

THE ROLE OF ENERGY STORAGE

IN AUSTRALIA'S
FUTURE ENERGY
SUPPLY MIX

HORIZON
SCANNING

 **ACOLA**
AUSTRALIAN COUNCIL OF LEARNED ACADEMIES

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PROJECT AIMS

Delivered as a partnership between the Australian Council of Learned Academies (ACOLA) and Australia's Chief Scientist, the Energy Storage project studies the transformative role that energy storage may play in Australia's energy systems; future economic opportunities and challenges; and current state of, and future trends in, energy storage technologies and their underpinning sciences.

The project examines the scientific, technological, economic and social aspects of the role that energy storage can play in Australia's transition to a low-carbon economy to 2030, and beyond.

EXECUTIVE SUMMARY

Australia is undergoing an energy transformation that promises to intensify over the coming decades. In the electricity generation sector this transformation involves: a greater reliance on renewable energy in response to climate mitigation policies; relocation of where energy is generated and distributed as a result of changing economics of energy costs and technological developments; and how and when energy is consumed with the advent of ‘prosumers’¹.

Energy storage is critical to a successful transformation as it provides the vital link between energy production and consumption (See Box 1) and allows for greater penetration of both utility scale variable renewable generation and distributed energy generation. Without effective planning, appropriate investment and also incentives to develop and deploy energy storage technologies, the costs of electricity in Australia will continue to increase and there will be less reliable (adequate and secure) electricity supply. These could have large negative implications on the Australian economy.

1. “Active energy consumers, often called ‘prosumers’ because they both consume and produce electricity, could dramatically change the electricity system. Various types of prosumers exist: residential prosumers who produce electricity at home – mainly through solar photovoltaic panels on their rooftops, citizen-led energy cooperatives or housing associations, commercial prosumers whose main business activity is not electricity production, and public institutions like schools or hospitals.” (European Parliament Think Tank, 2016).



Box 1: Energy security and reliability in Australia's electrical power system

Physical energy security for electricity generation and transmission comes from ensuring the ability to rapidly cope, within seconds or less, with fluctuations in energy demand and supply. Historically, security is provided by the 'mechanical inertia' of moving turbines. This inertia allows the system frequency (50 cycles per second in Australia) to cope with the ups and downs of supply and demand and ensures there is no blackout. Indeed, blackouts occur when the frequency drops too low because demand exceeds supply by too much and for too long. 'Load shedding', where demand is reduced or parts of the system are 'switched off', can be used – but with big disturbances in interconnected electricity grids there can be a cascading failure that results in a major power disruption.

Energy storage that can provide electricity into a grid at a moment's notice is an alternative to spinning turbines to provide electricity security and balance energy demand with supply. Adequate, appropriate and available (i.e. connected to the grid) energy storage in South Australia would have likely prevented the South Australian electricity blackout of 28 September 2016 as well as the need for emergency load shedding in New South Wales and South Australia in February 2017.

Energy reliability refers to the ability to balance electricity supply and demand over longer periods (other than seconds to minutes as explained above for energy security). For instance, there may be a peak load demand for electricity generation at the end of a very hot summer's day as people switch on their air conditioners when they return home from work. An adequate electricity supply is needed at these times to meet this peak demand, which may not coincide with peak variable renewable supply. Having readily available electricity generation sources (e.g. gas turbine generators) that can be powered up at these peak times can provide reliability, but this may be an expensive option if the plant only operates at peak demand periods.

An alternative is energy storage where the electricity is stored in a physical (pumped hydro), electrochemical (batteries) or high temperature thermal (e.g. molten salts, graphite or silicon) way when variable renewable energy is available (such as when the sun is shining for solar power or the wind is blowing for wind turbines). Energy storage is also a potentially less expensive alternative to keeping standby power plants idle most of the year, because of the other system purposes to which storage can be applied (i.e. security).

Uptake of Storage Solutions

Energy storage is an emerging industry globally and the application of storage in high volumes for both the stationary and transport sectors is still immature. Storage comes in many forms and can be applied in many scenarios. These include: in-front-of-the-meter large scale grid storage or community based or micro grid storage; behind-the-meter individual consumer storage coupled to solar generation (there are more than 1.8 million buildings, mostly households, in Australia with roof-top solar power systems); electrified transport (buses, cars, motorcycles and heavy and light vehicles for delivery); new defence requirements (notably the new submarine, unmanned aerial vehicle (UAVs) etc.); as well as numerous other applications with niche requirements (e.g. mining or off-grid applications).

While acknowledging these diverse applications for energy storage, this report primarily considers the transformative role that energy storage can play in Australia's electricity systems. It identifies future economic opportunities and challenges and describes the current state of and future trends in energy storage technologies. It examines the scientific, technological, economic and social economy aspects of the role that energy storage can play in Australia's transition to a low-carbon economy by 2030, and beyond to a low-carbon economy.

Over the coming decade or two there is unlikely to be only one favoured form of storage. Based on expected-cost curves, the most likely forms of energy storage will include: pumped hydro, batteries, compressed air and molten salt (coupled with solar power generation). These different technologies have varying costs and other characteristics, so determining which is the 'best' form of energy storage depends on where it is needed, for what purpose (either reliability or security

or both), the nature of the electricity grid, and the current and future types of electricity generation.

Battery systems are the most cost effective when stabilising the grid, provided they have a 'fast frequency response' (FFR) capability through appropriate power electronics to synthesise the FFR, and are ready for immediate discharge when required. By comparison, where geology and water availability permit, large-scale energy storage by pumped hydro is most cost effective for delivering energy reliability.

Both batteries and pumped hydro technologies can provide energy security and energy reliability. Notably, having invested in batteries for security then the incremental cost of adding more storage capacity for reliability depends on the relative cost of the battery cells and the balance of plant (the supporting components and auxiliary systems of a power plant needed to deliver the energy). There will be circumstances when adding cells to a battery storage scheme will be cheaper than using pumped hydro, even though pumped hydro would represent the cheapest stand-alone solution.

