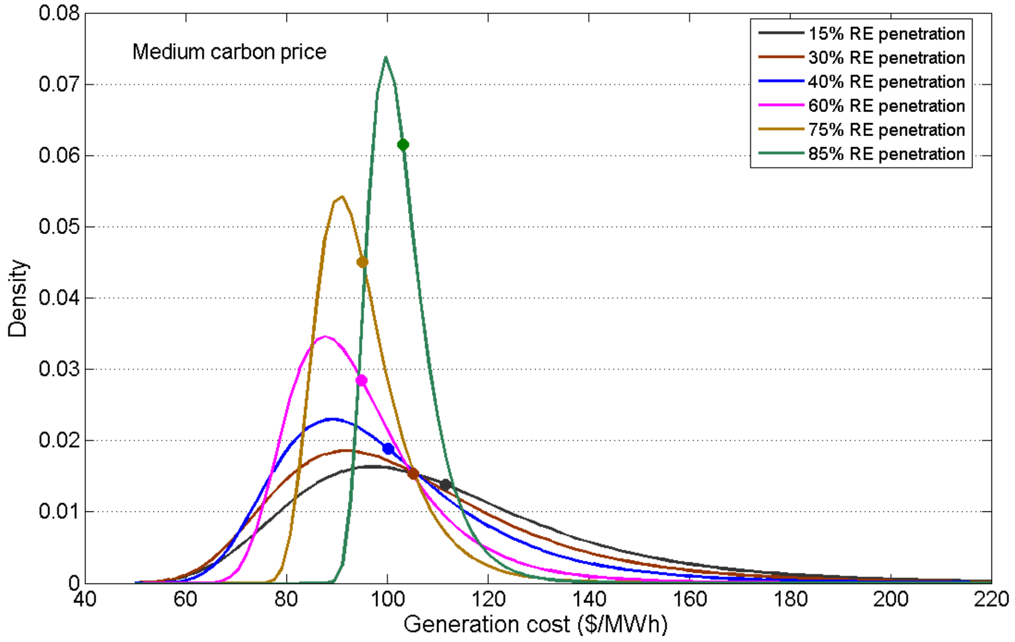
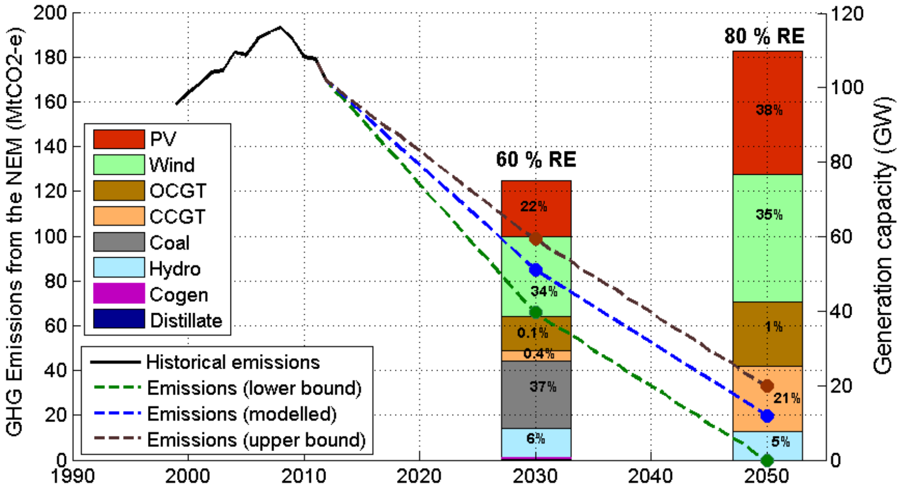
[20] Modelling for 2030, with $9/GJ gas price, and no carbon price. Transmission costs are not included.

