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A zero-carbon, reliable and affordable energy future in Australia

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A B S T R A C T

Australia has one of the highest per capita consumption of energy and emissions of greenhouse gases in the world. It is also the global leader in rapid per capita annual deployment of new solar and wind energy, which is causing the country's emissions to decline. Australia is located at low-moderate latitudes along with three quarters of the world's population. These factors make the Australian experience globally significant. In this study, a fully decarbonised electricity system is modelled together with complete electrification of heating, transport and industry in Australia leading to an 80% reduction in greenhouse gas emissions. An energy supply-demand balance is simulated based on long-term (10 years), high-resolution (half-hourly) meteorological and energy demand data. A significant feature of this model is that short-term off-river energy storage and distributed energy storage are utilised to support the large-scale integration of variable solar and wind energy. The results show that high levels of energy reliability and affordability can be effectively achieved through a synergy of flexible energy sources; interconnection of electricity grids over large areas; response from demand-side participation; and mass energy storage. This strategy could be a rapid and generic pathway towards zero-carbon energy futures within the Sunbelt.

1. Introduction

Solar photovoltaics and wind turbines comprised about 64% of global annual net new capacity additions in 2019 [1] and nearly 100% in Australia. Rapid deployment of solar and wind energy presents the most promising prospect for tackling climate change through the adoption of renewable energy in the electricity sector, along with electrification of heating, transportation and industry to displace fossil fuels. However, solar and wind energy are weather-based and hence are variable and uncertain in nature. Consequently, there are a range of technical challenges associated with the large-scale integration of variable renewable energy such as higher ramp rates, lower minimum generation levels, more frequent cycling and capacity inadequacy.

Energy storage is key to a reliable and affordable renewable energy future. Jacobson et al. [2,3] modelled thermal energy storage to support 100% wind, water and sunlight in the United States and the world's energy systems. Phase-change materials were included to store high-temperature heat from concentrated solar power, which was then used to drive steam turbines to generate electricity when needed. Hot water, chilled water, ice and underground rocks were used to store low-temperature heat from solar thermal collectors and electricity to meet heating and cooling demand for those times when energy supply and demand were not balanced. Demand response was also modelled where 15% of residential and commercial, 85% of transport and 70% of industrial loads were assumed to be flexible – providing up to 8 h of load shifting. Connolly et al. [4] and Lund et al. [5] investigated large-scale integration of solar and wind energy in Europe using a Smart Energy System solution. The electricity, heating, cooling and transport sectors were coupled through power-to-gas, where solar and wind energy were used to produce methane, methanol and dimethyl ether mainly for transport fuels, but also for electricity and heat generation. In this way, variable renewable energy can be stored in the form of electrofuels in gas and oil storage facilities, which are largely available today at low cost. Additionally, instead of being burned directly, biomass was utilised as a carbon source to produce bio-electrofuels using gasification and hydrogenation processes. Ram et al. [6] and Bogdanov et al. [7] modelled the energy transition required to decarbonise global power, heat, transport and desalination. Lithium-ion batteries were used for short-term energy storage i.e. energy day-night shifting. Power-to-gas and compressed air energy storage were utilised for medium-term to long-term energy storage to cope with seasonal variations of

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renewable energy resources. About 5% of electricity demand and more than 10% of heat demand were powered by synthetic natural gas through power-to-gas. Further, about 15% of heat demand was met by thermal energy storage, including industrial heat (medium- to high-temperature) and space and water heating (low-temperature). In the above studies, there was a general consensus that solar and wind energy would be the main energy sources, which constituted about 72%–95% of the primary energy supply. However, these studies differed in energy conversion and energy storage technologies utilised for balancing variable solar and wind energy, including thermal energy storage, oil and gas storage (power-to-gas), and stationary battery storage.

In this study, by contrast, the variability and uncertainty of renewable energy are addressed using different energy storage technologies, namely short-term off-river energy storage (STORES) and distributed energy storage (DES). STORES refers to closed-loop pumped hydro systems with large hydraulic head, which can be located away from rivers and hence offers vast opportunities to access cost-effective mass energy storage. Pumped hydro constitutes 97% (rated power) or 99% (storage capacity) of the global energy storage market [8]. A first-of-its-kind high-resolution global atlas of off-river pumped hydro included in Blakers et al. [9] demonstrated 616,000 cost-effective sites for pumped hydro development around the world with a total storage potential of 23 million GWh. DES, such as electric car batteries, can contribute significant storage capacity as well as large demand flexibility to future energy systems. Enabled by smart grid technology, these kW, kWh-scale storage systems can be aggregated and utilised for GW, GWh-scale demand response. In light of their high round-trip efficiencies (STORES 80%, DES 90%) and the large resource potentials, these two solutions are ideal for large-scale energy time-shifting. The novel features of this study include: (i) STORES and DES are utilised for short-term, diurnal energy storage facilitating high penetration of variable solar and wind energy; (ii) a high-voltage direct-current Super Grid is modelled, which spans millions of square kilometres on the Australian continent; (iii) dependence on energy generation, storage and transmission technologies already in large-scale production worldwide; and (iv) high-resolution simulations of energy supply-demand balance based on long-term, chronological meteorological and energy demand data.

A set of 100% renewable energy futures in Australia are modelled in this work. Australia has one of the highest greenhouse gas emissions per capita and is the largest exporter of coal (#1) and liquified natural gas (#2) in the world. However, Australia is a global leader in rapid per capita deployment of renewable energy as shown in Fig. 1. Over the years 2018–2020, the combined solar photovoltaics and wind deployment will be above 17 GW [10], which is greater than 200 W per capita per year – about 3–5 times the per capita rate for the European Union, the United States, China and Japan and 10 times the global average [9]. If this rate were to continue, Australia would be on track for 50% renewable electricity in 2025 and 100% in the early 2030s [11]. The modelling of a zero-carbon renewable energy future makes a timely contribution to the ongoing discussions on energy security and affordability. Importantly, about three quarters of the world's population lives in the "Sunbelt" (lower than 35° of latitude), where the solar irradiance is high, the seasonal variation in solar resource is low, and there is no significant heating load in winter. Therefore, short-term, diurnal energy storage would be required to cope with the variability of solar energy, rather than long-term, seasonal energy storage. Many Sunbelt countries could follow the Australian path, transitioning to a high renewable energy future and bypassing a fossil fuel era [9]. However, the renewable energy resource and energy demand are different from country to country, and therefore the analysis needs to be undertaken on a case-by-case basis.