Behind-the-meter energy storage will also increase as more consumers choose to take control of their electricity needs (e.g. those already with solar) and with the increasing possibility of microgrids being established. These types of deployment offer opportunities for aggregation of distributed storage assets to boost security and reliability, particularly at the local distribution level in electricity networks.

Models and requirements for uptake

A National Electricity Market (NEM) model was used to assess the requirements of energy storage out to 2030. The model was based on hourly supply and demand data for a year

where there was the longest period of low availability of variable renewable resources (worst case scenario for variable renewable supply). Three scenarios underpinned the modelling in this report: (1) 'LOW RE' low renewable energy scenario (where variable renewables account for approximately 35 per cent generation); (2) 'MID RE', where variable renewables account for approximately 50 per cent generation); and (3) 'HIGH RE', a high renewable energy generation scenario (where variable renewables account for approximately 75 per cent generation). State levels of variable renewable electricity generation are also provided in this model, and these could be as high as 100 per cent for South Australia and Tasmania, depending on the scenario.

Energy security requires higher overall storage power capacity (measured as GW) than required purely for energy reliability, but the latter requires considerably more

stored energy (GWh), as shown in Figure 1, particularly for high RE penetration levels. This is because for energy security purposes the electricity supplied is typically only required for very short periods (seconds or minutes), while for energy reliability the energy is needed for balancing supply and demand over several hours to meet peak loads.

Under the three scenarios, storage capacity requirements for energy security and reliability as a proportion of total generating capacity (GW) in the NEM in 2030 are shown in Table 1.

The requirements for energy reliability and security are calculated separately and have not been optimised. Therefore, the total energy storage required as a proportion of total capacity, especially in the high renewable energy scenario, would be less than the sum of requirement for the individual requirements for energy reliability and for energy security.

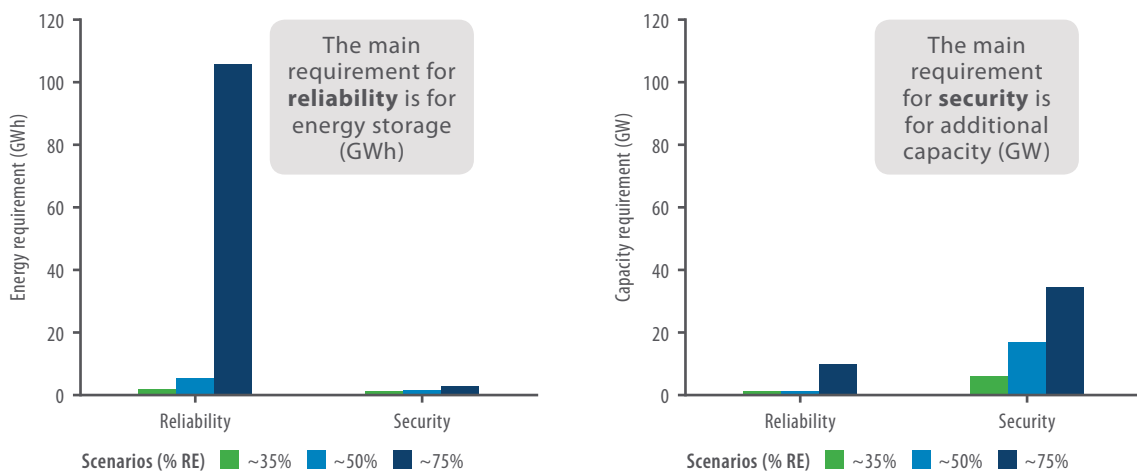


Figure 1: Reliability (GWh) and security (GW) requirements at 2030 across the three scenarios

Capacity (GW) Requirement	LOW RE	MID RE	HIGH RE
Reliability	0.5 per cent	2.4 per cent	9.8 per cent
Security	7.3 per cent	19.8 per cent	34.5 per cent

Table 1: Storage capacity requirements under the three scenarios

The costs of ensuring sufficient energy storage depend on assumptions about the levelised costs of storage in 2030. For energy security alone, the costs in 2030 prices could range from \$A3.6 billion, under the LOW RE scenario, to \$A11 billion under the MID RE scenario (which would also easily meet the reliability requirements at that time) and to as much as \$A22 billion under the HIGH RE scenario. By comparison, network capital spending in the NEM is currently between \$A5–6 billion each year, equating to approximately \$A70 billion in total if this level of expenditure is continued annually through to 2030.

Energy storage is both a technically feasible and an economically viable approach to responding to Australia's energy security and reliability needs to 2030, even with a high renewables generation scenario. Nevertheless, there will need to be suitable planning and policies, and financial incentives, for either states or the private sector to build the appropriate level of storage. Achieving the right balance between technology neutrality and making strategic choices is essential to achieving resilient and cost-effective outcomes.

Public Attitudes to Energy Storage

Australians' knowledge of, and attitudes towards, energy storage will shape acceptance and adoption. General knowledge of energy storage options is limited, and largely restricted to batteries (the 'Tesla effect'). This lack of knowledge is one of the factors limiting uptake of storage, especially at the domestic scale. From focus group and national survey work undertaken for this report, there is low trust in the Australian energy system's capacity to deliver consistent and efficient electricity provision at reasonable prices. This low level of trust

includes government, but also extends to energy providers and retailers. Regaining consumer trust in the energy system, including articulating the costs and benefits of energy storage, is vital for enabling the uptake of energy storage.

There is a demand for domestic scale energy storage by households across Australia as a means of future proofing against further electricity price rises and to take control of energy supply. Under certain conditions, Australians would be willing adopters of home-based batteries for energy storage. These conditions include policy and market certainty that allows households to calculate the costs and benefits of domestic scale storage, given that it requires significant initial outlay. Households would also like assurances that safety standards for batteries are in place and adhered to, and that battery systems are installed safely. While there is limited consumer knowledge of storage options, there are indications that should policy and market settings change then uptake may quickly follow. The experience of the post-2008 policy framework and rollout of rooftop solar photovoltaics (PV) is instructive for domestic-scale energy storage. With premium feed-in-tariffs being phased out, households with rooftop solar PV are likely to be early adopters of energy storage.