Figure 15 – Probability distributions for wholesale generation costs. Source: [35]



When these cost risks are explicitly taken into account, UNSW's modelling suggests that the lowest cost trajectory involves a target of around 60% renewables by 2030, and 80-100% renewables by 2050[21], as illustrated in Figure 16 [36, 35]. Increasing the 2030 renewable proportion to 75% only very slightly increases the expected cost (by $0.2/MWh), but significantly decreases the standard deviation of cost (representing the cost risk) [35].

Figure 16 – Least cost portfolios for the NEM, accounting for cost risk[22]. Source: [36]



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[21] The model used for this analysis wasn't capable of exploring scenarios with higher than 80% renewables, to calculate their cost and cost risk.

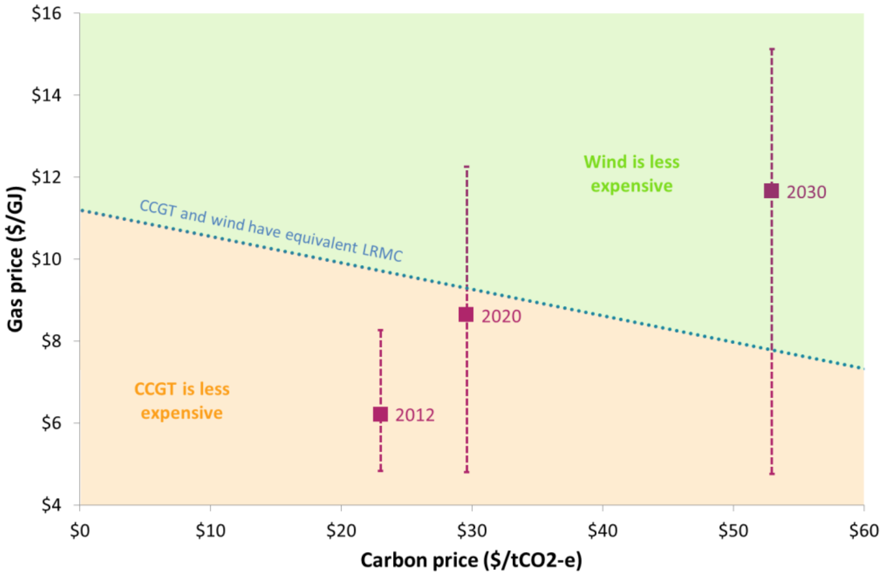
[22] Figure shows GHG emissions trajectories for the Australian NEM in the proportions of national targets recommended for Australia by the Climate Change Authority, with lowest cost portfolios that meet the targets in 2030 and 2050. Percentages indicate the % of energy supplied by each technology.

3.7 What about a "gas transition"?

CEEM's modelling suggests that portfolios sourcing significant quantities of energy from gas-fired generation in 2030 and 2050 are likely to be significantly higher cost and significantly higher risk than renewable alternatives [36]. High gas portfolios also do not achieve the greenhouse gas (GHG) emissions reductions levels that are required.

For example, the lowest cost portfolios in 2050 source less than 20% of energy from gas with the remaining energy sourced from renewables. Even in the absence of a carbon price, the lowest cost portfolio in 2050 sources only 30% of energy from gas-fired generation, with the remaining 70% of energy being sourced from renewable technologies [36]. This result occurs in part because there is significant uncertainty over future gas prices in Australia. Figure 17 shows ranges of gas price projections for 2020 and 2030. Depending upon the presence or absence of a carbon price, many of these gas prices are likely to put combined cycle gas turbine (CCGT) operation at a higher cost than wind generation. This indicates that baseload gas (CCGT) is unlikely to be cost competitive with wind generation, for bulk production of energy.

Figure 17 – Comparison of the long run marginal cost (LRMC) of wind and baseload gas (CCGT)[23]. Source: [37]



CEEM's modelling indicates that the optimal strategy for minimising costs, minimising cost risk and reducing GHG emission levels in the electricity sector involves minimising energy sourced from gas, and increasing renewable generation [36]. Gas-fired peaking generation (such as open cycle gas turbines, OCGT) is an exception; these

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[23] Figure indicates the combination of carbon and gas price at which the costs of CCGT and wind are equal. The points in magenta illustrate carbon prices from Treasury modelling [2] and 'medium scenario' gas price projections from the Bureau of Resources and Energy Economics [6, 7], Uncertainty bars indicate the range of the highest and lowest gas price projections forecast for that year from a selection of gas price projections. The CCGT is assumed to operate at a capacity factor of 80%; other technology costs for long run marginal cost (LRMC) calculation are from reference [18].

