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Beyond wind: furthering development of clean energy in South Australia

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The deep and rapid decarbonisation of electricity supply systems is an essential component of mitigating the impacts of climate change. Despite a high penetration of wind-generated electricity (27%), South Australia remains connected to, and reliant on, one of the most coal-intensive electricity grids in the world – Australia's National Electricity Market. Here we explore the changes to South Australia's electricity generation in the context of the recent, large expansion of wind-generated electricity, the impacts of this expansion, and the potential for alternative, low-emissions technologies to help the State complete the decarbonisation task. We find that although the expansion of the wind-generation sector in South Australia has delivered meaningful reductions in greenhouse-gas emissions in just over 10 years, the limitations of strongly correlated and variable electricity supply that is decoupled from electricity demand place upper limits on the plausible future contribution from wind. System costs arise from integrating these sources, both from managing uncorrelated supply and the declining availability of ancillary services such as the frequency control provided by synchronous generators. These costs have been minimal to date, largely due to the connection to the National Electricity Market and already available, open-cycle gas turbines as reserve margins. However, evidence of large-scale integration costs is emerging and expected to increase should wind continue to grow in penetration. Development of the South Australian hot dry-rock geothermal resource has confirmed the well-documented challenges in developing this energy source, with still no operating power supply after more than 30 years of development. Solar–thermal technology remains uneconomic in the absence of either substantial subsidies or high carbon pricing. Given these inherent constraints, the deployment of nuclear energy technology provides the pathway of greatest technical and economic certainty for the permanent displacement of fossil-fuelled baseload electricity generation in South Australia. Nuclear power is, however, hampered by legislative barriers and requirements for the development of legal and regulatory frameworks. Support for the nuclear option is broadening within South Australia, and innovative economic development strategies based on the deployment of generation IV 'integral fast reactors' could spur the necessary bi-partisan political support to transition the State's electricity supply entirely to low-emissions sources.

Keywords: South Australia; wind power; photovoltaic; solar-thermal; geothermal; nuclear; integral fast reactor; National Electricity Market

Introduction

The recent report from the Intergovernmental Panel on Climate Change (IPCC) has reinforced the now unequivocal finding (Cook et al., 2013) of the warming of Earth's

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climate and the progressive acceleration in the rate of greenhouse-gas emissions since 1970 (IPCC, 2013). The IPCC states that substantial cuts are required in anthropogenic greenhouse-gas emissions, achieved largely through large-scale changes in energy systems. Delaying further mitigation efforts beyond those in place today through to 2030 is estimated to increase substantially the difficulty of maintaining temperature change < 2°C relative to pre-industrial averages (Intergovernmental Panel on Climate Change, 2013). This growth in greenhouse-gas emissions from the energy sector has occurred simultaneously with increases in output from low-carbon energy sources. In electricity generation, the average annual growth rate of global production from wind and solar power sources was > 26 and > 50%, respectively for the 10 years to 2012, whereas global nuclear output recorded a slight decline over the same period of 0.8% $year^{-1}$, although the total energy supplied by nuclear (2463.5 TWh) was over four times greater than by wind (534.3 TWh) and > 23 times than by solar (104.5 TWh) due to a large existing capacity (Observ'ER, EDF & Fondation Energies pour le Monde, 2013).

Despite a strong focus on the deployment of renewable energy technologies, Australia has maintained one of the highest per capita rates of greenhouse-gas emissions from the consumption of energy in the world (18 t CO_2 $person^{-1}$ in 2011; Energy Information Administration, undated) and in particular, one of the most coal-and-gas-dependent electricity supplies (electricity generation in 2011/2012 was 69% coal and 20% gas) (Bureau of Resources and Energy Economics, 2013). Ironically, given current policy goals, production from renewables as a share of total electricity produced in Australia was greater in 1960 (19%) compared to today (< 10%), while the use of coal (in terms of total energy output) has grown approximately 10-fold over the same period (Green Energy Markets, 2011). The use of nuclear energy is prohibited federally under Section 140 A of the *Environmental Protection and Biodiversity Conservation Act 1999*(Australian Government ComLaw, 1999).

The State of South Australia has taken a proactive approach to the development of its wind resources and has achieved the highest penetration of wind generation of any Australian state, at 27% of electricity consumption for the 12 months to 30 June 2014 (Australian Energy Market Operator Ltd, 2014b). But is this enough? Will a focus on wind and other renewable technologies ensure South Australia delivers substantially greater cuts in emissions from the energy sector, and how logistically and economically feasible is the ongoing expansion of these non-fossil-fuel power-generation sources? The old age and the high emissions from South Australia's electricity-generating assets combine to present a compelling case for alternative-energy planning. In this analytical paper we examine the relevant historical data, discuss some of the intractable barriers to full reliance on renewable energy sources for this transition, and then present an alternative vision for the future of low-carbon electricity generation for the State.

South Australia's electricity profile

The underpinning infrastructure of the South Australia grid is getting old. Twenty-five per cent of South Australia's baseload generating capacity was commissioned before 1970, and 56% before 1980 (Figure 1). Gas dominates the baseload generation, followed by coal (Figure 2). Most of the State's greenhouse-gas emissions are produced from the coal-power stations located at Port Augusta at a rate of > 1000 g CO_2-e kWh^{-1} (Clean Energy Regulator, 2014b), followed by the burning of gas in the inefficient 'open cycle' plant at Torrens Island A and B at a rate of 580 g CO_2-e kWh^{-1} (Clean Energy Regulator, 2014b) (Figures 2, 3). By comparison, the more advanced and cleaner-burning combined-cycle

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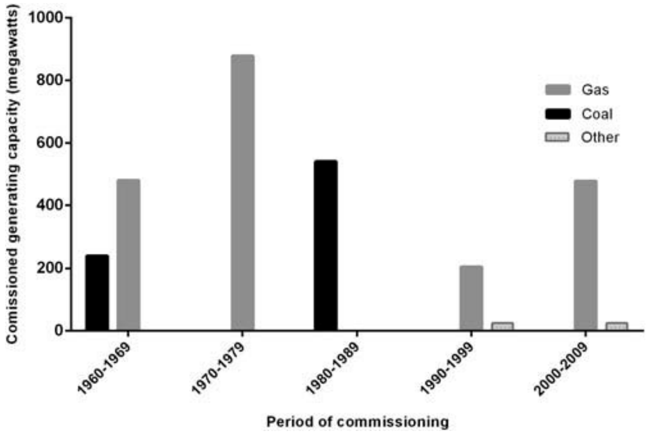

Figure 1. Commissioning period for currently operational South Australian baseload electricity generators expressed as peak installed capacity in successive decadal blocks. Source: Geoscience Australia (2008).

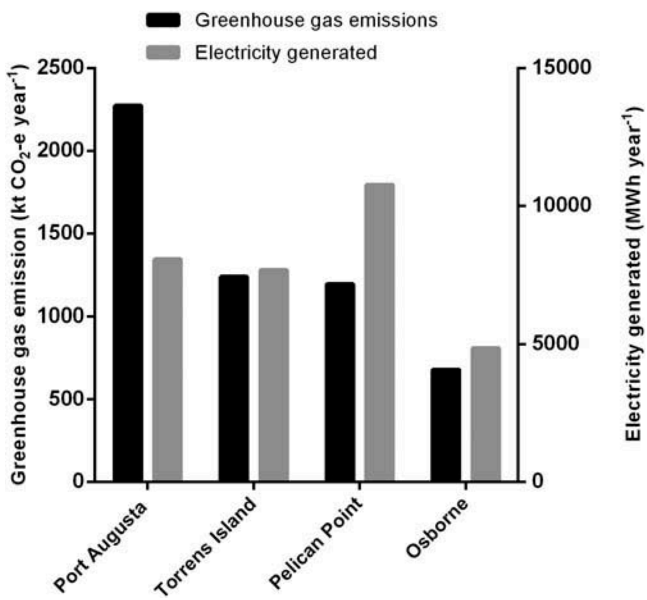

Figure 2. Greenhouse-gas emissions and electricity generated from South Australian baseload generators during the financial year 2012–13. Source: Clean Energy Regulator (2014).

gas plant at Pelican Point commissioned in 2001 delivers electricity at 400 g CO_2-e kWh^{-1} (Clean Energy Regulator, 2014a).