There is a latent demand for storage. Almost 60 per cent of people surveyed preferred a scenario comprised of a higher renewables mix in 2030, and nearly three-quarters of this group preferred that energy storage, rather than coal and gas, bolster grid reliability. Energy storage beyond the individual dwelling – at grid scale or for multiple dwellings – is not well known, with pumped hydro being the form most identified. People have environmental concerns with pumped hydro, but this may stem from inadequate knowledge.

Opportunities for Australia

This report identifies significant energy storage technology opportunities for Australia across global supply chains, as summarised in Table 2.

Australia has world-class resources of raw materials used in battery manufacturing, most notably lithium. Our raw materials, together with our world-class expertise in the development of energy storage solutions, including batteries, the design of software and hardware to optimise integration in smart energy systems, and expertise in the design and deployment of systems for off-grid energy supply and micro-grids, demonstrate that Australia has the potential to become a world leader.

While the possibility of Australia becoming a manufacturer of existing battery technologies is highly unlikely, there is opportunity for manufacturing of next generation battery technologies. This is particularly true in niche markets such as situations where safety is paramount, defence applications, and

for Australia's high ambient temperature conditions. Given that current lithium-ion technology was not designed for stationary storage or electric vehicles, but for portable electronics, then an Australian technology that is purposed for a specific application (e.g. hot conditions or defence applications) could underpin the establishment and growth of a local manufacturing capability. We are currently manufacturing, for example, lead-acid batteries specifically for Australian submarines.

Chemical storage is identified as a potential major new export opportunity as countries such as Japan and Korea embrace hydrogen energy. Australia is already committed to supply hydrogen to Japan, but this will be produced using coal. There are opportunities to use our solar energy resources to produce and export renewable hydrogen and ammonia, enabling growth of a new industry that may be suited to northern Australia.

While Australia is very capable in the research and development (R&D) of energy storage

Technology	Raw Resources	Beneficiation*	Manufacturing	Deployment	End of Life
Established Battery Technologies	✓✓✓	✓		✓✓✓	✓
Next-Generation Battery Technologies	✓✓	✓	✓	✓✓✓	✓
Renewable Hydrogen and Ammonia	✓✓✓		✓✓	✓✓✓	
Thermal Energy Storage			✓	✓✓	
Pumped Hydro Energy Storage	✓✓			✓✓	
Integration and Control Technologies			✓✓	✓✓✓	

Table 2: Overview of industry opportunities by technology across the energy storage supply chain

✓✓✓ excellent opportunity ✓✓ good opportunity ✓ potential opportunity if blank: not applicable

*Any process that improves the economic value of a mineral ore by removing commercially worthless minerals, which results in a higher-grade product and a waste stream.

technologies, we do not have a history of converting this in to growth in local manufacture or the development of a local industry, with several examples identified where technology based on Australian intellectual property (IP) has been developed overseas. Conditions required for Australia to create an energy storage industry may include the availability and support of start-up accelerators, creation of R&D incentives for industry to invest, and encouraging more venture capital.

The impact and risks of the various energy storage technologies vary. Pumped hydro was found to be a low risk, low impact technology. Despite the geographic limitations for pumped hydro, and the time (years) to implement new facilities, it is a technology that offers much potential for deployment in the grid.

While lithium-ion technology is the battery technology of choice for most energy storage applications, it comes with risks and impacts. For example, existing technologies rely on materials that have human rights impacts (for example mining of cobalt in the Democratic Republic of Congo) and availability of lithium resources. However, there is a potential opportunity for Australia, which has considerable lithium resources and where technologies for beneficiation of lithium ores are being developed.

Recycling is identified as an opportunity for Australia, with a history of recycling more than 90 per cent of lead-acid batteries. Opportunities to develop technologies to recycle components of lithium batteries

(including cobalt, nickel and lithium) could be further encouraged and supported.

Importantly, Australia has an opportunity to encourage product stewardship across the whole life cycle, including responsible sourcing of materials, development of mining standards and sustainability codes, and disposal.

Options for Further Work

Our findings provide reassurance that both energy reliability and security requirements can be met with readily available storage technologies. Notwithstanding, the market and technologies for energy storage and its integration into electricity networks continue to evolve. Research investment in the following will be valuable:

- The optimum balance of generation, storage and interconnection, taking into account cost optimisation and the long-term strategic opportunities for Australia.
- The role of 'prosumers' including their effects on the market, the system (equity and pricing concerns) and on their contribution to the energy transformation that is underway.
- The broader question of public literacy as Australians' knowledge of, and attitudes towards, energy storage will shape its acceptance and adoption.
- A deeper analysis of opportunities for growth of a substantial energy storage industry in Australia.

Conclusion

Over the past decade, Australia's electricity market has experienced change on an unprecedented scale. In a decentralised, yet integrated 21st century energy future, electricity networks must enable new opportunities for managing the complexity of multiple pathways for flows of electricity and payments. Energy storage has the potential to upend the industry structures, both physical and economic, that have defined power markets for the last century.

There is a legitimate role for governments to ensure that the right policy settings are enacted to drive growth in energy storage. Policy leadership will result in innovation, investment, the establishment of new high technology industries, the growth of existing high technology industries and increased or new energy exports. A proactive approach will provide the opportunity for Australia to lead and facilitate re-skilling of workforces and the creation of jobs across all levels of the value chain from mining and manufacturing through to consumer spending.

“Australia needs to move much faster to ensure its energy market is keeping pace with rapid technological change. The electricity system and regulation hasn't kept up with the furious pace of technology development ... Technology is evolving so quickly ... That's really where we're going in energy.”

Audrey Zibelman

Chief Executive Officer

Australian Energy Market Operator (AEMO)

(Australian Financial Review, 28 March, 2017)

KEY FINDINGS

The key findings presented below are drawn from the four major chapters within this report – modelling of storage requirements for reliable electricity in Australia; opportunities for Australian research and industry in global and local energy storage supply chains; environmental benefits and risks from the uptake of energy storage; and the social drivers and barriers to uptake of energy storage.