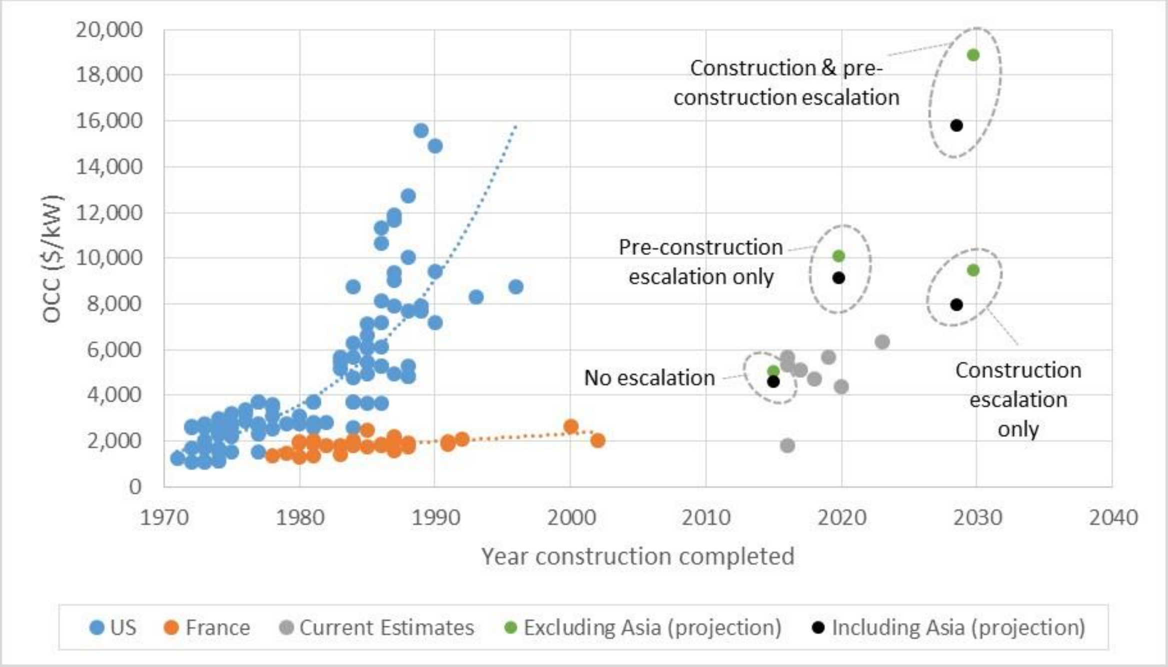
technologies provide valuable peaking capacity at minimal cost, and due to their rare operation do not contribute significant greenhouse gases.

3.8 What about nuclear?

Nuclear generation is an important low carbon technology. Asia, in particular, has significant nuclear build programs under way at present, and is achieving competitive nuclear plant costs. CEEM conducted a comprehensive international literature review to determine the likely costs of establishing nuclear power in Australia, as an alternative approach to reduce greenhouse gas emissions.

Cost estimates for nuclear generation were found to be in the range \$122 to \$138/MWh, which is competitive with some forms of renewable generation. However, these estimates fail to take into account the very long construction durations for nuclear generation, and the cost escalation that is consistently observed over that duration. As illustrated in Figure 18, historical cost escalation observed in both France and the USA during their nuclear build programs was significant, averaging 3.6% pa in France, and 8.1% pa in the USA. CEEM's review revealed that if these levels of cost escalation are properly taken into account, nuclear generation becomes prohibitively expensive [38]. Projected capital cost values including escalation are illustrated in Figure 18, and the corresponding levelised cost values in Figure 19. If historically observed levels of pre-construction and construction cost escalation are included, nuclear technology has average costs in the realm of \$345 to \$428/MWh, far more expensive than many renewable technologies [38].