This appraisal suggests that a rational approach to cutting greenhouse-gas emissions would focus on direct replacement of the Port Augusta coal and Torrens Island gas power stations. Instead, South Australian electricity has been getting cleaner through the incremental addition of new generation in the form of wind, with little attention to substitution of the baseload generators.

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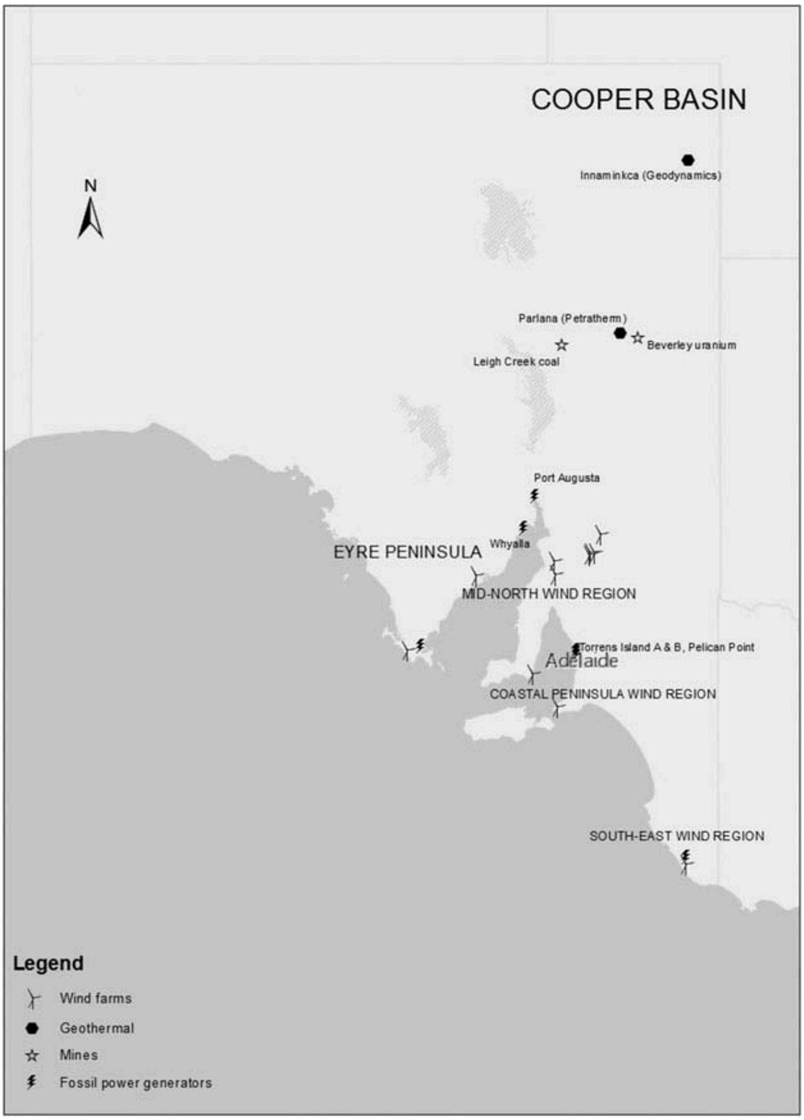

Figure 3. Map of South Australian energy infrastructure and regions.

Reliance on the national electricity market

Since 2003, the contribution of wind power to electricity generation in South Australia has grown to around 27% of total annual electricity supplied to the State (Australian Energy Market Operator Ltd, 2014b). This increased wind generation has come mainly at the expense of generation from existing coal and gas generators which are now run less frequently (Australian Energy Market Operator Ltd, 2014b). Yet despite the rapid increase in wind-generated electricity in the State, South Australia still depends on participation in the National Electricity Market for a reliable supply of electricity.

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The National Energy Market is spatially the largest electricity grid in the world and serves approximately 9.5 million end-use customers (Australian Energy Regulator, 2014). It is a wholesale market for the supply of electricity to retailers and end users in Queensland, New South Wales, the Australian Capital Territory, Victoria, Tasmania and South Australia. Exchange of electricity is facilitated through a pool where the output from all generators in the network is aggregated and scheduled at short (15-minute) intervals, to meet demand across the network. Within the National Electricity Market, electricity is indistinguishable from one generator to another, but network stability concerns mean that there is a need to have generators operating across a wide geographical spread of network nodes. The purpose of the market is to provide efficient and above all, secure electricity supply to meet a dynamically changing electricity demand efficiently (Australian Energy Market Operator Ltd, 2010b).

South Australia's connection with the National Electricity Market supports both reliability of supply and the efficient use of the wind resource, typically exporting power when the output is high and demand is low (as commonly occurs around 04:00) (Australian Energy Market Operator Ltd, 2013b). Over the entire National Electricity Market, wind contributed 4.4% of total electricity generation output in 2013–2014, with 74% coming from coal, and 12% from gas (Australian Energy Regulator, 2014). Despite the ability to sell low-emissions power from wind, South Australia imported 2010 GWh in 2013–2014, six times the quantity exported (338 GWh) (Australian Energy Market Operator Ltd, 2014b).

Trading between adjacent National Energy Market regions relies on high-voltage transmission lines called 'interconnectors', which are used to import electricity into a region when demand is higher than can be met by local generators, or when the price of electricity in an adjoining region is low enough to displace the local supply (Australian Energy Market Operator Ltd, 2010b). The efficient use of South Australia's wind generators relies on two interconnectors to Victoria, as well as substantial transmission infrastructure within South Australia. South Australia's larger Heywood Interconnector (460 MW) was used at 100% capacity for 8.7% of the time in financial year 2012–2013 (Australian Energy Market Operator Ltd, 2013d). A $108-million upgrade of Heywood, to be commissioned in July 2016, aims to accommodate the increase in wind generation that has occurred over the last few years (Electranet, 2013). The recently approved development of Australia's largest wind farm (199 turbines for 600 MW at a cost of ~ $1.3 billion), to be located on the Yorke Peninsula, includes investment in 60 km of undersea cables to transmit the power to load centres, as well as two converter stations (The Ceres Project, 2013). In another study, capital costs of > $900 million were identified for the additional transmission requirements to support development of the extensive Eyre Peninsula wind resource, with annual operational and maintenance costs of > $18 million year^{-1}(Baker & McKenzie, Worley Parsons & Macquarie, 2010).

With the benefit of the National Electricity Market ensuring security of supply and efficient export of surplus generation, the wind sector has driven total greenhouse-gas emissions from South Australia's electricity sector down by one quarter over the last 10 years: from just over 8 megatonnes (Mt) CO_2-e year^{-1} to just over 6 Mt CO_2-e year^{-1} (Australian Energy Market Operator Ltd, 2014c). South Australian electricity now has the second-lowest emissions intensity (> 0.6 kg CO_2-e kWh^{-1}) of the Australian states and territories (Figure 4), having diverged sharply from approximate parity with Queensland, New South Wales and the South West Interconnected System from 2005 until today (the South West Interconnected System is a smaller electricity grid that serves the south-west of Western Australia; it is not part of the