2. Methods

Energy generation, storage and transmission were simulated in three 100% renewable energy scenarios for Australia. Within all three scenarios, the electrical energy demand included the current electricity demand in the electricity sector together with electrified land transport, heating, manufacturing and mining. Powered by renewable energy, this represents a reduction of 80% in total Australian greenhouse gas emissions, which currently amount to 532 megatonnes CO_2-e [13] or 21 tonnes per person. As part of this 80% reduction, fugitive emissions from Australia's exports of coal and gas were also assumed to be eliminated.

Scenario 1: "7 Grids". This is the baseline scenario in which the regional electricity markets were assumed to be operated separately in 7 Australian states and territories: New South Wales (NSW), Northern Territory (NT), Queensland (QLD), South Australia (SA), Tasmania (TAS), Victoria (VIC) and Western Australia (WA). In other words, each state/territory (sub-scenarios 1.1–1.7) transitioned to a zero-carbon energy future in its own way: for example, hydropower played a significant role in the island state of TAS, while solar photovoltaics (PV) and wind constituted the majority of the energy mix in the mainland states/territories of NSW, NT, QLD, SA, VIC and WA. This scenario reflects the status quo of the existing Australian electricity systems, which are weakly interconnected and isolated from electricity networks in neighbouring countries such as Indonesia and New Zealand.

Scenario 2: "Super Grid". In this scenario, energy systems in NSW, QLD, SA, TAS and VIC were fully integrated as a National Electricity Market (NEM), along with 3 potential extensions (sub-scenarios 2.1–2.8) to Far North Queensland (FNQ, 1,500 km), NT/Alice Springs (1,200 km) and WA/Perth (2,400 km). As shown in Fig. 2, a high-voltage direct-current (HVDC) backbone was envisaged on top of the existing transmission network, connecting widely dispersed renewable energy zones across the Australian continent.

Scenario 3: "Smart Grid". This scenario (comprising sub-scenarios 3.1–3.8) was built based on the Super Grid scenario, with an additional assumption that distributed energy storage such as electric car batteries contributed large demand flexibility to the electricity system, enabled by smart grid technology. In the modelling, 80% of passenger cars were assumed to be compatible with flexible charging in response to energy deficits or surpluses in the electricity system. This scenario represents a promising future for active demand-side participation in the energy market.

Energy supply-demand balance was carefully examined through a high-resolution analysis of energy generation, storage and transmission in the renewable energy scenarios. A "net load" approach was used in the modelling where the net load is defined as the difference between electric load and renewable energy supply on a 30-min basis. As noted in Section 1, energy storage is key to achieving high levels of energy supply-demand balance. When the net load was greater than zero, the electricity system experienced a deficit, and hence energy storage was operated as generators to fill the gaps. In contrast, if the net load was negative, then there was a surplus of energy supply, and energy storage was operated as pumps to absorb the excess power. Existing hydropower and biomass were strategically dispatched to mitigate the difference between energy supply and demand while subject to the energy constraints. The model was validated with Blakers et al. [14] which was focusing on the electricity sector only.

The modelling framework is illustrated in Fig. 3. The nucleus of the model is a high-resolution analysis (30-min intervals) of energy supply-demand balance based on long-term (2020–2029), chronological meteorological and energy demand data. The modelling input included the information on renewable energy, energy

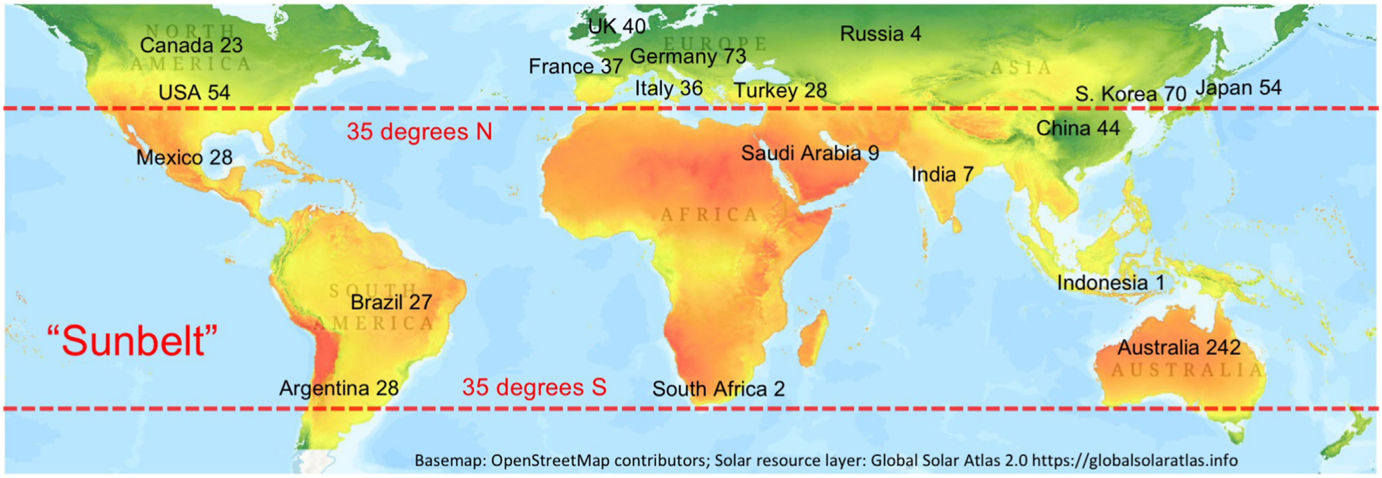


Fig. 1. Renewable energy deployment rates (watts per person per year) in 2019. Data source: International Renewable Energy Agency [1]. Green to red colours denote the daily average Global Horizontal Irradiation ranging from 1.3 to 7.5 kWh per square metre. Data source: Solargis [12]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