Figure 18 – Nuclear plant overnight capital costs (OCC)[24], comparing historical values with projections for Australia. Source: [38]



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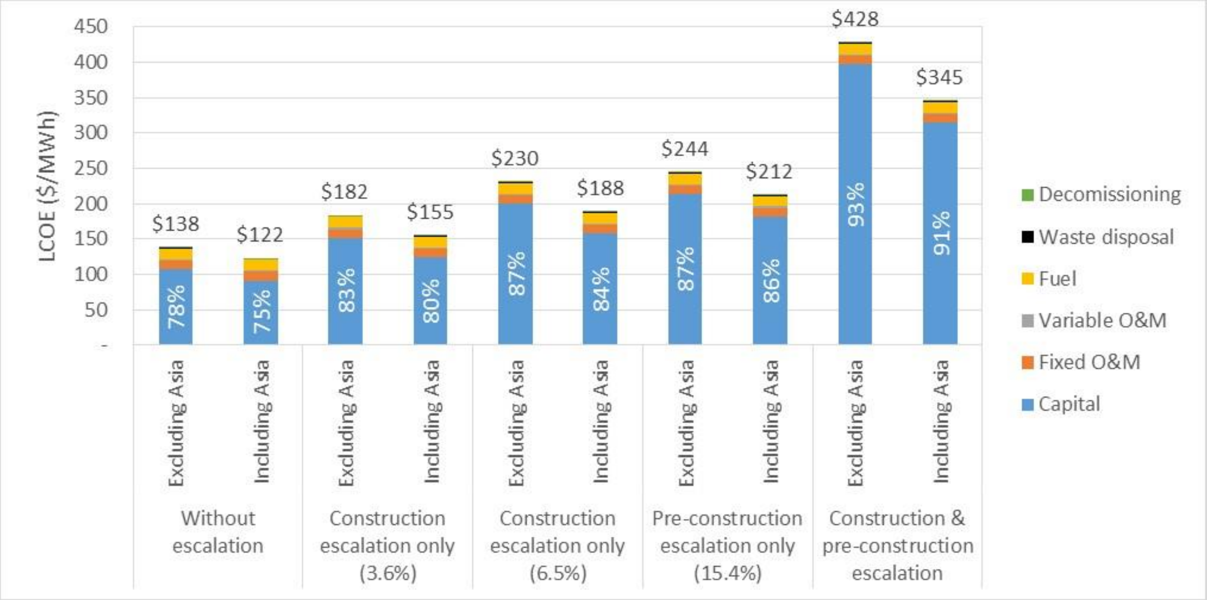
[24] Projected values in 2015 are central estimates without escalation, values in 2020 are with pre-construction escalation only, and values in 2029 and 2030 are with pre-construction and construction

Figure 19 – Nuclear levelised cost projections[25]. Source: [38]



3.9 What about CCS?

Carbon Capture and Storage (CCS) is also likely to be prohibitively expensive, when compared to renewable alternatives. There remains significant uncertainty over the capital cost of coal-fired plant with CCS, and around the storage costs ($/tonne of CO_2 stored). Figure 20 shows the total electricity system cost calculated for a range of possible CCS costs, compared with the cost of a 100% renewable power system (RE100). This modelling shows that only under a few, and seemingly unlikely, combinations of costs can any of the fossil fuel scenarios compete economically with 100% renewable electricity in a carbon constrained world.