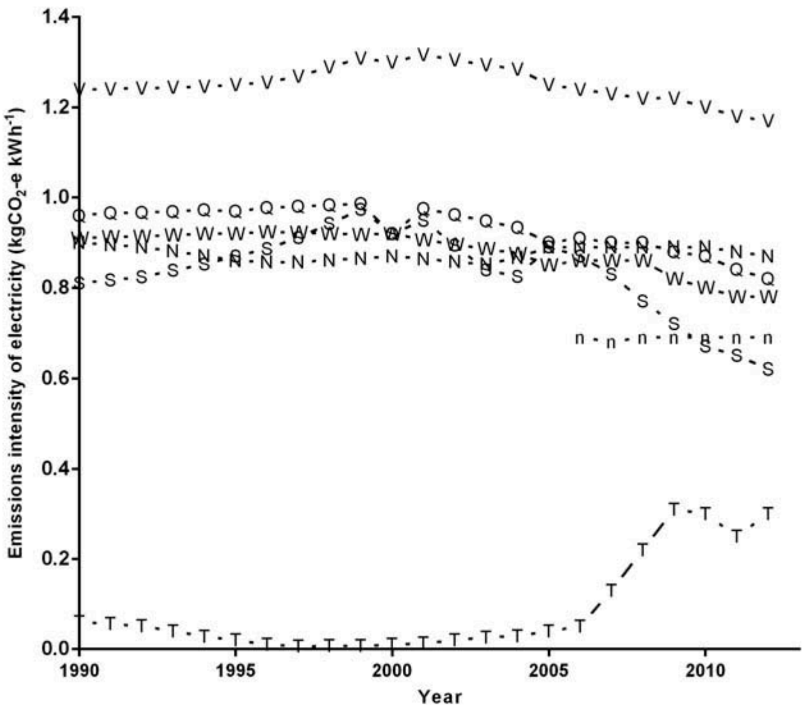

Figure 4. Emissions intensity of electricity for New South Wales (N), Victoria (V), Queensland (Q), South Australia (S), Tasmania (T), Northern Territory (n) and South West Interconnected System (W). Sources: Department of Environment and Heritage Australian Greenhouse Office (2006); Department of Climate Change (2008); Department of Climate Change (2009); Department of Climate Change and Energy Efficiency (2010); Department of Climate Change and Energy Efficiency (2011); Department of Climate Change and Energy Efficiency (2012); Department of Climate Change and Energy Efficiency (2013).

National Electricity Market). Until recent connection with the National Electricity Market, Tasmanian electricity generation had nearly zero emissions due to a predominant supply from hydro-electric generation. It has retained the lowest-emission electricity of any National Electricity Market region (0.2 kg CO_2-e kWh^{-1}), but its relative emissions intensity has risen sharply following the interconnection. Victorian electricity releases approximately 1.2 kg CO_2-e kWh^{-1} due to a dependence on combustion of lignite (brown coal) for electricity supply.

Electricity from wind generation brings challenges related to its variable and intermittent supply. As installed capacity grows, the frequency of sudden changes in wind farm output also increases, rendering the management of power systems and transmissions networks more challenging (Australian Energy Market Operator Ltd, 2013d). A review of the aggregated wind output across three defined geographical regions in South Australia (Mid-North, South-East and Costal Peninsula regions) has found that spatial dispersion of wind generation helps to reduce overall variation in supply, but cannot substantially mitigate it (Australian Energy Market Operator Ltd, 2013d).

The relationship between wind generation and consumer electricity demand, shows 'little correlation... between the aggregate wind output and demand in any region'(Australian Energy Market Operator Ltd, 2011a). At times wind supply can be

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negatively correlated with demand during heat waves (Australian Energy Market Operator Ltd, 2011b). So while the geographic distribution of wind provides some smoothing, the combined variability of wind and consumer demand means that other generation sources are required to respond to rapid changes of supply during periods of low output from wind (Australian Energy Market Operator Ltd, 2013d). For example the largest five-minute change in supply from wind in South Australia was a decrease of 294 MW (Australian Energy Market Operator Ltd, 2013d). To manage this variation, capacity in excess of an entire, large generating unit (280 MW of coal generation from Northern power station) had to be sourced at short notice (Australian Energy Market Operator Ltd, 2013d). Such challenges will increase in size and frequency, and therefore potential economic cost, as wind power supply increases, notwithstanding improving prediction of the availability of electricity from wind (Edis, 2014).

The lack of correlation between electricity demand and supply from wind has another long-term impact on overall system costs: the constrained ability to retire other 'baseload' (in reality, 'dispatchable' (sensu Nicholson, Biegler, & Brook, 2011), generators from service. This is best illustrated by the poor correlation between supply and peak demand. During periods of peak demand, only a small amount of the total installed wind capacity can be relied on firmly to be providing electricity; the Australian Energy Market Operator currently assumes only 8.6% for summer and 7.9% for winter peak demand in South Australia (more precisely, for every MW of wind-generating capacity installed, the Market Operator can only rely on a statistically 'firm' 8.6% of that capacity being available during 85% of the top 10% highest demand periods of the year) (Australian Energy Market Operator Ltd, 2013c). During periods of low wind penetration, the cost impact is minimal. Pre-existing margins of reserve supply, which insure against the sudden loss of fossil-fuel generators, can also cover the wind variability. As wind-power penetration increases, however, the cost implications become ever more daunting. These subsidised, variable generators supply electricity at low marginal costs (e.g. no fuel requirements, no need for permanent staff at the power plant, etc.). This removes potential generating hours for other (baseload) generators with higher marginal costs to sell power and raise revenue. However, little of this dispatchable generation can permanently exit the market (Schaber, Steinke & Hamacher, 2012). Most of it must be retained to cover periods of peak demand when wind is generating little electricity. South Australia has 1473 MW of existing and committed registered generation capacity from wind, but the maximum 'firm' contribution is only 93 MW (Australian Energy Market Operator Ltd, undated). Just 60 MW of coal has been taken out of service (Australian Energy Market Operator Ltd, 2013a) and the market operator has not been advised of any plant retirements within the 10-year planning outlook (Australian Energy Market Operator Ltd, undated). In the 11 years since wind first entered the South Australian market, registered generation capacity increased 62% while peak demand grew only 13% (Figure 5). South Australia has been through a period of system overbuilding (Brook, 2010), exemplifying Tainter's 'complexity spiral' whereby societies become more complex as they attempt to solve problems, with increasing costs and diminishing returns as the complexity increases (Tainter 1990 cited in Palmer, 2014). Perversely therefore, the addition of variable, low marginal-cost generators gradually places upward pressure on overall system costs, in order to keep all necessary generators in the market (Ueckerdt, Hirth, Luderer, & Edenhofer, 2013). There is already evidence of this effect in South Australia (see below).

Initially, the average wholesale price of electricity in South Australia declined from a spot price of > \$80 MWh^{-1} in 2009–2010, to \$42 MWh^{-1} in 2010–2011 (Australian Energy Regulator, 2013). The decline in wholesale price was due in part to wind

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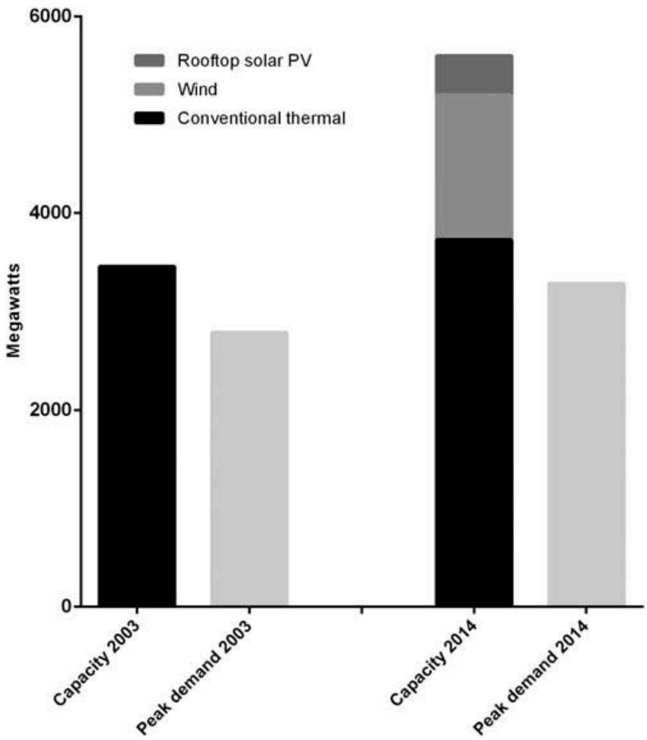

Figure 5. Comparison of registered generation capacity by energy source, expressed as peak installed capacity, with peak demand, 2003 and 2014. Sources: Electricity Supply Industry Planning Council (2003), Australian Energy Market Operator Ltd (2013b, 2014c).

generators sometimes bidding at negative prices because of their ability to earn and sell renewable energy certificates to cover their costs (Australian Energy Regulator, 2012). However in 2012–2013, the South Australian wholesale electricity spot price rose by over 70% (Australian Energy Regulator, 2013). The main driver of this rise was a price spike in autumn. This was unusual; autumn is a period of typically subdued demand, and the event occurred against a backdrop of generally lower demand in the National Electricity Market (Australian Energy Regulator, 2013). The Australian Energy Regulator attributed the price spike to commercial decisions (i.e. cost control) from non-wind suppliers to take some generating capacity offline, which increased the wholesale price of electricity (Australian Energy Regulator, 2013). The Australian Energy Regulator highlighted that the State's reliance on wind-generated electricity had driven down spot prices, thereby eroding the returns for other generators. During this event, South Australia's electricity imports were at their highest for six years (Australian Energy Regulator, 2013). This illustrates system costs rising perversely from increasing reliance on subsidised, variable renewable energy generators whose output is uncorrelated with demand.