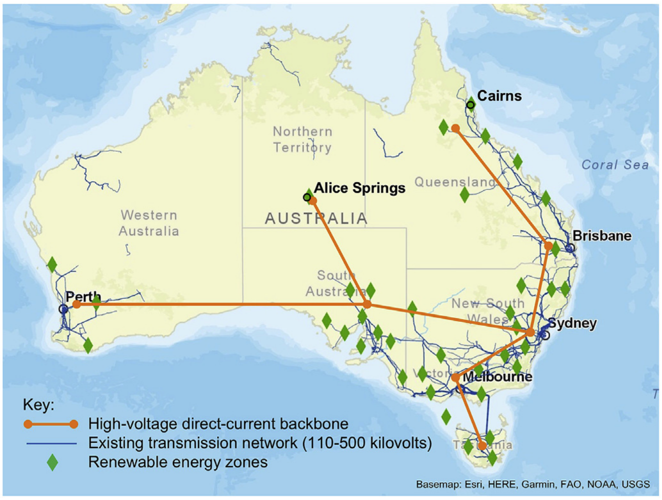


Fig. 2. A hypothetical high-voltage direct-current backbone (orange) lies on top of existing transmission network (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

storage, electricity transmission and energy demand, which are discussed in Section 2.1-2.4. The modelling outputs were the energy statistics from the simulations and also the power flows between the states and territories of Australia. Then the levelised costs of electricity, generation and balancing (LCOE/LCOG/LCOB) were calculated based on the cost assumptions detailed in Section 2.5. The configurations of energy generation, storage and transmission technologies were optimised using Differential Evolution [15] to find the lowest-cost solutions for the energy system, subject to a variety of constrains.

2.1. Renewable energy

In this study, solar and wind energy were the major energy sources in the renewable electricity systems, with support provided from existing (but no new) hydropower and biomass. Half-hourly solar and wind energy traces for 2020–2029 were obtained from the Integrated System Plan 2018 developed by AEMO [16]. The Integrated System Plan detailed a transition pathway for the Australian National Electricity Market in the coming decades and included a set of projected solar and wind energy time series for 34 renewable energy zones across eastern and south-eastern Australia, as illustrated in Fig. 2. For WA and NT which are not connected to the National Electricity Market and were not covered by the report, the 2008–2017 meteorological data from the Australian Bureau of Meteorology [17,18] were used and "downscaled" to 30-min intervals by interpolation where required. The methodology of solar and wind energy conversions was described in Section 4.1, 4.2 of Lu et al. [19]. On average, the capacity factors across the renewable energy zones are 30% AC for solar PV with single-axis trackers and 41% for onshore wind, respectively.

For other renewables such as existing hydro and bio, it was assumed that they would stay unchanged from the current level (no further expansion) and were fully dispatchable throughout the simulated period, subject to current energy and power constraints. Historically, the annual electricity generation from existing hydro and bio ranged from 15 to 22 TWh since 2000 [20,21]. Thus, the contribution of hydro and bio was constrained to a maximum of 20 TWh per year in the modelling. Future opportunities for significant expansion of river-based hydropower [22] are small compared with the massive scale of solar PV and wind required to reach 100% renewable energy. Intensive use of bioenergy, whether by the burning of biomass or utilisation of biofuels, would contribute to significant air pollution and increased ozone-related health risks. Additionally, large-scale utilisation of biomass competes with food, forests and ecosystems for land, water, fertilisers and pesticides [23].

Nuclear energy is not included in this study. Nuclear energy is associated with public perceptions of weapons proliferation, accidents and waste disposal. Furthermore, the nuclear industry has a low growth rate in terms of global net new generation capacity: an average of 2.2 GW per year over the past decade [24].

2.2. Energy storage

Energy storage makes energy time-shifting possible and also provides a variety of ancillary services, which can facilitate large-scale integration of solar and wind energy in an electricity system. Large-scale energy storage technologies include pumped hydro, high-temperature thermal (power-to-heat), grid-scale battery, compressed air, electrolytic hydrogen and renewable

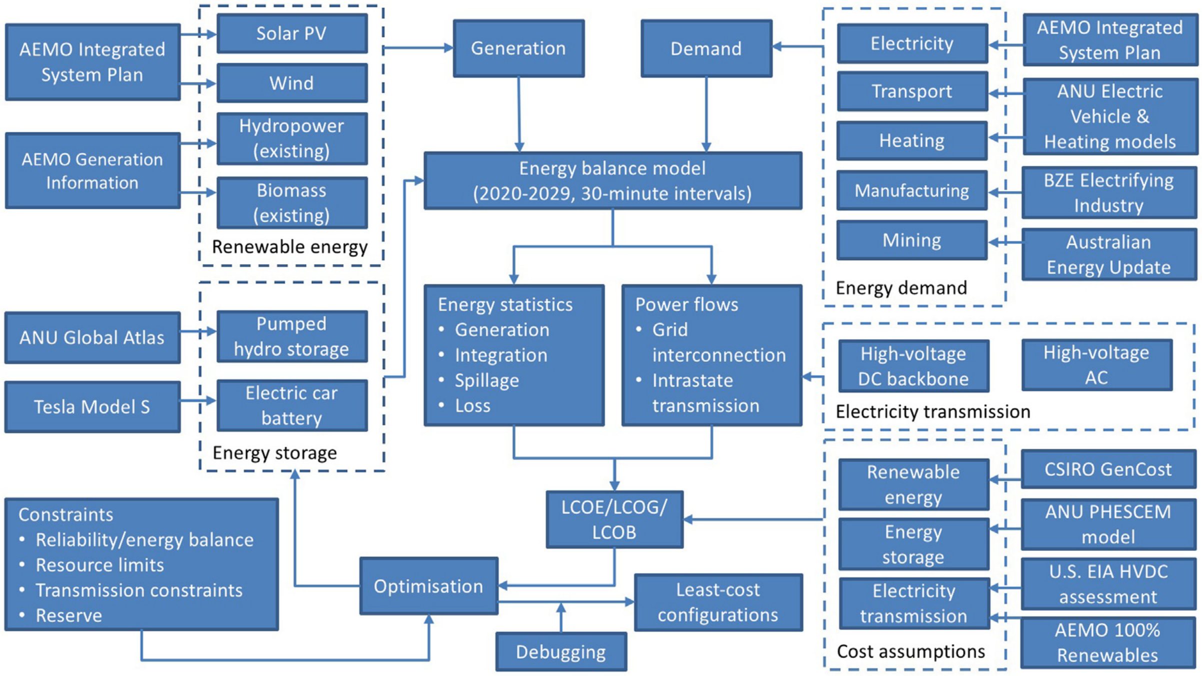


Fig. 3. Modelling framework. Acronyms and abbreviations: Australia Energy Market Operator (AEMO), Australian National University (ANU), Beyond Zero Emissions (BZE), Commonwealth Scientific and Industrial Research Organisation (CSIRO), U.S. Energy Information Administration (U.S. EIA).

electrofuels (power-to-gas).