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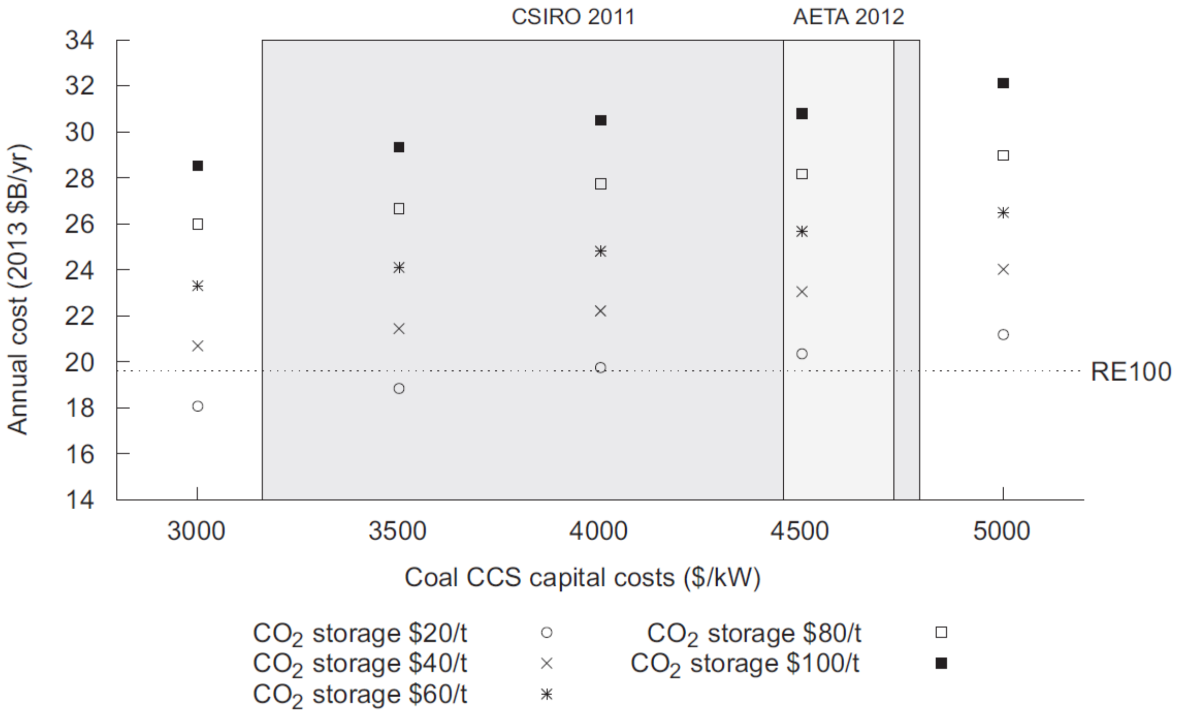
escalation, or with construction escalation only as indicated. Values are shown based upon inclusion of (lower cost) Asian plant in the cost assessment, or excluding Asian plant, as indicated.

[25] Percentages illustrate the proportion of the levelised cost related to capital expenditure. Labels above columns indicate the total Levelised Cost of Energy (LCOE).

Figure 20 – NEM annual cost, depending upon CCS capital costs and storage costs. Source: [17]



4 Challenges on the path to 100% renewables

It is important to acknowledge that a 100% renewable electricity system will operate very differently to the present system, so there are a wide range of changes that will need to be implemented.

Technical challenges

As a part of their 2013 study on 100% renewables, AEMO conducted a high level review of the "operational considerations" that will need to be addressed to operate a 100% renewable system. They noted a number of technical challenges, including [1]:

- ***Frequency control (managing variability and uncertainty)* –** Large wind and PV ramps over periods of hours may require additional types of frequency control "reserves" to ensure sufficient system flexibility over those timescales. Also, increased regulation reserves are likely to be required to manage increasing variability and uncertainty over timescales of minutes.
- ***Frequency control (inertia)*** – Synchronous generators (such as coal and gas-fired plant) automatically provide inertial response to the power system, which helps to keep the frequency stable on timescales of seconds. Wind and PV are non-synchronous, and therefore don't naturally provide inertia. This means that frequency control on these very short timescales will need to be managed differently, either by maintaining a minimum amount of

synchronous generation operating (such as biogas turbines, CST, or hydro), by installing synchronous condensers, or via other innovative methods.