Another reliability issue is the provision of necessary ancillary services to the network to ensure systems stability and power quality, such as frequency-control capability and reactive support (Australian Energy Market Operator Ltd & Electranet, 2014). These services are provided by 'synchronous' generators, typically traditional coal and gas generation or hydro (in some states), where electricity is generated through turbines spinning in synch at close to 50 Hz. Ancillary services are a physical requirement of any electrical system and have been necessary since the development of reticulated power (Australian Energy Market Operator Ltd, 2010a). However as shown, increased wind participation displaces traditional (non-hydro) synchronous generators from the market. The associated ancillary services reduce or disappear (Australian Energy Market Operator Ltd & Electranet, 2014).

The rapid influx of wind generation, combined with proposals for over 3000 MW of additional wind generation (Australian Energy Market Operator Ltd, 2014a) spurred the Australian Energy Market Operator and transmission network operator Electranet to 'identify existing limits to secure SA power system operation with high levels of installed wind generation and PV relative to SA electricity demand'(Australian Energy Market Operator Ltd & Electranet, 2014). The report stipulates that the asynchronous generation of wind and solar PV 'by themselves, are not able to provide the required controls to ensure system security'(Australian Energy Market Operator Ltd & Electranet, 2014, p. 2). The report finds that South Australia is able to operate securely with high generation from these sources, even more than 100% of demand, provided at least one of the following two conditions are met: (a) the Heywood Interconnector linking South Australia and Victoria is operational; or (b) sufficient synchronous generation, such as coal or gas thermal generators, is connected and operating on the South Australia power system (Australian Energy Market Operator Ltd & Electranet, 2014, p. 2).

AEMO and Electranet examined the credible event that future market conditions could push the number of synchronous generators in South Australia to zero at any given time, and this coincided with a loss of interconnection. They found:

> Where SA has zero synchronous generation online, and is separated from the rest of the NEM, AEMO is unable to maintain frequency in the islanded SA power system. This would result in state-wide power outage.(Australian Energy Market Operator Ltd & Electranet, 2014, p. 12)

This finding provides insight into how South Australia needs to view variable renewable energy. In electricity terms, South Australia is not, in normal circumstances, an island. The current and future success of integrating variable renewable energy in South Australia hinges on the reliability provided by the rest of the NEM network. In that context, pursuing high penetrations of variable renewables in South Australia, as an end itself, becomes a parochial pursuit more so than a meaningful contribution to decarbonising the National Electricity Market. Proposed solutions to mitigate this risk include payments for minimum synchronous generation to remain online, development of a new market in ancillary services, network augmentation and even curtailing supply from wind and photovoltaics (Australian Energy Market Operator Ltd & Electranet, 2014). This again points to system costs that are not represented by technology-specific metrics such as capital cost or levelised cost of electricity of the renewable generator. Such costs would spread nation-wide were other states to follow South Australia's lead, with each new addition of variable renewable energy eroding the buffer of reliability on which the overall system depends and increasing their implicit operating subsidy.

These phenomena argue strongly that South Australia should plan both for more wind integration, but also on how to move beyond a sole focus on maximising wind capacity. Other forms of low-emissions generation must finish the decarbonisation job that wind has begun, and ultimately meet the role of largest provider. There are no credible plans for decarbonisation of Australian electricity that rely on variable supply alone, so this cannot

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come from merely a wind-plus-solar photovoltaic combination. Studies that have sought to address this challenge have applied varying combinations of energy storage and dispatchable, synchronous 'clean' energy (e.g. burning biomass) to support the variable renewable generators (Australian Energy Market Operator Ltd, 2013e; Elliston, Diesendorf, & MacGill, 2012; Seligman, 2010; Wright & Hearps, 2010). The only real question is just what these constant, dispatchable and synchronous sources of supply should be. In the absence of a large hydro-electric resource, options such as geothermal and large-scale solar-thermal have been the subjects of considerable attention, research and development in South Australia. At a national level, the capture and storage of carbon dioxide from coal combustion has also been the subject of ongoing research. In the subsequent sections, we discuss the progress, realism and prospects of each.

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Carbon capture and storage

The capture and permanent storage of carbon dioxide from power plants offers the potential for continued exploitation of coal resources and existing power-generating infrastructure with reductions of greenhouse gas emissions of 80–90% (Nicholson et al., 2011). With the high dependence on coal both globally and in Australia, carbon capture and storage therefore merits consideration.

A globally important carbon capture and storage project is the US$1.35 billion Boundary Dam in Saskatchewan, Canada. This 110 MW redevelopment of an existing coal-fired generator has the economic advantage of using the captured CO_2 for enhanced oil recovery in a nearby oil field (Sask Power, 2013). In Australia, carbon capture and storage is at various stages of research, development and piloting (CO2CRC, 2014). The most advanced Australian pilot project involved a one-off storage of 65000 t CO_2-e in Victoria's Otway Basin (CO2CRC, 2014). Against annual emissions from Australia's electricity sector of around 2 million t CO_2-e (Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education, 2013), there remains a large gulf between existing development and a meaningful contribution to reducing greenhouse gas emissions.

The unavoidable energy and cost penalties of carbon capture and storage at the plant, as well as the need for substantial new pipeline infrastructure, will pose a barrier to deployment. Hammond, Akwe, and Williams (2011) estimate an energy penalty of between 14 and 30% compared to reference plants without capture, and an increase in the cost of electricity of between 27 and 142%. Commercial deployment would therefore require a carbon price at which alternative clean energy sources, particularly nuclear energy, would likely have clear commercial advantage (Nicholson et al., 2011). An analysis based on an existing 425 MW facility in Australia assumed geo-sequestration 500 km from the site (Hardisty, Sivapalan, & Brooks, 2011). A carbon price of US$75 would be required before the plant operator could justify a retrofit of the plant. Herzog (2011) estimated a required carbon price of US$65 per tonne for an n^{th} plant (in the range of the 5th–10th plant constructed). Based on existing developments, uncertainty of successful deployment and high cost, carbon capture and storage is a poor candidate for meaningful decarbonisation of South Australia's electricity sector.

Geothermal

Geothermal power used for electricity generation in many parts of the world is based on near-surface hydrothermal resources. These resources make use of steam derived from natural aquifers associated with volcanic systems. Unfortunately, Australia lacks this type of easily developed resource (Geoscience Australia & ABARE, 2010). However, Australia has extensive, deep geothermal resources in the form of hot sedimentary aquifers and hot-dry rocks, reported at over 2.5 million petajoules (1 PJ = 10^{15} J), against total primary energy consumption of around 6000 PJ year^{-1} (Geoscience Australia & ABARE, 2010). Of these resources, South Australia has a smaller endowment of hot sedimentary aquifers in the south-east of the State and one of the world's best hot-dry rock resources in the far north of the State. This hot-dry rock resource has been the focus of considerable development and investment (Geoscience Australia & ABARE, 2010).

The challenge of tapping South Australia's hot-dry rock resource in an economically efficient way has been a slow and fraught process. Geothermal drilling has high engineering, financing and non-discovery risks (Sacher & Schiemann, 2010), particularly in Australia where geothermal exploration is in its infancy (Jennejohn, 2009). The necessary temperatures are found at depths of ≥ 5 km (Finger & Blankenship, 2010) in solid, impermeable granites. Circulation of fluids through the heat-bearing rock requires deep drilling and precise directional fracturing to allow fluid to be pumped through the heat source and then recovered via another well, and the use of specialised methods to prevent localised over-cooling and mineralisation of fractures (CSIRO, 2012). Compared to most oil and gas exploration, geothermal formations are hot, hard, abrasive, highly fractured and often contain corrosive fluids (CSIRO, 2012). Drilling is usually difficult, with slow rates of penetration and low lifespan for drill bits (Finger & Blankenship, 2010), and frequent challenges such as loss of circulation of drilling fluid or instability of the well bore itself. Such problems might often cause drilling to take twice as long as conventional drilling, and effectively double the costs (Sacher & Schiemann, 2010). Compared to oil and gas drilling, engineered geothermal projects suffer higher risks for a lower value product (hot water), and therefore an inferior ratio of investment to return (Vollmar, Wittig, & Bracke, 2013). Increased research and development is required, both in exploration and development, but there is 'no panacea'(Jennejohn, 2009).