Compared with alternative energy storage technologies, pumped hydro has low costs, by far the highest technology maturity, and a high round-trip efficiency of typically 80%. However, in many parts of the world, hydro energy resources are extremely limited and hence opportunities for further developments of large-scale river-based hydroelectric projects in these regions are restricted. In addition, developments of significant hydroelectric schemes are usually associated with a wide variety of environmental concerns such as biodiversity, nutrient flows and landscape destruction.

By contrast, short-term off-river energy storage (STORES) refers to closed-loop pumped hydro systems, which are located away from rivers and have large hydraulic head (typically > 300 m). A typical example of STORES is the Presenzano Hydroelectric Plant located in Italy. Compared with conventional river-based hydropower, the advantages of STORES include: (i) STORES offers vast opportunities to access cost-effective mass energy storage. The resource potential is large and not constrained by resource availability or accessibility; (ii) a large difference in altitude between upper and lower reservoirs enables significant amounts of energy to be stored in pairs of medium-sized closed-loop reservoirs. Therefore, the consumption of water is modest i.e. initial fill and evaporation minus rainfall; and (iii) there is no or low interaction with the ecosystem of main stem rivers, which means the environmental footprints are moderate. A global atlas of pumped hydro (off-river) has been developed at the Australian National University [9], which discovered 616,000 cost-effective sites for pumped hydro development around the world — 3,000 of them are located in Australia with a total storage potential of 163,000 GWh. These prospective sites were identified through a comprehensive, high-resolution site survey based on the suitability of topography [25]. A further feasibility study into geology, hydrology, land acquisition and environmental impact will be required for any specific site on the atlas. In this study, STORES is included in the modelling and utilised for large-scale renewable energy time-shifting and energy demand balancing.

As well as large-scale energy storage, small-scale distributed energy storage (DES) systems, such as electric car batteries, were also included in the modelling. DES systems could be utilised for effective demand response to mitigate energy and power deficiency due to occasional low availability of renewable energy. In the Smart Grid scenario, the charging of 80% of the passenger cars was assumed to be fully flexible and regulated according to a real-time energy supply-demand balance, while subject to a minimum state-of-charge constraint of 25%.

2.3. *Electricity transmission*

In addition to energy storage (energy time-shifting), wide geographic dispersion of solar and wind resources can also effectively mitigate intermittency in energy production (energy geo-shifting). Renewable energy resources and electricity demand are generally less correlated or even anti-correlated over a large geographic area such as millions of square kilometres in Australia.

Modern high-voltage direct-current technology, with either line-commutated converter or voltage-source converter, enables cost-effective delivery of GW-scale electric power over thousands of kilometres with relatively low transmission loss (3% per 1,000 km). In the Super Grid and Smart Grid scenarios, the hypothetical HVDC backbone was utilised for large-scale export of renewable energy from FNQ/Cairns, NT/Alice Springs and WA/Perth to the National Electricity Market and for stronger interconnection between the electricity grids in NSW, QLD, SA, TAS and VIC, which are currently weakly interconnected.

However, while HVDC technology has the advantage of long-distance bulk power transmission at moderate cost, there is a risk that even a single-pole transmission failure could lead to loss of GW-scale electric power, which may cause severe capacity inadequacy in the system. Therefore, for both HVDC transmission lines and converter stations, an “N-1” redundancy was included in the cost assumptions which incorporated 25% reserve capacity in a two-circuit bipolar HVDC transmission route. Additionally, the renewable energy zones were assumed to be connected to adjacent HVDC nodes by high-voltage alternating-current (HVAC) transmission. The capital costs of both the HVDC and HVAC were factored into the cost calculation, which is a critical component as demonstrated in the results.

2.4. Energy demand

The modelled operational demand (excluding behind-the-meter rooftop solar) was 397 TWh p.a. on average. This included energy demand in the current electricity sector and the fully electrified energy consumption for residential & commercial, manufacturing, mining and land transport. As shown in Fig. 4, electricity generation (34%) was decarbonised using renewable energy (Category I). Residential & commercial (3%), manufacturing (6%), mining (9%) and land transport (17%) were decarbonised through direct electrification (Category II). In addition, fugitive emissions (11%) will vanish as fossil fuels phased out from the energy industry (Category III). This energy transition would allow for an 80% reduction in total Australian greenhouse gas emissions. Accordingly, the historical electricity demand in the NEM (203 TWh) was doubled.

Similar to the solar and wind energy traces, energy demand (30-min time series) in the electricity sector in the NEM was obtained from AEMO [16] for 2020–2029, with the assumptions that economic growth and the future uptake of distributed energy technology are moderate (neutral). For WA/Perth, the historical electricity data from 2008 to 2017 were used [27]. The average annual energy demand in the original electricity sector is 201 TWh compared with about 203 TWh in 2017–18, which reflects a flat operational consumption over the simulated period.