- ***Grid code performance standards*** – The grid code performance standards define the behaviour of generators, particularly with regards to their ability to "ride through" faults. Generators must meet these standards in order to connect to the system. These standards are likely to need to be revised to better suit the properties of renewable generators in order to operate a secure 100% renewable system.
- ***Fault level in-feed*** – In the present system, when a fault occurs there is a much higher current flow than usual, allowing protection systems to detect and isolate the fault. This current flow doesn't occur with a system predominantly composed of non-synchronous generators (such as wind and PV). To address this, it may be necessary to keep a certain minimum quantity of synchronous generation operating in each region, or there may be other innovative solutions (such as the re-design of protection systems).
- ***Reliability assessments*** – AEMO conducts ongoing assessments of the ability of the system to meet anticipated demand over short, medium and long timeframes. The appropriate valuation of variable resources in these assessments will need to be determined, and it may be necessary to entirely re-design the assessment methodology over some timeframes.

Note that many of these technical challenges relate to the fact that wind and PV are non-synchronous, and are not related at all to their variable and uncertain availability.

Market design

In many ways, the NEM has an excellent market design for integration of renewable technologies [39, 40]. For example:

- ***The NEM is large –*** The NEM is fully integrated with generator dispatch co-optimised across the whole grid. This allows the variability in wind and PV to be smoothed across a vast land area very efficiently, minimising the need for expensive reserves for "balancing" in each region.
- ***The NEM is fast –*** The NEM dispatch is fully re-calculated every five minutes. This allows the uncertainties in wind and PV forecasts to be corrected often, ensuring they remain small and inexpensive to manage.
- ***Sophisticated frequency control markets –*** The NEM has very sophisticated frequency control markets, which manage variability, and are therefore going to become increasingly important as levels of wind and PV grow [41]. This makes frequency control very inexpensive in the NEM compared to other jurisdictions.
- ***Strong price signals –*** The NEM has very strong spot market price signals, allowing prices to range from -$1,000/MWh to $13,800/MWh [42]. This creates strong incentives for all generators to react quickly to changes in the market, including incentives to stop generating (if possible) when there is oversupply.
- ***Renewables treated (mostly) like any other generator –*** Renewables in the NEM are dispatched and managed very similarly to other generation types, meaning that the transition from a fringe technology to a fully participating

and important contributor doesn't require dramatic market changes. Renewables are already expected to respond to price signals, network constraints and market directions, pay for market services, and allowed to participate in ancillary services markets (providing grid services) as long as they can demonstrate the appropriate technical capability.
- ***Energy-only market –*** The NEM has an "energy-only" market design, which means that market participants are financially rewarded only for the energy (MWh) they provide. Many other jurisdictions have implemented a "capacity market" or some other form of Capacity Remuneration Mechanism [43, 44, 45], which provides additional compensation for the provision of firm capacity (MW) to the market. Debate continues as to the merits and disadvantages of each market framework. However, CEEM's research suggests that energy-only market models avoid many renewable integration challenges (such as questions on how to value the "firm capacity" contribution of variable renewables), and may be able to function effectively in a 100% renewable system [46, 47, 22].

The sophisticated design of the NEM gives Australia a significant head start on other jurisdictions, which will require much more substantial market changes to allow efficient integration of renewables. Many challenges do, of course, remain. Changes will be required to many market design aspects, including:

- ***Transmission investment frameworks –*** The regulatory frameworks utilised at present to determine where and when new transmission network is installed are likely to be inadequate, particularly for facilitating the construction of large new scale-efficient links to connect new renewable generation centres. Entirely new frameworks are likely to be required. The significant "Transmission Frameworks Review" conducted from 2010 to 2013 recommended an "Optional Firm Access" model, which would have helped to address some of the issues, but also proposed grandfathering of the existing network during the transition [48, 49]. This model was explored further over the period 2013 to 2015, and was eventually rejected. This is a challenging problem, with few to no good solutions identified internationally thus far [50].
- ***Demand-side participation –*** The present NEM design has many barriers to demand side participation. Addressing these barriers will enable more efficient and cost effective high renewable scenarios [46].
- ***Distribution network investment frameworks –*** Distribution networks are the most expensive part of residential consumer electricity bills, and the present investment frameworks are not well suited to a rapidly changing energy market landscape. Significant changes to these investment frameworks are likely to be required to efficiently integrate distributed resources, such as electric vehicles, home battery storage, and distributed energy such as photovoltaics.