The practical outcome is that geothermal exploration and development has delivered little financial return for South Australia. After listing to the Australia Stock Exchange in 2002, the company *Geodynamics* successfully commissioned a 1 MW-electric (MWe) demonstration geothermal plant in 2013, which has now ceased operations. The major joint venture partner, *Origin Energy*, departed in 2013 (Spence, 2013). *Geodynamics* is now seeking funding to develop a 5–10 MWe facility selling electricity to gas producers in the Cooper Basin (Geodynamnics, 2013). Against a baseload electricity supply of around 3000 MW in South Australia alone, the shortfall of much greater than two orders of magnitude is obvious. *Geodynamics* acknowledges that the development of geothermal resources remains a long-term challenge in South Australia (Spence, 2013). Another lead developer, *Petratherm*, is now targeting a 3.5 MW development to supply the off-grid Beverley uranium mine. Further development plans comprise 300 MW of gas and wind generation, followed by another 300 MW of large-scale geothermal and solar (Petratherm, 2011). The project is designed to enable the financing of the geothermal resource (Petratherm, 2011). Investment, research and development in geothermal will likely continue in South Australia, and globally. Based on progress to date it remains unclear whether geothermal will proceed to play the medium-term decarbonisation role touted by the Australian Government over the last five to 10 years (Australian Government Treasury, 2011; Government of South Australia, 2007), but its prospects for being a major solution to displacement of coal- and gas-fired electricity seem a distant hope at best.

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Solar-thermal with storage

The growth rate of solar power over the last few years, both globally and in Australia, has been substantial. In 2013, slightly more peak global capacity (i.e. 'nameplate' capacity, which does not account for average output or 'capacity factor') was installed in solar (36.5 GW) than in wind (35.5 GW) (Pernick, Wilder, & Belcher, 2014) with annual average growth for the 10 years to 2012 of > 50% (Observ'ER, EDF & Fondation Energies pour le Monde, 2013). In the global context, solar has grown from a tiny initial base of 0.01% to a more substantive 0.5% (i.e. > 50-fold increase) of global electricity supply from 2002 to 2012 (Observ'ER, EDF & Fondation Energies pour le Monde, 2013). With over a million solar photovoltaic installations in Australia alone, solar now provides > 4 GWh of electricity year^{-1} (Clean Energy Regulator, 2014a), or approximately 1–2% of Australia's current annual electricity consumption.

In South Australia, the proportional uptake of solar photovoltaic is greater than the national average, with 560 MW of registered capacity providing over 5% of electricity annually (Australian Energy Market Operator Ltd, 2014c) from over 20% of registered residential customers. The rate of photovoltaic installation has, historically, risen and fallen with the availability, and periodic withdrawal, of subsidies including direct financial assistance, renewable energy certificates with multipliers, and generous feed-in tariffs (Figure 6). With the removal of the multiplied value of the renewable energy certificates and more recently, the feed-in tariffs, the month-to-month installation rate of solar photovoltaic has fallen to a mean of approximately 5600 kW for the 10 months to November 2014. This is against a mean monthly installation rate of approximately 12,600 kW for the 36 months to January 2014. (Clean Energy Regulator, 2012, 2014c, 2014d) (Figure 6).

Nonetheless, further reductions in the price of photovoltaic systems in the medium to long term, with the potential addition of cost-effective distributed storage, could support continued expansion of solar photovoltaics in South Australia. The potential disruption of the electricity retail market from high photovoltaic penetration has been explored in detail by a collaboration of industry experts (Graham et al., 2013) and modelled to devise a 100% renewable-energy system for Australia (Australian Energy Market Operator Ltd, 2013e). In both cases, the need for large, dispatchable, utility-scale electricity generation is reduced, but remains. The long lead times to these outcomes reinforces the need to hasten action to replace fossil-fuel baseload, not delay it. Detailed recent analysis by Palmer (2014) also suggests that the broadly unappreciated limitation and difficulties presented by high penetrations of solar photovoltaics to networks, along with questionable energy return on investment, might work against such high penetration scenarios.

It is certain that distributed solar photovoltaics will play an increasing role in South Australia, and it is equally certain that utility-scale, dispatchable, clean electricity will remain a requirement in the long term. Such a service might be conceivably provided by concentrating solar power (used interchangeably here with 'solar-thermal') with the addition of large, external energy storage. Globally, concentrating solar power has experienced a much lower rate of uptake than photovoltaics. Progress has been intermittent since the early 1980s, with growth tied directly to strong incentives, particularly in the USA and Spain (Hernández-Moro & Martínez-Duart, 2012). With the highest average direct solar radiation of any continent (Geoscience Australia & ABARE, 2010), Australia has the greatest solar resource potential in the world. In raw terms, the annual solar radiation reaching Australia is 10,000 times our total primary energy consumption (Geoscience Australia & ABARE, 2010), but such figures can be misleading. Areas

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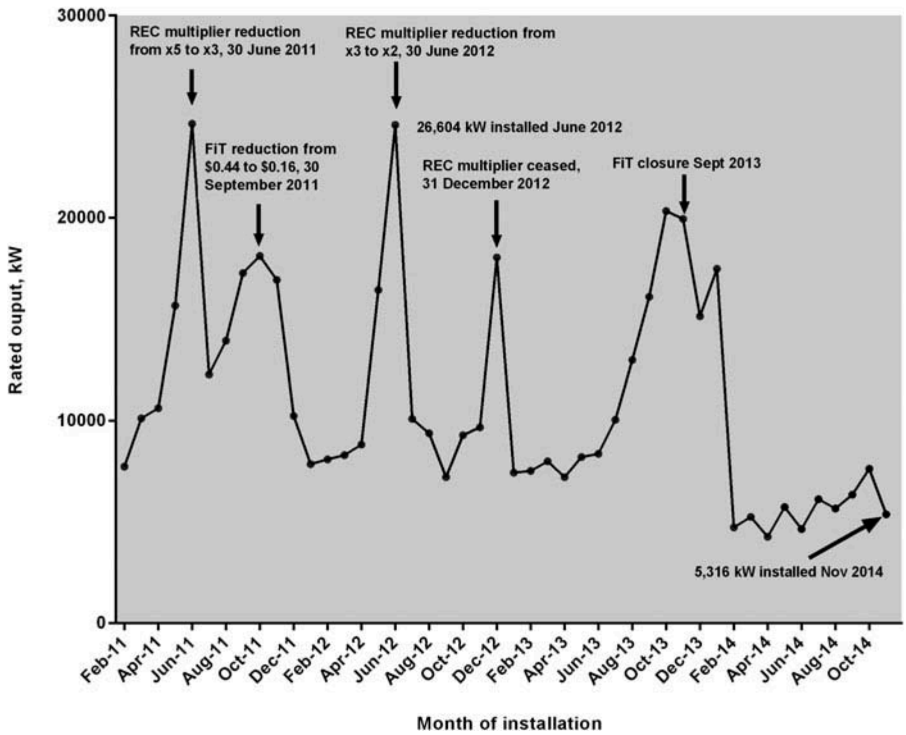

Figure 6. Monthly solar photovoltaic installation in South Australia (kw month^{-1}) from February 2011 to November 2014 showing reduction and withdrawal Renewable Energy Certificate (REC) multipliers and Feed in Tariff (FiT). Sources: Clean Energy Regulator (2012), Clean Energy Regulator (2014c).

with the necessary technical characteristics for large-scale solar power must be overlaid with other relevant limitations of site suitability such as proximity to load, high-capacity transmission lines, and auxiliary fuel, as well as exclusions based on existing land use. When accounting for these real-world limitations, the size of the area in Australia that is suitable for potential development of utility-scale solar could be reduced by as much 99% (Dawson & Schlyter, 2012).