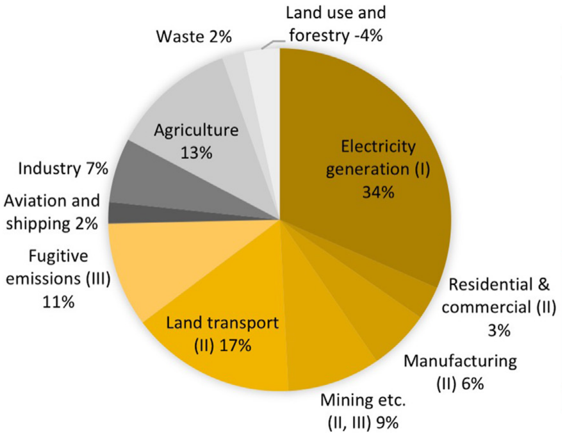
Land transport and heating (including space heating, water heating and cooking) data were obtained from the Australian National University's electric vehicle and electric heating models. The total energy use in 2017–18 for transport and heating [28] was utilised as a benchmark. Energy consumption patterns for passenger cars, light commercial vehicles, rigid trucks, articulated trucks, non-freight trucks, buses and motorcycles were derived from publicly available sources as noted in Table SI1.1 in the Supplementary data. The heating load profiles were calculated based on the temperature, occupancy and historical usage profiles in residential and commercial buildings. Overall, electrification of land transport and heating resulted in a 58% increase (transport 48%, heating 10%) to the original electricity demand. Tables SI1.1, SI1.2 in the Supplementary data include a summary of the assumptions for the modelling of electrified land transport and heating.

Industrial loads, such as manufacturing, mining and construction, were derived from the Australian Energy Update and Beyond Zero Emissions reports [28,29] with the overall fuel efficiency boosted by a factor of 2 using electric arc/resistance furnaces for heating, and electric mining and construction equipment for motive energy. A flat 24/7 electricity consumption pattern was assumed, which translated to a continuous electricity load of 9 GW. A significant off-grid industrial centre, Mt Isa located in Far North Queensland, was connected to the renewable energy zones as well as the HVDC node in the Super Grid and Smart Grid scenarios. Electrification of manufacturing, mining and construction contributed another 40% increase in the original electricity demand, bringing the total increase to the original electricity load to 98%.

It is noted that electrification is not the only pathway to deep decarbonisation of the energy sector. For example, solar thermal energy can be collected through solar hot water systems (low-temperature heat) or concentrating solar collectors for power generation (high-temperature heat). However, in light of the rapidly declining cost of solar PV and the advantages of electric applications, such as high efficiency of energy conversion and current cost parity, renewable electricity from solar PV and wind turbines is likely to be dominant in high renewable energy futures. In other words, 100% renewable electricity and 100% renewable energy (including transport, heating and industry) may converge in the future energy systems.

Aviation and shipping are not included in the modelling. Direct electrification of aviation and shipping is difficult when compared with that of other transport modes, because they are more sensitive to the energy density (gravimetric and volumetric) of alternative transport fuels. While battery storage with electric motors could be a practical solution for short-haul flights and ships, the energy technologies to electrify long-haul flights and ships are still being developed. Nevertheless, renewables-based fuels such as hydrogen, ammonia and synthetic hydrocarbons via water electrolysis and chemical synthesis present a promising prospect for zero-carbon alternatives to jet fuel and heavy oil fuel.

In addition, Australia has relatively small emissions per capita from industry because Australian manufacturing of items such as iron and steel, cement and plastics is a relatively small fraction of the economy. Full electrification of industry in some other countries will be a relatively larger endeavour than in Australia. Production of synthetic hydrocarbon fuels (such as jet fuel) and plastics requires a



Category	Pathway towards deep decarbonisation of energy sector	
I	Renewable energy	▪ Power generation: solar photovoltaics, wind, existing hydro and bio ▪ Energy storage: pumped hydro, batteries and thermal energy storage ▪ Electricity transmission: high-voltage direct-current and alternating-current
II	Direct electrification	▪ Heating: electric heat pumps and appliances, electric arc/resistance furnaces ▪ Transportation: electric vehicles ▪ Industry: electric mining and construction equipment
III	Vanishing as fossil fuels phased out	

Fig. 4. Australia's greenhouse gas emissions by sector in 2018–19 and the pathway towards deep decarbonisation of energy sector. Data source: Australian Department of the Environment and Energy [13]; emissions breakdown based on the National Greenhouse Gas Inventory [26].

sustainable source of carbon, which will probably necessitate carbon capture from the air.

2.5. Cost assumptions

Cost assumptions for electricity generation, storage and transmission technologies were included in Table 1. The costs quoted are in Australian dollars, which has a value of about US$0.7. A nominal discount rate of 6.5% was assumed in the cost calculation to reflect the integrated rates for the returns on investment (30% of the capital with a 10% internal rate of return) and the interest rates from banks (70% of the capital with a loan interest rate of 5%). This translated to a real discount rate of 5% by factoring in an inflation rate of 1.5%.

In Australia, the prices of solar PV and wind energy have already been in the range of $50–65/MWh and continue to fall rapidly [11]. The figures for solar PV and wind in Table 1 are equivalent to a levelised cost of electricity of $50/MWh for both solar PV and wind in the 2020s, assuming an average capacity factor of 30% AC for solar PV and 41% for wind. Similarly, existing hydro and bio were assumed to be available at a purchase price of $50/MWh, rather than merely factoring in their operating and maintenance (O&M) costs.

3. Results and discussion

The modelling results are shown in Fig. 5. Details of energy generation, storage and transmission information are included in Table 2.

3.1. Energy affordability

As shown in Fig. 5 and Table 2, in the 7 Grids scenario (S1.1-S1.7), the LCOE ranges from $52–124/MWh in QLD, NSW, NT, SA, TAS, VIC and WA with a volume-weighted average of $99/MWh. The storage requirements are 65 GW, 2,049 GWh in total. By contrast, in the Super Grid scenario (S2.1-S2.8), the LCOE of an integrated National Electricity Market (including QLD, NSW, SA, TAS and VIC) is in the range of $75–88/MWh depending on whether connections to FNQ, NT and WA are built. The total storage requirements in the Super Grid scenario decrease to 481–746 GWh - only equivalent to the storage requirement in a single state, NSW or VIC, in the 7 Grids scenario. In the Smart Grid scenario, with flexible charging of electric cars, the LCOE reduces further still to $70–82/MWh and the total storage requirements range from 321 to 493 GWh.