- 1. There is a near-term requirement to strengthen energy *security*² in NEM jurisdictions. Maintaining acceptable energy security levels for customers will dominate energy *reliability*³ requirements until well in excess of 50 per cent renewable energy penetration.⁴**
 - Batteries are cost-effective for system security when installed with a high power-to-energy ratio, noting that there are other ways to strengthen system security (e.g. installation of more fast-start gas turbines, use of spinning reserve in wind turbines, and demand response and load shedding measures).
- 2. At an aggregated national level⁵, Australia can reach penetrations of 50 per cent renewable energy without a significant requirement for storage to support energy *reliability*.**
 - Installing the levels of storage power capacity (GW) required for the purpose of *security* creates the opportunity to expand energy stored (GWh) capacity for *reliability* at a lower marginal cost than would otherwise be the case.
 - Despite significant development time, pumped hydro energy storage (PHES) is presently the cheapest way to meet a reliability requirement. Projections indicate that the most cost-effective energy storage

2. “System security” is the ability to deliver near-instantaneous power (GW) for short periods (seconds to minutes) as fast frequency response to withstand sudden changes or contingency events in electricity generation (e.g. failure of a large generator), transmission (loss of a transmission line) or demand.

3. “System reliability” is the ability to meet electrical energy demand (GWh) at all times of the day, the year, and in future.

4. Ensuring system reliability and system security is a core function of the Australian Energy Market Operator (AEMO).

5. The storage requirements differ at a state level.



options available in 2030 will be PHES, lithium-ion batteries and zinc bromine batteries. These all have similar levelised cost of storage (LCOS), depending on the PHES sites selected and uncertainty in the rate of reduction of battery costs.

3. Australia is well placed to participate in global energy storage supply chains. Business opportunities will arise, given appropriate policy decisions at State and Commonwealth levels, and incentives.

- Australia has abundant raw mineral resources for batteries (most notably lithium), but could capture greater value through beneficiation (value-adding to the raw mineral resources).
- Australian companies and researchers are commercialising their energy storage intellectual property (software and hardware for battery integration, design and deployment of off-grid energy supply

and micro-grids, and battery technology and components) through international and global partnerships.

- Australia has abundant resources (e.g. solar), appropriately skilled workforces and established supply chain relationships to generate renewable hydrogen and ammonia at the volumes required to supply potential export markets, such as Japan and Korea.

4. Australia's research and development performance in energy storage technologies is world class, but would benefit from strategic focus and enhanced collaboration.

- Australia is recognised as conducting world-leading research in several energy storage disciplines including electrochemistry, materials development and materials processing for advanced batteries, and power system design and modelling.

- Deriving the full return-on-investment from this research requires improved research translation through national and international industry-research collaboration and commercialisation.

5. The availability of private sector risk capital and profitable revenue streams for Australian energy storage start-ups and projects is a challenge for new ventures, as is policy uncertainty.

- Profitable revenue streams from energy markets together with consistent, stable and integrated energy and climate policies will be essential to drive investment in energy storage and other technology solutions that support decarbonisation of the electricity system while ensuring system security and consumer equity.
- Technology-neutral market-based reforms will be required to address these challenges at least cost.

6. A high uptake of battery storage has a potential for significant safety, environmental and social impacts that would undermine net benefits.

- The development of safety standards is required given anticipated rapid uptake of batteries.

- As an early market “test bed” for batteries, Australia has an opportunity to promote and lead development of sustainable supply chains from mining to disposal. This would use Australia’s expertise in sustainable mining to lead and support the development of international standards.

- There are opportunities for consumers to influence commercial behaviour globally through improved awareness of the environmental and social impacts of battery development.

7. Unless planned for and managed appropriately, batteries present a future waste management challenge.

- Australia has an opportunity to play a product stewardship role to ensure the sustainable repurposing of used electric vehicle batteries and recycling of all batteries.
- Focused development of recycling infrastructure and technology will be crucial and provides an opportunity for industry development and job growth.

8. Australians are deeply concerned by the sharp rise in electricity prices and affordability. They hold governments and energy providers directly responsible for the perceived lack of affordability.

- Deregulation of the electricity market, changes in feed-in-tariff schemes and other time of use tariffs have led to an underlying general mistrust of the government and energy providers.
- Focus group participants believe that individual consumers who can afford home battery storage units may elect to become independent of the grid to avoid rising energy costs.

9. Energy storage is not a well-known concept in the community and there are concerns that a lack of suitable standards at the household level will affect safety.

- A majority of respondents surveyed said they did not know enough to make an informed decision about whether to purchase a home battery storage unit.

- Although a battery storage installation standard is currently being developed, there are concerns that an early incident may have serious ramifications for household deployment, with many referring to the “Home Insulation Program” failure.

- “Pumped hydro” was recognised by some as an established utility scale technology, but that possible “social licence” issues may arise due to the perception of competing land use and a potential lack of water.

- There is an opportunity for governments to increase the public’s knowledge and awareness of energy systems (from energy generation through to storage – at utility and consumer levels).

10. Australians favour a higher renewable mix by 2030, particularly PV and wind, with significant energy storage deployed to manage grid security.

- The majority of those surveyed suggested they would look to government to play a role in the future energy mix, but lacked confidence that their preference for higher renewables would be achieved without consistent energy policies.

BACKGROUND

Delivered as a co-funded project between the Australian Council of Learned Academies (ACOLA) and Australia's Chief Scientist, this report considers the transformative role that energy storage can play in Australia's energy systems; identifies economic opportunities and challenges; and describes the current state of, and future trends in, energy storage technologies. It examines the scientific, technological, economic and social aspects of the role that energy storage can play in Australia's transition to a low-carbon economy over the coming decade and beyond. While acknowledging the diverse applications and services that energy storage technologies can provide (including for transport), this report focuses on storage of low-carbon energy for electricity supply in Australia, together with industry, export and research opportunities.