Even taking such constraints into account, Australia has many potentially suitable sites for developing utility-scale solar energy (Dawson & Schlyter, 2012; Geoscience Australia & ABARE, 2010), including in South Australia's Port Augusta region (Wyld Group & MMA, 2008) (Figure 3). Home to the State's most polluting coal-fired power stations (emissions < 2.2 million t CO_2-e in 2012–2013; Clean Energy Regulator, 2014b), it is unsurprising that Port Augusta has become the focus of lobbying in favour of solar-thermal development. A 2012 report from the not-for-profit lobby group *Beyond Zero Emissions* (Beyond Zero Emissions, 2012) proposed the replacement of the coal-fired power plants in Port Augusta with a hybrid renewable solution combining wind and solar–thermal with storage technology. A select committee of the South Australian Parliament was formed to investigate the replacement of the Port Augusta coal-powered stations by a concentrated solar–thermal power station (Select Committee on the Port Augusta Power Stations, 2013). The interim report states that high and uncertain costs remain the major barriers to solar–thermal technology (Select Committee on the Port Augusta Power Stations, 2013). The costs

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provided were on the basis of a proposal including only 5 hours of energy storage under the assumption that capacity factor of 50% is sufficient (Beyond Zero Emissions, 2012). This would represent a diminished capability in reliable electricity generation in South Australia compared to the existing coal plants.

The challenge for utility solar power with on-site energy storage (cf. the now widespread rooftop solar photovoltaic units with output that is both cyclical and variable) is that replacing coal-fired generation is likely to be cost-prohibitive under anything but a policy of high carbon pricing (Wyld Group & MMA, 2008). Previous professional economic and engineering assessments provided little support for the development of solar-thermal in South Australia (Wyld Group & MMA, 2008). Lovegrove et al. (2012) indicated that for utility-scale solar, the lowest-risk technology at the most favourable site (i.e. parabolic trough at Longreach in Queensland) would have a levelised cost of electricity of \$252 MWh^{-1}, compared to a volume-weighted average price of \$74 MWh^{-1} for South Australia in 2012–2013 (Australian Energy Regulator, 2013). Initial assessments by Alinta Energy were similar, stating that subsidies of \$200–400 MWh^{-1}, or capital contribution of at least 65% of construction costs, would be required (Dimery, 2012).

A \$2.3 million feasibility study, co-funded by Alinta and the Australian Renewable Energy Agency, has considered exclusive solar-thermal generation and a coal–solar hybrid option for Port Augusta (ARENA, 2014; Dimery, 2012). Based on the findings of the early study's preliminary cost estimates for a 50 MW, stand-alone solar-thermal plant of \$15,926 kW^{-1} installed, and a levelised cost of electricity of \$258 MWh^{-1} (Alinta Energy, 2014a), commercial development would require long-term offtake agreements with ≥1 customers to purchase the electricity generated from the concentrated solar power facility (Alinta Energy, 2014a, p. 19). According to the potential proponent, these costs are currently prohibitive (Alinta Energy, 2014b).

The commercial feasibility of this option will be studied further 'with the due diligence it warrants' to provide information for potential investors 'should the cost of technology or regulatory environment change' (Alinta Energy, 2014b). This detailed consideration might provide a more positive assessment of the economic case for stand-alone solar-thermal. Some assessments suggest that solar technologies will become cost-competitive by 2020 and beyond (Hernández-Moro & Martínez-Duart, 2012, 2013; Reichelstein & Yorston, 2013; Viebahn, Lechon, & Trieb, 2011) and others identify the many specific avenues of research, development and learning that might be the actual drivers of this reduced cost (Khan, Dauskardt, Geyer, Pearsall, & Meerfeld, 2009; Lovegrove, 2013; Lovegrove et al., 2012; Nithyanandam & Pitchumani, 2014).

In Australia, there is evidence that the outlook for solar has been overly optimistic. In 1994, an analysis suggested that the price and availability of solar–thermal in Australia could make it highly competitive, possibly before the year 2000 (Mills, Monger, & Keepin, 1994). More recently, the 2012 report prepared for the Australian Solar Institute acknowledged that there has been some progress, but not as much as previously suggested (Lovegrove et al., 2012). The Australian Solar Institute recommends an early focus on smaller-scale deployment in market sectors where the cost-revenue gap for solar is smaller than in the market for grid-connected electricity supply. Suggested options include off-grid applications that compete with diesel generation and also hybrid applications with existing fossil-fuel technologies (Lovegrove et al., 2012). This suggests many smaller systems of around 50 MWe each to reduce the risk of individual projects failing, broaden the deployment and industry 'know how', and incrementally build relationships and experience with incumbent stakeholders in Australia's energy market. Clearly, it will be a slow and difficult path.

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Nuclear power

Given the problems identified in the above review, we argue that a compelling case to close South Australia's aging fossil fuel-generated baseload can only be formed if the solution is a technology that matches the reliability of the incumbent generators (unlike wind or photovoltaics), is more cost-competitive than solar-thermal, and more mature than engineered geothermal or exotic forms of chemical energy storage. This could call for the exploitation of one of South Australia's other impressive energy resources; nuclear power might represent the technology that most effectively answers the challenge (Brook & Bradshaw, 2015).

In terms of performance and reliability, nuclear power is not subject to the speculation and uncertainty associated with unconventional geothermal technology or solar–thermal with heat storage. A commercially mature technology with substantial global experience, there are over 437 nuclear reactors in operation in over 30 nations, today providing around 11% of total global electricity supply and over 40% for jurisdictions including Sweden, France and the Canadian province of Ontario (World Nuclear Association, 2015). Where the largest enhanced geothermal development worldwide is the 5 MW proposal in South Australia, nearly 75,000 MW (i.e. 15,000× more) of nuclear generation is currently under construction, mainly in China, Russia, India and South Korea (World Nuclear Association, 2015). Despite some well-documented miscalculations in terms of cost and delivery times at various points in the history of the nuclear power industry (Kessides, 2012), nuclear deployment remains the only pathway, with the exception of geographically constrained, large hydro-electricity schemes, to have successfully demonstrated the decarbonisation of electricity supply for large, developed nations (Table 1). For example, the Canadian province of Ontario, with a population of nearly 14 million people, delivers electricity at a maximum of \$0.135 kWh^{-1} to residential customers (Ontario Electricity Board, 2014), with greenhouse gas emissions rarely exceeding 75 g CO_2-e kWh^{-1} (Gridwatch, 2014). This has been achieved with a supply mix of approximately 50% nuclear, with the balance provided by hydro, gas and wind power; all coal has been retired.

Rapid Organisation for Economic Co-operation and Development (OECD) nuclear-build programs left a legacy of reliable, cheap and clean electricity. Between 1971 and 1993, Ontario commissioned nearly 13 GWe of new nuclear generating capacity (World Nuclear Association, 2014b). Sweden commissioned 9.5 GWe in the 22 years between 1972 and 1985(World Nuclear Association, 2014f) and France commissioned over 63 GWe in the 20 years to 2000 (World Nuclear Association, 2014e). It is therefore evident

Table 1. Comparison of electricity supply by greenhouse-gas intensity (kg CO_2-e kWh^{-1}) and price (AU\$ MWh^{-1}) in nations with varying percentage penetration of nuclear electricity. All data from the International Energy Agency (2012), except the Australian price (Australian Energy Market Commission 2013, p. 12). Prices adjusted for purchasing power parity based on Organisation for Economic Cooperation and Development (2014).

Nation	Emissions intensity (kg CO_2-e kWh^{-1})	% nuclear	Residential price (AU\$ MWh^{-1})	Industry price (AU\$ MWh^{-1})
Australia	847	0	271	-
Denmark	385	0	450	\$127
Germany	468	23	282	\$126
Switzerland	27	40	269	\$156
Sweden	22	40	241	\$101
France	77	76	157	\$102

that the construction of nuclear technology itself poses no obstacle to the rapid retirement of fossil baseload.