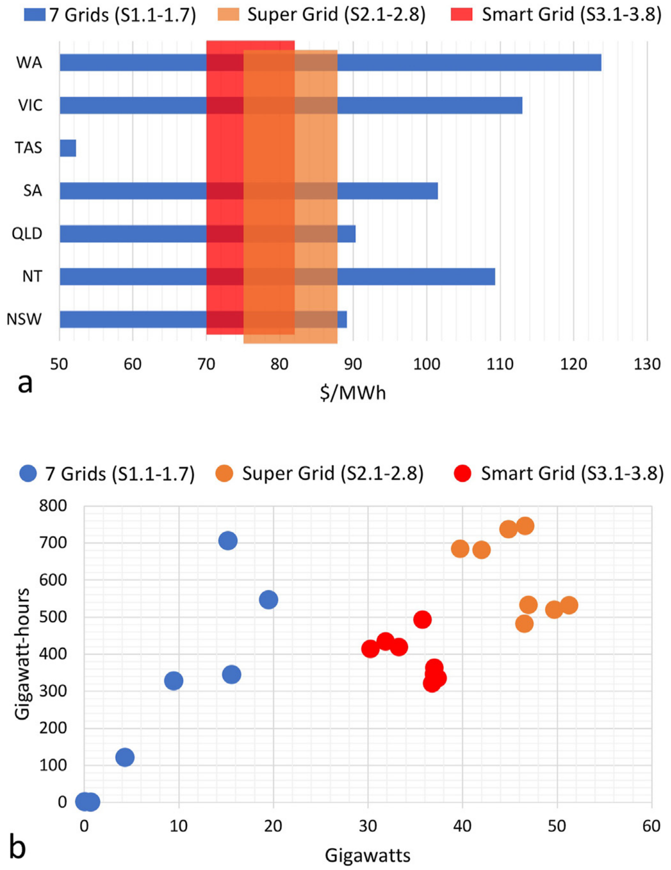


Fig. 5. Levelised costs of electricity (a) and storage requirements (b) in the 7 Grids (blue), Super Grid (orange) and Smart Grid (red) scenarios. The volume-weighted average of LCOE in the 7 Grids scenario is $99/MWh. The total storage requirements in the 7 Grids scenario are 65 GW, 2,049 GWh. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In particular, a fully integrated energy system of NEM + FNQ, NT, WA in S2.8 costs only $78/MWh, which represents a reduction of $21/MWh in LCOE when compared to the volume-weighted average in the 7 Grids scenario. Of the HVDC extensions to FNQ, NT and WA, the NEM-FNQ link has the most significant influence on the reduction of LCOE in the NEM, as it provides access to a less-correlated wind resource in the Far North (17–19° of latitude). In comparison, the NEM-NT and NEM-WA links primarily help to reduce the costs in NT (from $109/MWh in S1.2 to $85/MWh in S2.3) and WA (from $124/MWh in S1.7 to $88/MWh in S2.2). In the Smart Grid scenario, a fully integrated energy system of NEM + FNQ, NT, WA in S3.8 costs $72/MWh and requires 32 GW,

Table 1

Cost assumptions for electricity generation, storage and transmission technologies. Data source: Graham et al. [30], Blakers et al. [14], U.S. EIA [31], Tamblyn [32], Ardelean & Minnebo [33], AEMO [34].

Technology	Capital cost	Fixed O&M cost	Variable O&M cost	Lifetime (years)
Photovoltaics (1-axis tracking)	$1,200/kW (DC)	$15/kW p.a. (DC)	0	25
Wind (onshore)	$1,850/kW	$36/kW p.a.	$3/MWh	25
Pumped hydro (off-river)	$800/kW $70/kWh[a]	$10/kW p.a.	0	50
High-voltage direct-current (overhead)	$320/MW-km $160,000/MW[b]	$3.2/MW-km p.a. $1,600/MW p.a.	0	30, 50[b]
High-voltage direct-current (submarine)	$4,000/MW-km[c]	$40/MW-km p.a.	0	30
High-voltage alternating-current	$1,500/MW-km[d]	$15/MW-km p.a.	0	50

Note.

[a] $/kW for power components including turbines, generators, pipes and transformers; plus $/kWh for storage components such as dams, reservoirs and water.

[b] $/MW-km for transmission lines (50 years); plus $/MW for a converter station (30 years).

[c] Including submarine power cables and converter stations.

[d] Including transmission lines and substations.

Table 2

Rated power (GW), storage capacity (GWh), the annual average of energy production and consumption (TWh), and cost ($/MWh) information for each scenario.