This project was commissioned in July 2016. Events since commissioning have focused the interest of governments, industry and the community on the potential and need for energy storage to play a role in Australia's transitioning energy supply mix. These events include:

- Extreme weather events that resulted in South Australia's state-wide blackout in September 2016, and emergency load-shedding in New South Wales and South Australia in February 2017.
- The announcement in November 2016, and completion on 31 March 2017, of the closure of Hazelwood power station in Victoria.
- Commissioning of two major reviews by the Australian Government:
 - 'An independent review into the future security of the National Electricity Market' led by Australia's Chief Scientist, Dr Alan Finkel (announced in October 2016); and
 - A review into retail electricity pricing in Australia to be undertaken by the Australian Competition and Consumer Commission (announced in March 2017).



- Establishment by the Australian Senate in October 2016 (report published in April 2017) of a Select Committee into the *Resilience of Electricity Infrastructure in a Warming World*. This inquiry reported on the role of storage technologies and localised distributed generation to provide Australia's electricity networks with the resilience to withstand the increasing severity and frequency of extreme weather events driven by global warming, and recommend measures that should be taken by federal, state and local governments to hasten the rollout of such technologies.
- Announcement by the Minister for the Environment and Energy in April 2017 that a special review on power system security, electricity prices and emission reductions was to be delivered jointly by the Climate Change Authority and the Australian Energy Market Commission. The report was delivered by 1 June 2017 to provide advice on policies to enhance power system security and to reduce electricity prices consistent with achieving Australia's emission reduction targets in the Paris Agreement.

- The development by Energy Networks Australia and CSIRO of an *Electricity Network Transformation Roadmap* (published in April 2017) which outlines a national plan to “keep the lights on, make sure bills are affordable and decarbonise our electricity industry by mid-century” (Graham, 2017).
- Announcements by the Premiers of South Australia and Victoria in March 2017 that their governments would invest \$A150 million and \$A25 million respectively into the delivery of energy storage projects in support of system security within those states.
- Announcement by the Australian Government (March 2017) that it would invest up to \$A2 billion into the expansion of the Snowy Mountains Hydro Scheme (badged as Snowy Mountains Scheme 2), with a feasibility study to be concluded by the end of 2017.
 - In the 2017 Budget, announced on 9 May, the Australian Government indicated that it might take greater ownership of the Snowy Mountains Hydro Scheme from Victoria and New South Wales.
- Announcements of major projects involving energy storage including a \$A1 billion project led by Lyon Energy to build a 330 MW solar farm with a 100 MW battery with four hours of storage in South Australia, the 250 MW Kidston solar farm and pumped hydro storage project in North Queensland (250 MW with six hours’ storage), and the Lakeland solar project in North Queensland (a 10.8 MW solar farm and a 5.3 MWh battery).

Methodology

Two underpinning phases supported the development of this report:

- Phase I – provided an outline of the Australian context for energy storage, an overview of relevant policy and regulatory developments, a range of emerging energy storage technologies, and the potential diversity of their application.
- Phase II – consisted of four discrete work programs that investigated key aspects of the market identified in Phase I. Specifically:
 - A multiple-scenario approach to model the potential requirement for uptake of energy storage to ensure Australia’s energy security (undertaken by UTS: Institute for Sustainable Futures)
 - The opportunities for Australian research and industry in global and local energy supply chains (undertaken by the Australian Academy of Technology and Engineering (ATSE))
 - The cradle-to-grave environmental and safety benefits and risks presented by uptake of energy storage (undertaken by the UTS: Institute for Sustainable Futures)
 - The social drivers of, and barriers to, energy storage uptake, and the potential benefit or detriment to the public in achieving energy storage uptake targets (undertaken by the University of Queensland).

Scope

The objective of this study has not been to forecast the stationary⁶ energy mix that may be in place at 2030, but rather to determine the range of energy storage requirements that may arise given possible energy generation pathways. Three scenarios were chosen to study likely energy storage requirements:

- LOW RE – low uptake of renewable energy
- MID RE – medium uptake of renewable energy solutions
- HIGH RE – high uptake of renewable energy solutions.

The three scenarios, including energy from variable and dispatchable (able to adjust their power output supplied to the electrical grid on demand) renewable energy sources, respectively account for approximately 35 per cent, 50 per cent, and 75 per cent of total electricity generated and supplied in 2030. Sources of electricity include rooftop solar, large-scale solar, wind, pumped hydro or any other renewable energy technologies included in the 2030 energy mix. The modelling relied on other studies to provide data and to support the anticipated rapid expansion of small-scale storage requirements.

The key energy storage technologies reviewed for their potential application in Australia's energy mix include:

- Mechanical
 - Pumped hydro energy storage (PHES)
 - Compressed air energy storage (CAES)

- Electrochemical
 - Batteries
- Chemical
 - Power-to-gas (fuel synthesis using renewable energy)
- Thermal⁷
 - Molten salts
 - Liquid air energy storage (LAES)
- Thermo-chemical
 - Ammonia dissociation-recombination

Solar fuels and algal biofuels as a storage medium did not form part of the scope of this work.

The energy scenarios and the key energy storage technologies, as outlined, have informed the development of each of the four discrete work programs. The Expert Working Group comprising of Fellows or nominees from each of the four Australian Learned Academies (Australian Academy of the Humanities, Australian Academy of Science, Academy of the Social Sciences in Australia, and Australian Academy of Technology and Engineering) identified organisations to undertake each of the discrete work programs. The outcomes of these programs have, in turn, informed the development of this report.

The individual reports that resulted from the discrete work programs are available on the ACOLA website (www.acola.org.au).

6. Because Australia is not a vehicle-manufacturing nation, this report has not attempted to forecast local use and supply of batteries for, nor to ascertain consumers' and other stakeholders' views on, electric, plug-in hybrid and hybrid vehicles. However, the contribution of Australian R&D and the implications for, and opportunities from, re-purposing, recycling and disposal of transport batteries are implicitly covered in this report.