It is somewhat perplexing then that among OECD nations and now many developing nations, Australia actively refuses the use and development of nuclear power (Australian Nuclear Science and Technology Organisation, 2014). This is despite Australia's involvement in mining and export of uranium fuel for foreign reactor programmes, as well as highly developed nuclear-research and nuclear-medicine sectors, and the presence of an established regulatory body. There have been several governmental and non-governmental processes for modelling, forecasting or proposing electricity generation mixes for Australia at different milestones to 2050 (Australian Energy Market Operator Ltd, 2013e; Australian Government Treasury, 2011; Elliston et al., 2012; SKM & MMA, 2011; Stock, 2014; Wright & Hearps, 2010), but none to date has openly considered the potential contribution from nuclear power.

Wright and Hearps (2010) rather dubiously justify the exclusion based on the 2020 timeframe of their energy plan and that nuclear power could not be implemented within 10 years. Another model commissioned by the Australian Government simply assumed that, beyond coal and gas, there was 'no other viable thermal power alternative' (SKM & MMA, 2011). Likewise, Elliston et al. (2012) specifically excluded large coal, gas and (arbitrarily) nuclear plants, and the Australian Energy Market Operator Ltd (2013) explicitly excluded nuclear based on the terms of reference provided by the Department of Climate Change and Energy Efficiency. In an apex moment for circular reasoning, a report from the Climate Council explained that 'Nuclear is not considered in this report because of the focus of future options for the Australian electricity sector vis-à-vis fossil fuels and renewables'; quite literally, nuclear is not being considered because nuclear is not being considered (Stock, 2014, p. i). However, these exclusions run contrary to a 2006 bi-partisan Federal Parliamentary Committee report that found that nuclear power represents the only current reliable and proven technology to reduce emissions while supplying the world's high energy demand (House of Representatives Standing Committee on Industry and Resources, 2006).

More recent considerations of nuclear power by the Australian Government have been sporadic. The *Australian Energy Projections* (Syed, 2012) duly references the highly competitive cost finding of the *Australian Energy Technology Assessment* (Bureau of Resources and Energy Economics, 2012), yet follow this solely with scenarios that have zero contribution from nuclear power generation to 2050, without justification. The *Draft Australian Energy White Paper* (Department of Resources, Energy and Tourism, 2011) expressly excluded nuclear and stated that the technology is not permitted under the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999* (Section 140A: No approval for certain nuclear installations).

The Australian Energy Technology Assessment (Bureau of Resources and Energy Economics, 2012) included both gigawatt-scale nuclear and small modular nuclear power. Even though the 2013 update to this model included a 'special emphasis' on operational and maintenance costs and improvement rates for all wind, solar-thermal and solar photovoltaic technologies (Syed (BREE), 2013, p. 26), no comparable data are modelled for understanding future costs for nuclear technologies despite the availability of recent, credible assessments (Abdulla, Azevedo, & Morgan, 2013; Chen et al., 2013; Nuclear Energy Agency, 2011; Rosner & Goldberg, 2013). This partial review instead generated a questionable output, in which small modular reactor technology (which is yet to be deployed and is intended to be factory manufactured), was projected with no decline in

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price to 2050 (Syed (BREE), 2013), again without justification nor reconciliation against the fact that all other alternative-energy technologies were modelled to include sharp cost reductions over time.

Nuclear power in South Australia

To explore the potential role of nuclear power for South Australia, a 2012 report compared the hybrid wind–solar proposal for replacing the Port Augusta power station to a 'reference' nuclear solution, and then these options were evaluated against thirteen economic, environmental and social criteria (Heard & Brown, 2012). This assessment found that for nearly half the capital cost, the nuclear option delivered more electricity with superior reliability and dispatchability (power on call), allowing more direct displacement of the most emissions-intensive coal power stations from South Australia's generation profile. The electricity provided was also cheaper than that provided by the solar–thermal generator by at least \$112 (to \$160) MWh^{-1} (competitive with estimates for newly commissioned modern coal power) and required 90% less land and 340,000 tonnes less steel, with at least double the lifespan of the infrastructure (Heard & Brown, 2012).

Despite the demonstrated economic and sustainability superiority of nuclear power in large-scale decarbonisation (Heard & Brown, 2012; Hong, Bradshaw, & Brook, 2014; Nicholson et al., 2011; Syed (BREE), 2013), any economic advantage for nuclear in the Australian setting hinges on longer-term assessments of national interest. While the cost advantage against comparable renewable generation is large, high up-front investment renders nuclear unpalatable compared to fossil fuels in liberalised energy markets that have come to prioritise short-term investor returns (Owen, 2011a, 2011b). Deployment of nuclear energy in Australia is unlikely to thrive without a strong policy shift, either related to reduction of greenhouse-gas emissions, air pollution or simply planned renewal of energy infrastructure.

Since 2003, overall construction costs for nuclear build have escalated in line with all types of large-scale engineered projects including (but at a greater rate than) gas and coal plants (Deutch et al., 2009). Early indications from new build programs in OECD nations presents a mixed picture of cost, ranging from AU\$5200 kW^{-1} (AREVA European Pressurised Reactor in Flammeville, France) (World Nuclear Association, 2014a) to AU \$7650 kW^{-1} (AREVA European Pressurised Reactor in Olkiluoto, Finland) (World Nuclear Association, 2014d). Delivery ranges from behind schedule and over budget (e.g. Westinghouse AP1000 in Georgia, USA) (Henry, 2015) to substantial time and cost overruns (e.g. Olkiluoto, Finland). These nascent OECD build programs are for new reactor designs with advanced safety features, expected capacity factor of > 90% and a design lifespan of 60 years, compared to 30–40 year design lifespans of earlier generations of nuclear reactors.

It is the rapidly developing Asian markets, particularly the substantial build program of China, that provide a more reliable indicator of the mature construction costs of nuclear new build (Nicholson et al., 2011). Generation III reactors such as the AREVA European Pressurised Reactor under construction in Taishan, are scheduled to be brought online within 40 months (AREVA, 2013), with reported costs of approximately \$2500 kW^{-1}. Construction of four AP1000 reactors at Sanmen is on schedule at an estimated cost of \$2615 kW^{-1} (World Nuclear Association, 2014c) and Korean vendor KEPCO have sold turn-key nuclear development to the United Arab Emirates at a competitive price of \$3643 kW^{-1} (Nicholson et al., 2011). With seven reactors currently under construction and another 183 reactors on order or planned (World Nuclear Association, 2015),

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Australia's late entry to nuclear power may reap the benefit of a globally mature and competitive market in generation III reactor construction.

Despite the glacially slow progression in the future planning of South Australia's energy portfolio, many stakeholders in South Australia, and nationally, appear keen to increase serious consideration of nuclear energy. For example, *Business SA* recently favoured informed debate on the benefits, costs and risks of establishing a nuclear industry in the State (Business SA, 2014). Likewise, the Academy of Technological Sciences and Engineering concluded that nuclear is a viable candidate to replace coal-fired power stations and that there was no reason to omit its consideration in the generation mix (The Academy of Technological Sciences and Engineering, 2013). Even academics are turning public opinion. University of Adelaide climate scientist Tom Wigley recently joined international colleagues in an open letter to environmental organisations calling for an embrace of nuclear power to tackle climate change (Hansen, Caldiera, Emanuel, & Wigley, 2013). An international group of 75 conservation scientists signed a similar letter in 2015, with a focus on the benefits of nuclear power for biodiversity preservation (http://conservationbytes.com/2014/12/15/an-open-letter-to-environmentalists-on-nuclear-energy). Professor Ove Hoegh-Guldberg, Director of the Global Change Institute at the University of Queensland, issued a public statement calling for the deployment of nuclear power as 'the one real option to significantly reduce global carbon emissions'(Hoegh-Guldberg & McFarland, 2014). Random polling of > 1200 South Australians recently showed much higher support for nuclear power (48%) than opposition (32.6%), with strong support outweighing strong opposition (29 and 20%, respectively) (South Australian Chamber of Mines and Energy, 2014). Such growth in visible support for the consideration of nuclear power might have been influential in the decision by South Australian premier Jay Weatherill in early 2015 to call a Royal Commission to investigate the potential for South Australia to expand activity in the nuclear-fuel cycle.