These aspects can be addressed progressively as we move towards a higher renewable system.

Closing coal-fired generation

One of the biggest economic challenges could be the orderly closure of coal-fired generation. These plants have very low operating costs, and could be kept in service well past their original design lifetime. It appears likely that some form of mechanism to facilitate efficient and timely plant closures is an important part of a policy framework for transitioning to a 100% renewable system. An auction-based market mechanism has been proposed by researchers at ANU, and appears to have some promising characteristics [51]. Whatever mechanism is implemented, it will be important to avoid exacerbating barriers to exit by creating the perception that attractive payments for closure could await those who remain in the market [52].

5 Conclusions and next steps

The available research, by UNSW and others (including the Australian Energy Market Operator) now shows that 100% renewable electricity portfolios are likely to be feasible for Australia. The technical challenges can be managed, and the costs are likely to be competitive with other kinds of portfolios that may be operating in 2030.

A 100% renewable power system will be very different to the one we operate at present in Australia, and the transition will be significant. However, no convincing reason why 100% renewables is not feasible for Australia has been identified.

Given the technical feasibility and attractive economics for a 100% renewable NEM, questions around next steps arise. Given Australia's pressing clean energy challenges, there are excellent reasons to set higher and more ambitious renewable generation targets than those established at present. While there are significant opportunities to reduce the costs of renewable options through judicious R&D and demonstration, major deployment has proven a key driver of reducing cost and improved expertise.

As renewable penetrations climb, we should not underestimate the challenges in effectively and efficiently integrating them into the NEM. Current NEM arrangements have proven remarkably resilient to regionally significant wind and PV penetrations to date (by comparison with some other electricity industries around the world). However, a 100% renewable NEM will inevitably operate very differently to the present, and significant resources will be required for all electricity industry stakeholders to understand, drive and adapt to these changes. Such profound electricity industry transition will also require societal consensus on the importance of addressing our clean energy challenges and renewable energy's role in addressing them. Beyond these challenges lie the opportunity for Australian leadership and innovation in creating a clean energy future for Australia and others around the world.

6 Acknowledgements

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7 Acronyms

AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator

BREE	Bureau of Resources and Energy Economics (Australian Government)
BZE	Beyond Zero Emissions
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CEEM	Centre for Energy and Environmental Markets
CO_2	Carbon Dioxide
CST	Concentrating Solar Thermal
EGS	Enhanced Geothermal System (a type of geothermal technology)
GHG	Greenhouse Gas
GT	Gas Turbine
GW	Gigawatt (a measure of capacity)
HSA	Hot Sedimentary Aquifer (a type of geothermal technology)
LCOE	Levelised Cost of Energy (a measure of the cost of producing energy from a particular technology, taking into account the proportion of time over which it operates).
MWh	Megawatt hour (a measure of energy)
NEM	National Electricity Market
NSP	Non-synchronous Penetration (a limit on the amount of non-synchronous generation, such as wind and PV, that can be operating at any time)
O&M	Operations and Maintenance
OCC	Overnight Cost of Capital (the capital cost of building a plant, if it could be entirely constructed overnight, without any need for financing over the construction duration).
OCGT	Open Cycle Gas Turbine
PSH	Pumped Storage Hydro
PV	Photovoltaics
RE	Renewable Energy
SWIS	South-West Interconnected System
TWh	Terrawatt hour (a measure of energy)
UNSW	University of New South Wales
WACC	Weighted Average Cost of Capital

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