7. Thermal storage in this context refers to storing energy in the form of high temperature heat for later use (electricity generation, process heat for industry) as opposed to low temperature thermal storage such as solar hot water or passive solar building features.

INTRODUCTION

Electricity is both a basic part of nature (lightning being the most obvious example) and one of the most widely used forms of energy. It is a *secondary energy source* because *primary sources* of energy such as coal, natural gas, nuclear energy, solar energy and wind energy must be converted into electrical power. Electricity is also an *energy carrier*, which means it can be converted to other forms of energy such as mechanical energy or heat.

Traditionally, electricity is generated when a turbine spins to create an electric current. Energy to spin these turbines comes from burning coal or natural gas; capturing heat from nuclear reactions, the earth itself (geothermal energy) or concentrated solar energy; or harnessing the wind to rotate wind turbine blades. Solar energy can also be converted directly to electricity (solar PV), a technology increasingly deployed worldwide.

Sending electricity from a generating station to customers relies on complex transmission and distribution networks. Transmission lines are generally of a higher voltage to carry more power across longer distances, while distribution lines above or below city streets carry power to individual consumers. Both sets of networks are critical to deliver power to consumers.

The electricity system supporting Australia's economy and lifestyle was built on the economies of scale associated with large centralised generation technologies delivering electricity via one-way transmission and distribution networks to industrial, commercial and residential customers (Figure 2). This regulated, predominantly government-owned business model drove down the cost of electricity, fostered universal access, and provided reliable electric service.

To maintain a reliable and secure electricity transmission grid, an intricate physical balance must constantly be maintained between the amount of power that is generated and the amount that is consumed. Without energy storage, once electricity is generated it must be consumed at nearly the same time. All the fast-spinning turbines that are joined together



by three-phase electrical currents twisting along the transmission network maintain this delicate balance. Australia has the longest transmission network in the world.

Turbines are synchronised to deliver an alternating current at Australia's 50 Hz grid frequency, which is maintained with remarkable precision. Consumers provide

the drag that slows the rotation of turbines, by drawing energy out of the system, while fossil fuel or hydro generators – and more recently wind and solar generators – provide the acceleration. The Australian Energy Market Operator (AEMO), which also has the parallel role of facilitating energy trading, is the system operator.

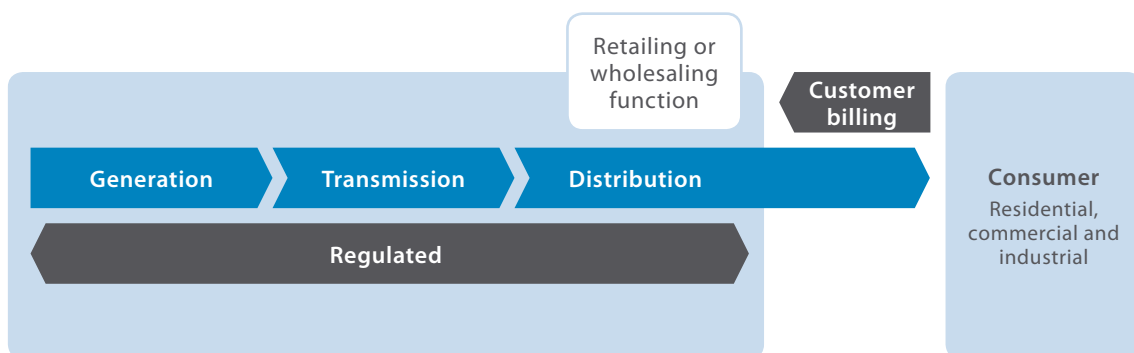


Figure 2: The 'one-way' traditional structure of the vertically integrated utility business model (adapted from Tuttle et al., 2016)

Australia's National Electricity Market (NEM) commenced operation in December 1998 as a wholesale market for the supply of electricity to retailers and end-users in Queensland, New South Wales, the Australian Capital Territory, Victoria and South Australia. Tasmania joined the NEM in 2005 and operations today are based in five interconnected regions that largely follow state boundaries. The NEM operates on the world's longest interconnected power system – from Port Douglas in Queensland to Port Lincoln in South Australia – a distance of around 5,000 kilometres. In 2016–17 more than \$A16 billion of wholesale electricity was traded in the NEM to meet the demand of almost 10 million Australian Homes and businesses (AEMO, 2017).

Over the last decade, the NEM has experienced change on an unprecedented scale, and

that change continues unabated. State and territory government-owned generators, transmitters and distributors of electricity has been variously privatised or broken up, with intrastate and interstate retail competition strongly encouraged and adopted.

The ownership and operating structures of most of the businesses in Australia's electricity systems, and particularly in the NEM, are radically different from those of 20 years ago.

In 2001, the Renewable Energy Target (RET) was established by the Commonwealth Government with the initial aim to source two per cent of Australia's electricity from renewable sources. The RET has undergone reviews and changes since, and in January 2011 was split into two parts:

- The Large-scale Renewable Energy Target, which creates a financial incentive to establish and expand renewable power