Barriers to nuclear deployment

The deployment of nuclear power in South Australia still faces many barriers. Unlike the technical, reliability and (relatively much higher) cost barriers faced by geothermal and solar-thermal, a nuclear power sector will need to develop the necessary licensing and regulatory arrangements, as well as obtain a skilled workforce and garner majority support by the public. A previous Government assessment suggested 10–20 years would be required between the establishment of a national strategy and the commencement of reactor operations (Commonwealth of Australia, 2006). Getting such a process underway requires open, Government-led public discussion to reach sufficient community consensus, especially regarding the management of spent nuclear fuel and understanding of risks and benefits.

Aside from depending on proactive political leadership, the pace at which a nuclear sector could develop likely depends on the extent of South Australia's international commitment to facilitate technology, knowledge, education and skills transfers into Australia (Heard & Brown, 2012). International precedent set by the partnership between the United Arab Emirates and South Korea has once again demonstrated the rapid up-scaling of nuclear electricity-generation capacity, with 5600 MWe contracted in 2009 to be staged into operation by 2020 (World Nuclear Association, 2014g). The World Nuclear Association recently reinforced that rapid deployment pathways might be open to South

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Australia because of its well-equipped political, legal and educational infrastructure (Agneta Rising cited in Eckermann, 2014).

Opportunities for South Australia also lie in the most innovative end of nuclear technology. Development concepts based on generation IV fast-reactor technology, coupled with full fuel recycling (collectively called 'integral fast reactors'), could overcome traditional objections to both spent nuclear fuel storage and nuclear power generation (Brook & Bradshaw, 2015), thereby economically bootstrapping the deployment of new clean energy generation.

Previously, proposals for economic development through the acceptance of spent fuel by Australia have been predicated on long-lived hazardous waste that requires isolation for hundreds of millennia (Commonwealth of Australia, 2006; The Nuclear Fuel Leasing Group, 2006). Emphasis is placed on remote locations, favourable geology and political stability as key competitive advantages for Australia (Business, 2014). The emphasis on these competitive advantages arguably serves to reinforce perceptions of spent fuel acceptance as hazardous and with an essentially infinite timeline for management – a major point of objection and political and social opposition.

By contrast, integral fast-reactor technology recycles > 99% of spent nuclear fuel for zero-carbon electricity generation, providing 150 times more electricity from uranium fuel compared to the current generation of reactors (Till & Chang, 2011). The technology provides major improvements in safety related to the use of metal fuel and metal coolants, which make accidental meltdowns a physical impossibility, and ensure indefinite passive removal of decay heat in the event of emergency shutdown (Till & Chang, 2011). The small quantity of eventual waste produced by integral fast reactors has a half-life of approximately 30 years. Secure storage is thus required for about 10 half-lives (only 300 years) after which activity is reduced to the levels of natural uranium ore. The engineering requirements for safe storage are therefore considerably simpler, with existing United States Environmental Protection Agency standards met *a priori* at many sites (Till & Chang, 2011).

With dry-cask storage now approved in the USA for up to 100 years (Feiveson, Mian, Ramana, & Hippel, 2011), it would be possible to couple a committed integral fast reactor program with the establishment a multinational spent-fuel storage bank based on longer-term storage using rolling review and approval of established, above-ground storage technologies (Werner, 2012). These characteristics could render integral fast-reactor development a game-changing economic concept for South Australia. South Australia could access the huge, already-established market in acceptance of spent nuclear fuel (valued in 1998 at $200 billion) (Access Economics, 1998) with a known, understood and beneficial end-use for the material. Using recycling and establishing simpler engineered storage for a smaller quantity of shorter-lived waste would unblock the back end of the nuclear fuel cycle for international customers. That in turn would facilitate more rapid global growth in nuclear development with subsequent benefits to South Australia via growth in uranium exports.

Each integral fast reactor development (an installation of twin, compact power modules) would add 622 MWe of dispatchable, zero-carbon generation for either consumption or export to the National Energy Market. This could improve South Australia's role in meeting the 50% projected increase in Australian electricity demand to 2050 (Syed, 2012). Sufficient integral fast-reactor units to displace all coal and gas generation in South Australia (3500 MW) would require a throughput of a mere 150 t year^{-1} of recycled spent fuel or depleted uranium tails, of which just 10 t year^{-1} would be fissioned for energy (based on figures in Carmack et al., 2009). Taking custody of even a modest quantity of spent nuclear fuel would secure South Australia's energy independence for many centuries. The small size of the generating units (311 MWe) means additional transmission and network requirements would be negligible.

Both the reactor and fuel-recycling technologies have been extensively and successfully demonstrated over 30 years of operation and development at the Argonne National Laboratories in the USA (Till & Chang, 2011). The integral fast reactor is commercially available as the PRISM reactor from GE-Hitachi (GE Hitachi, 2014). The design, layout and operations of the PRISM reactor, including the various fuel configurations, have been described in detail (Triplett, Loewen, & Dooies, 2010) as has the coupled fuel-recycling technology (known as pyroprocessing) (Argonne National Laboratories/ US Department of Energy, Undated; Till & Chang, 2011; Williamson & Willit, 2011; Yoo, Seo, Kim, & Lee, 2008) and the characteristics of the different metal fuel options (Carmack et al., 2009; Crawford, Porter, & Hayes, 2007). All technical characteristics of the technology have been summarised in non-specialist formats (Archambeau et al., 2011; Blees, 2008), and the requirements for eventual waste storage have been elaborated in persuasive technical detail (Till & Chang, 2011).

Conclusions

South Australia will not meet its obligations for deep and permanent cuts in emissions from electricity through a continued, single-minded focus on the expansion of wind generation. The relative success of wind integration to date (27% in South Australia, 3–4% across the entire National Energy Market) is a credit to the proactive approach South Australia has taken, and the approach of seeking efficient market and regulatory solutions to the challenges posed by wind generation. This should continue. While further wind developments are likely to provide an efficient means of cutting emissions within South Australia and as an export to the National Electricity Market, there is no answer to the inherent limitation of strongly correlated and variable supply that is uncorrelated with demand. With further installation, wind penetration will run into ever-firmer upper limits of supply, at which point-efficient market solutions to managing this limitation are exhausted, the costs to the overall system become too high, and the strongly correlated peak supply pushes prices down to the point where wind would cannibalise its own share of the market. The absence of vital ancillary services from the non-synchronous wind generation reinforce that this source of generation is basically unsuitable for high penetration. Therefore, a dispatchable, synchronous source of low-emissions electricity is required.

Exploration and development of the hot-dry rock geothermal resource has to date served only to reinforce the difficulty in converting this large, raw, but difficult-to-access energy resource into a large, reliable and cost-effective supply of electricity. Solar-thermal offers a possible solution, but has a nascent global record of successful delivery of dispatchable electricity and so many uncertainties remain about its capacity to compete at large scales. Australian industry advocates acknowledge the long road ahead to commercial competitiveness with fossil fuels and there is no answer to the increased consumption of land and materials this option demands, as well as the potentially shorter lifespan. Solar-thermal offers a pathway of great uncertainty at a time where response to climate change demands greater certainty.

Contrasting these, nuclear power offers a mature technology from a competitive global market of suppliers with a solid track record of delivering deeply decarbonised and reliable electricity supply in concert with other technologies. Here we have argued that a commitment to the deployment of the most advanced nuclear technologies provides South Australia with a means to upscale low-emission baseload generation rapidly while earning revenue

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through the establishment of a new industry in the custody and recycling of spent nuclear fuel. Progress in the development of nuclear-energy sector remains hampered by a lack of political will that seems increasingly out of step with South Australia's business, scientific and academic communities, as well as the public at large. South Australia needs to open the way for serious considerations of the deployment of nuclear energy and this must be led by government. Bi-partisan support should be achieved on the basis of the inarguable interest represented by a new, service-oriented industry that also provides future-proofing development of low-emission electricity generation while offering the ultimate in fuel security and energy density. These developments can take place alongside, not in place of, the further development of South Australia's wind resource.

For too long the perceived political risk of nuclear energy has been treated as less tractable to change that the technical and economic limitations of immature, low-emission alternatives. It is time for a reversal in approach. Continuing South Australia's response to the challenge of climate change and energy demands political leadership on the pathway of greater technical and economic certainty provided by nuclear technology. We contend this pathway can now be taken with the confidence that South Australia is ready to follow.

Disclosure statement

No potential conflict of interest was reported by the authors.

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