Scenario		Geographic coverage	Energy demand (TWh)	HVDC loss (TWh)	Solar PV		Wind		Hydro & bio		Pumped hydro		High-voltage direct-current (GW)							LCOE ($/MWh)	LCOG ($/MWh)	LCOB ($/MWh)		
					GW	TWh	GW	TWh	GW	TWh	GW	GWh	FNQ-QLD	NSW-QLD	NSW-SA	NSW-VIC	NT-SA	SA-WA	TAS-VIC			Storage	Transmission	Spillage & loss
7 Grids	S1.1	NSW	116	0	41	86	16	56	3	3	19	546	0	0	0	0	0	0	0	89	49	27	2	12
	S1.2	NT (Alice Springs)	0.3	0	0.1	0.3	0.1	0.2	0.0	0.0	0.1	2	0	0	0	0	0	0	0	109	45	33	2	29
	S1.3	QLD	95	0	34	71	16	61	0.6	0.2	16	345	0	0	0	0	0	0	0	90	47	23	2	19
	S1.4	SA	23	0	9	20	4	13	0.0	0.0	4	121	0	0	0	0	0	0	0	101	48	31	2	21
	S1.5	TAS	14	0	0	0	1	3	2	11	0.7	2	0	0	0	0	0	0	0	52	47	3	1	1
	S1.6	VIC	98	0	22	42	28	107	2	1	15	706	0	0	0	0	0	0	0	113	48	36	3	26
	S1.7	WA (Perth)	47	0	19	38	12	48	0.0	0.0	9	328	0	0	0	0	0	0	0	124	46	37	3	38
		NEM summary[a]	346	0	106	219	64	240	8	15	55	1,720	–	–	–	–	–	–	–	95	48	28	2	18
		7 Grids summary[b]	393	0	125	257	76	288	8	15	65	2,049	–	–	–	–	–	–	–	99	48	29	2	20
Super Grid	S2.1	NSW, QLD, SA, TAS, VIC	346	7	74	157	69	263	8	13	47	533	0	19	36	24	0	0	2	85	47	13	12	13
	S2.2	NSW, QLD, SA, TAS, VIC + WA	393	7	105	218	77	295	8	11	51	532	0	22	23	25	0	10	2	88	47	12	12	17
	S2.3	NSW, QLD, SA, TAS, VIC + NT	346	5	96	202	63	242	8	11	47	481	0	18	14	25	1	0	2	85	47	12	10	16
	S2.4	NSW, QLD, SA, TAS, VIC + NT, WA	393	7	96	201	81	312	8	11	50	520	0	22	30	23	2	10	2	88	47	12	13	17
	S2.5	NSW, QLD, SA, TAS, VIC + FNQ	350	7	57	119	61	244	8	19	42	681	16	20	12	20	0	0	2	76	46	14	11	5
	S2.6	NSW, QLD, SA, TAS, VIC + FNQ, WA	397	10	65	135	69	278	8	19	47	746	20	21	15	18	0	9	2	77	46	14	13	5
	S2.7	NSW, QLD, SA, TAS, VIC + FNQ, NT	350	7	51	106	63	254	8	19	40	684	16	17	14	19	3	0	2	75	46	14	11	5
	S2.8	NSW, QLD, SA, TAS, VIC + FNQ, NT & WA	397	10	59	123	72	291	8	19	45	737	18	30	15	20	2	9	2	78	45	13	14	5
Smart Grid	S3.1	NSW, QLD, SA, TAS, VIC	346	4	87	184	61	236	8	11	37	335	0	19	13	33	0	0	2	79	47	9	10	12
	S3.2	NSW, QLD, SA, TAS, VIC + WA	393	6	87	183	82	317	8	10	37	347	0	19	19	31	0	13	2	82	47	8	13	15
	S3.3	NSW, QLD, SA, TAS, VIC + NT	346	4	81	171	66	252	8	11	37	321	0	18	18	27	0	0	2	79	47	9	10	13
	S3.4	NSW, QLD, SA, TAS, VIC + NT, WA	393	6	83	173	83	318	8	11	37	363	0	21	19	27	1	13	2	82	47	8	12	14
	S3.5	NSW, QLD, SA, TAS, VIC + FNQ	350	6	42	87	69	277	8	19	33	419	17	20	6	19	0	0	2	71	46	9	10	5
	S3.6	NSW, QLD, SA, TAS, VIC + FNQ, WA	397	9	50	103	76	305	8	20	36	493	19	19	13	20	0	10	2	72	45	10	13	5
	S3.7	NSW, QLD, SA, TAS, VIC + FNQ, NT	350	7	43	88	67	270	8	20	30	414	19	18	7	18	5	0	2	70	46	9	11	5
	S3.8	NSW, QLD, SA, TAS, VIC + FNQ, NT & WA	397	10	47	99	77	308	8	20	32	434	18	21	23	19	2	10	2	72	45	8	14	5

Note. Energy demand is operational, which means rooftop PV is not included in the LCOE calculation, neither in the cost (numerator) nor in the energy (denominator) components.

[a] Here the National Electricity Market (NEM) is defined as a fully integrated electricity market including NSW, QLD, SA, TAS and VIC, but excluding FNQ, NT and WA.

[b] Mt Isa, which is located in FNQ and currently off the grid (energy consumption: 4.2 TWh p.a.), is connected to the main network only in the Super Grid and Smart Grid scenarios.

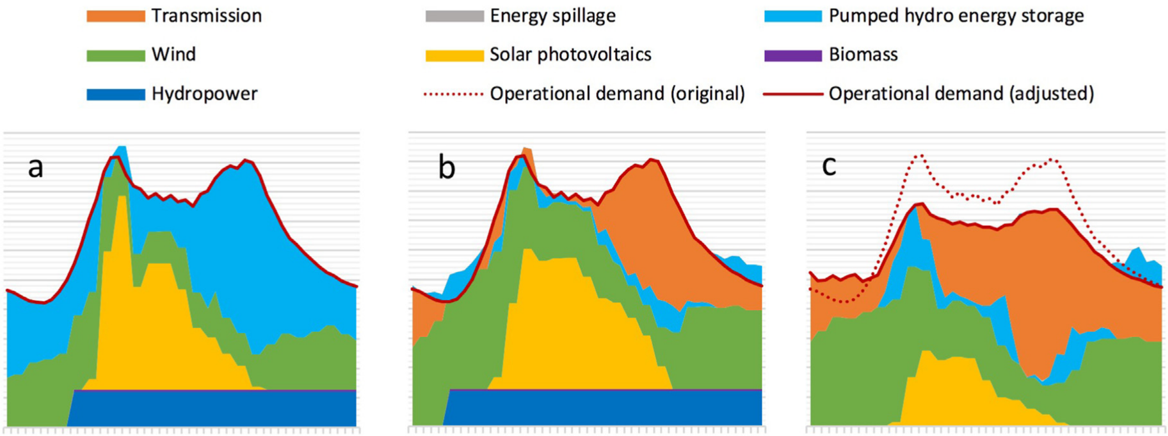


Fig. 6. Load profiles and generation mix for a day with low availability of wind energy in New South Wales in the 7 Grids (a), Super Grid (b) and Smart Grid (c) scenarios. Fig. 6-b and 6-c represent a fully integrated NEM + FNQ, NT and WA electricity system in the Super Grid (S2.8) and the Smart Grid (S3.8) scenarios, respectively.

434 GWh of storage capacity.

The LCOE comprises 4 components: (i) the LCOG which refers to the cost of energy sourced from solar, wind, existing hydro and bio; (ii) the storage; (iii) the transmission; and (iv) occasional energy spillage & loss. The LCOB is made up of the storage, transmission and energy spillage & loss components and is summed together with the LCOG to find the LCOE. As shown in Table 2, while the LCOG are similar across the scenarios ($45–49/MWh), the large differences in the LCOB can be observed which reflect the characteristics of each scenario. For example, compared with the 7 Grids scenario, the Super Grid scenario features higher costs of transmission ($10–14/MWh) due to the construction of the HVDC backbone. However, the storage and energy spillage & loss components in the Super Grid scenario decrease substantially, which leads to large reductions in the LCOE as a whole.