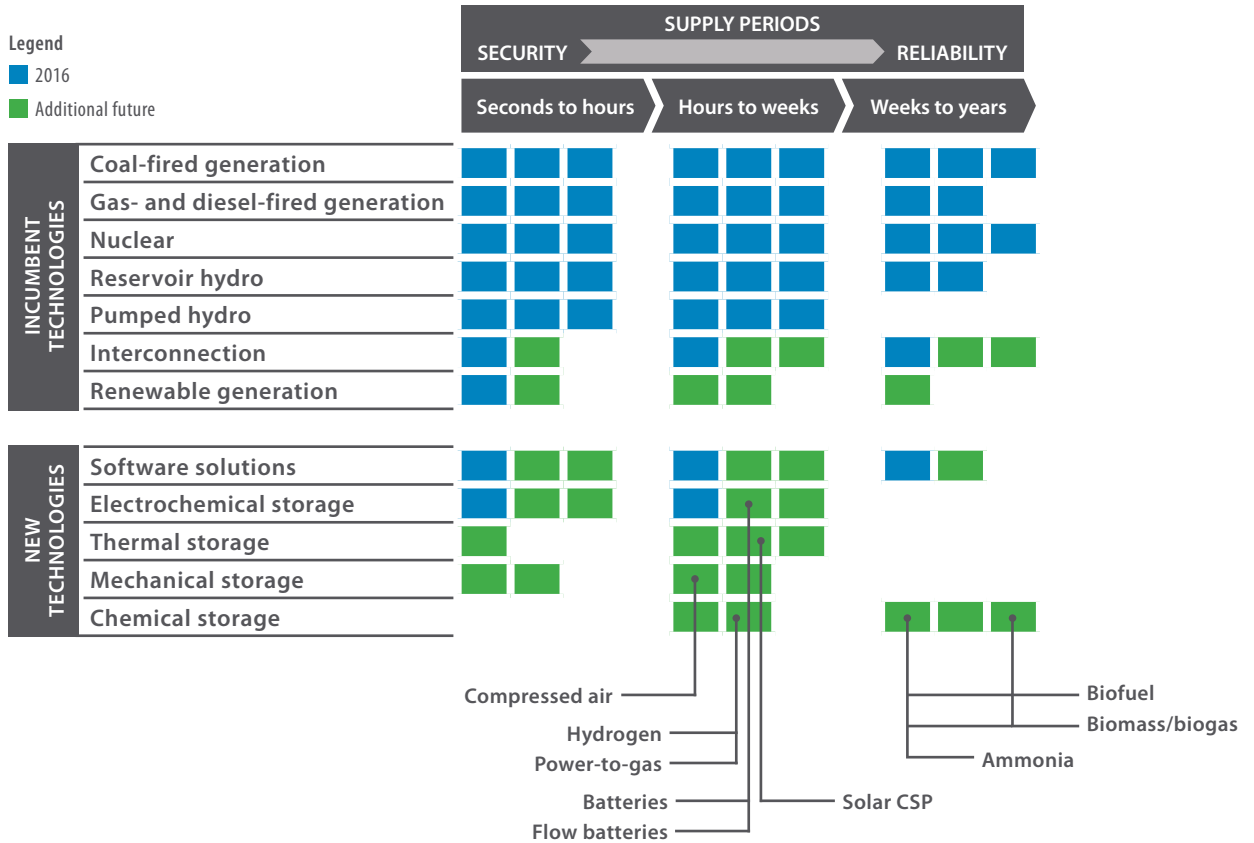


Figure 3: Technology options for balancing the future grid. The number of boxes represents the technology's ability to meet current (blue) and future (green) supply period demands (adapted from Liebreich, M., Bloomberg New Energy Finance, 2016).

stations such as solar farms, wind farms and hydro-electric power stations and deliver the majority of the 33,000 GWh 2020 target.

- The Small-scale Renewable Energy Scheme (SRES), which creates a financial incentive for individuals and small businesses to install eligible small-scale renewable energy systems such as solar panel systems, small-scale wind systems, small-scale hydro systems, solar water heaters and air source heat pumps.

Encouraged by the SRES as well as state and territory technology-specific energy policies, many Australians and Australian businesses have invested in new generation technologies (principally solar panel systems). This has allowed them to take control of both their energy use and supply (becoming 'prosumers') to support action on climate change while remaining connected to the established electricity networks.

The positive and negative impacts of these changes – together with a growing

range of technology options (Figure 3) – are encouraging companies in Australia's electricity industry to adopt new technologies and business models as policy makers re-shape the regulatory regime and electricity market structures. Australia's continued transition to an electricity market with greater input from renewables will require market regulations that are both adaptable and dynamic to market needs.

Energy storage is seen by many as the next big change facing Australia's electricity system. The technology can solve challenges that range from smoothing the intermittency of renewable generation to providing power quality support, and managing peak demand to reducing customers' electricity bills. (Cavanagh et al., 2015)

In a decentralised yet integrated 21st century energy future (Figure 4), electricity networks must enable new opportunities for managing the complexity of multiple pathways for flows of electricity and associated payments, while ensuring energy security, energy equity and

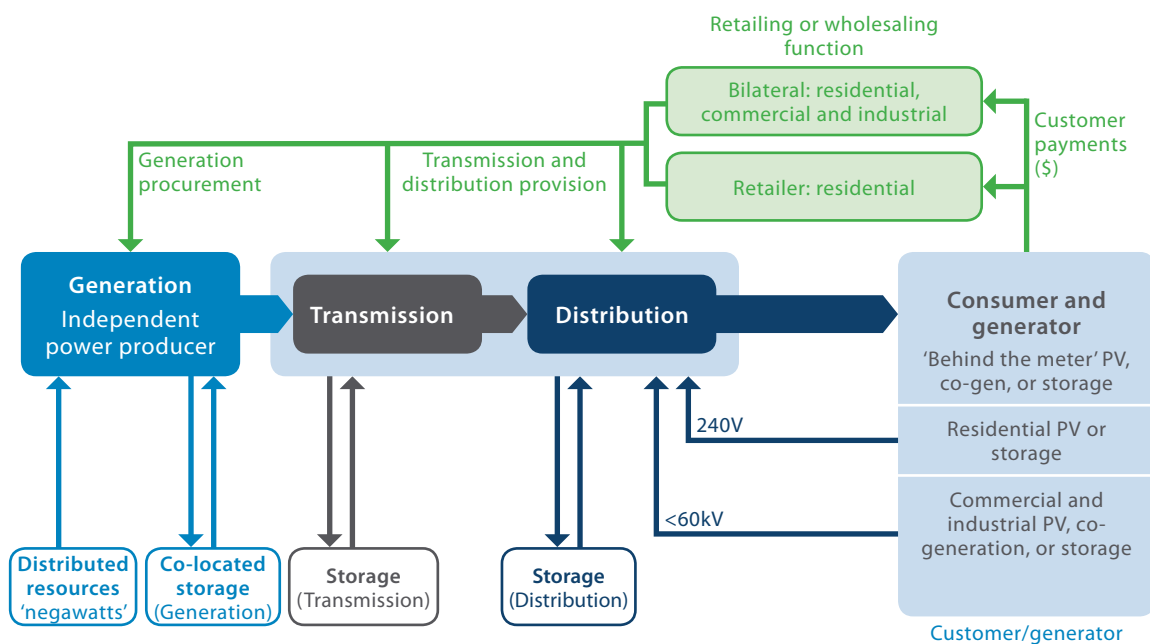


Figure 4: The electricity system of the 21st century will have multiple pathways for two-way flow of both money and electricity (adapted from Tuttle et al., 2016)

environmental sustainability. Energy storage can play a vital role in providing a balanced solution to this energy challenge (Figure 5).