The results also suggest that large-scale grid interconnection in the Super Grid scenario and the introduction of demand-side participation in the Smart Grid scenario help to reduce the cost of 100% renewables by 11–24/MWh and 17–29/MWh respectively. This is significant: each dollar of decrease in the LCOE equates to about $400 million of cost savings in the energy industry per year. In fact, as shown in Table 2, in the Super Grid and Smart Grid scenarios, the installed capabilities of solar PV, wind and storage (both GW and GWh) are remarkably reduced when compared with the capacities in the 7 Grids scenario due to the benefits of wide geographical dispersion of solar and wind energy and the flexibility of electric car charging. Significantly, the costs of 100% renewables including energy generation, storage and transmission can be competitive with current electricity prices in the Australian wholesale energy market ($80–110/MWh on average in 2019 [35]) and are lower than the costs of new-build coal and gas power stations (> $80/MWh) in Australia [30].

The modelling input and assumptions were further examined in a sensitivity analysis, where the values of cost components in the scenario S3.8 were varied between +25% and −25%. The LCOE was most sensitive to changes in the cost of wind turbines and the discount rate. For example, a 25% increase in the discount rate led to a $9 increase in the LCOE. By contrast, the LCOE was less sensitive to the costs of solar PV, HVDC transmission, energy storage, existing hydropower and biomass, and HVAC transmission. Given that the energy technologies included in this model have already been deployed on a large scale worldwide, the costs are well-known, and so these cost estimates for renewable energy systems are expected to be robust compared with technologies that are under research & development or in the demonstration stage.

3.2. Energy security and reliability

A snapshot of the load profiles and generation mix is included in Fig. 6. As illustrated, in each of the 3 hypothetical 100% renewables scenarios, energy storage is responsible for large-scale energy shifting which is the key to energy supply-demand balance with high penetration of solar and wind energy. In addition to energy time-shifting, STORES and DES also contribute to a variety of ancillary services such as frequency control and black start capability, which help to build the resilience of the energy system. The energy supply-demand balance data for the entire simulated period (10 years with 175,344 half-hourly intervals) are included in the Supplementary data.

Demand-side participation in the Smart Grid scenario only refers to the flexibility of electric cars that charge in response to energy sufficiency in the system. The modelling shows that the key requirement to effective use of car batteries to help meet demand is to avoid charging the batteries during morning and evening peak periods that last for a few hours each. Provided this criterion is met, the actual charging pattern matters little. Vehicle-to-grid (V2G) technology was not included, though V2G could further lower the cost through peak shaving. The impact of V2G on lithium-ion batteries is being investigated. On one hand, V2G has been linked with accelerated degradation, but others believe that the degradation of battery capacity and power output due to extensive charging and discharging operations can be effectively minimised through careful management of vehicle charging and discharging [36]. A future study to explore the benefits and challenges of utilising V2G technology will explore this opportunity.

Additionally, in this model, millions of electric car batteries were aggregated and modelled as a “giant” battery. This provided a rough estimate of the benefit of integrating demand flexibility. A representation of distributed energy resources including hot water storage and household batteries with a high level of granularity would be included in future studies.

4. Conclusions

This study demonstrates that a zero-carbon, reliable and affordable electrical energy system can be built based on: (i) solar photovoltaics, wind turbines, existing hydropower and biomass for power generation; (ii) pumped hydro (off-river) and electric car batteries for energy storage; and (iii) high-voltage direct-current and alternating-current for electricity transmission. All of these energy technologies are commercially available today and have already been deployed on a large scale worldwide. At the end of 2019, the global installed capacities were: solar photovoltaics 580 GW [1], wind turbines 623 GW [1], pumped hydro 181 GW [8], high-voltage direct current > 200 GW [37], and the deployment of electric cars had reached 7.2 million worldwide [38]. High levels of energy reliability and affordability can be achieved through a synergy of flexible energy sources; interconnection of electricity grids over large areas; response from demand-side participation; and mass energy storage.

The conclusions of this study include:

- Zero-carbon energy enables removal of 80% of the greenhouse gas emissions from the Australian economy. Electricity generation can be directly decarbonised with renewable energy, while residential & commercial, manufacturing, mining and land transport can be decarbonised through direct electrification. Finally, the fugitive emissions will vanish as fossil fuels phased out from the energy industry.
- STORES and DES can effectively maintain the balance between renewable energy supply and energy demand and hence facilitate large-scale integration of variable solar and wind energy. The energy storage resources are largely available in Australia. The storage requirements are 321–2,049 GWh in the 7 Grids, Super Grid and Smart Grid scenarios, which are only 0.2%–1.3% of the storage potential in Australia (163,000 GWh). In addition, the aggregation of millions of kW, kWh-scale distributed energy storage can contribute to GW, GWh-scale demand flexibility. STORES and DES ensure a high level of energy security and reliability through energy balancing and a variety of ancillary services.
- Large-scale interconnection of electricity grids over millions of square kilometres, the Super Grid, smooths out local weather and hence deceases the dependence on energy storage. The NEM-FNQ link has the largest impact on the cost reduction, while the NEM-NT and NEM-WA links would primarily benefit the Northern Territory and Western Australia by sharing of low-cost electricity from the National Electricity Market.
- A levelised cost of electricity of $70–99/MWh is estimated for zero-carbon energy in Australia, using the current technology costs. These cost figures can compete with that of the current and new-build future fossil energy systems. As the technology advances and economies of scale in renewable energy development, the technology costs will be reduced further, and zero-carbon energy would become the lowest-cost solution in the Australian energy markets.

Australia is located at low-moderate latitudes along with the majority of the world's population living in the Sunbelt. Here long-term, seasonal energy storage requirements are low compared with much of Europe, North America and Northeast Asia. Therefore, short-term off-river energy storage and distributed energy storage can be ideal solutions for balancing variable solar and wind energy on timescales of hours to a day. As noted by Hensen et al. [39], there have been few studies in the existing literature modelling of high renewable energy futures in the regions such as Southeast Asia, South America and Africa. This strategy designed for Australia could be a rapid and generic pathway towards zero-carbon energy futures within the Sunbelt.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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