Although energy storage is an emerging industry globally, it is not a new concept. There is a diverse range of energy storage technologies available with differing characteristics for a similarly diverse range of applications and services.

Importantly, energy storage can play a vital role in removing the energy and transport sector's reliance on fossil fuels through electrifying the transport sector and facilitation of high proportions of variable renewable electricity generation. Moreover, the domestic and global markets for energy storage technologies and services

are expected to grow dramatically in the coming years, which presents an economic opportunity for Australia.

Storage will be an important component of intensely distributed electricity systems, providing operational flexibility. Widespread deployment of distributed storage systems will require overcoming market, regulatory and cost barriers. Meanwhile, the development and demonstration of cost-competitive storage systems continues internationally – and Australia historically has a strong reputation in electrochemical battery research and development, including successful commercialisation of novel battery technologies locally and internationally. (Australian Academy of Technology and Engineering, 2013)

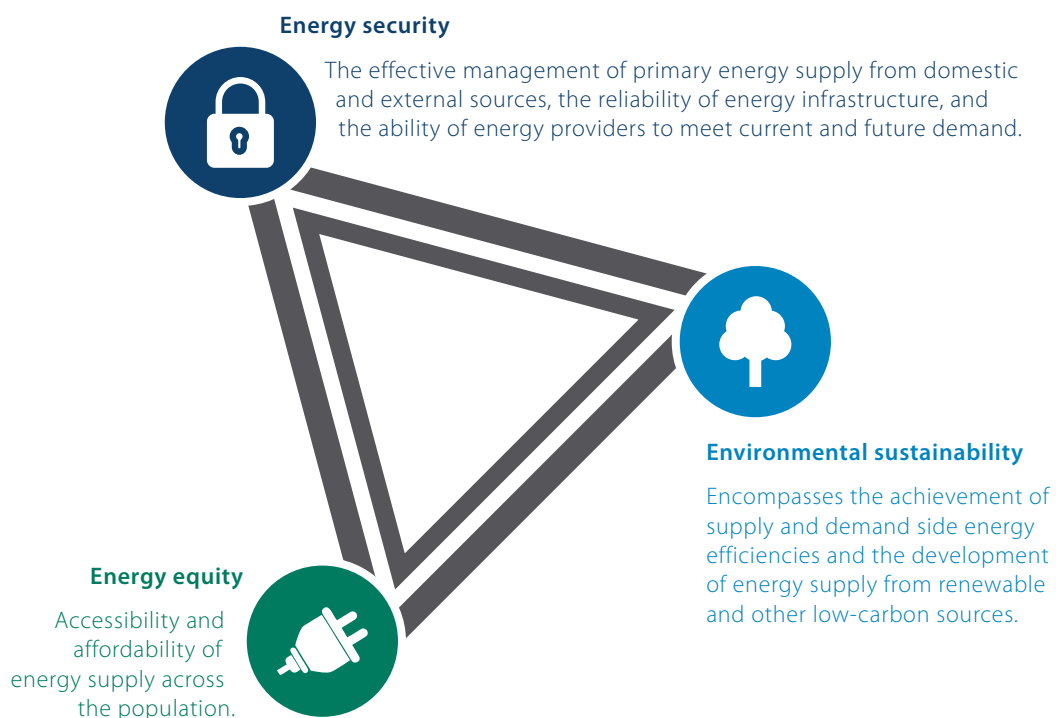


Figure 5: Balancing the energy trilemma (adapted from World Energy Council, 2016)



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CHAPTER 1

MODELLING OF

ENERGY STORAGE

REQUIREMENTS

FOR AUSTRALIA

1 Introduction

Energy storage and the reliability of Australia's electricity systems are very much in the public eye. A transition towards electricity supply from renewable resources, particularly wind and solar, is accelerating as investment in renewable electricity generation and deployment continues and the potential to reduce greenhouse gas is appreciated. Despite this transformation being extensively debated, the implications for reliability of supply during this transition are not fully understood.

Energy storage has the potential to contribute to the two aspects of reliable supply:

- System *security* – the ability to deliver near-instantaneous power (GW) for short periods (seconds to minutes) as fast frequency response so as to withstand sudden changes or contingency events in electricity generation (e.g. failure of a large generator), transmission (loss of a transmission line) or demand.
- System *reliability* – the ability to meet electric energy demand (GWh) at all times of the day, the year, and in future.

Ensuring reliability and security are a core function of the Australian Energy Market Operator (AEMO) and the regulations that underpin the market.

While there are many other uses for energy storage that are currently driving an active market – particularly in residential battery storage – this report is focused on the contribution of energy storage to reliability of supply. The rapidly maturing supply chain and the improving business case for energy storage technologies are helping to make them cost-effective.



Storage requirements for a given demand profile are determined by the generation mix available, and in particular, the proportion of variable renewable sources such as wind and solar, compared to dispatchable sources such as gas, coal, hydro, or bioenergy that can adjust their power output supplied to the electrical grid on demand. The energy reliability requirement will be driven by the longest period of low variable renewable supply, while the security requirement will be driven by the ability of the specific generation mix to respond to and ride through frequency variation events.

The energy generation mix for 2030 is, of course, unknown but is a crucial consideration to understanding both the reliability and the security of a power system. This study has reviewed the likely generation mix between a “no change” energy scenario which involves continued growth of renewable energy under present conditions, and a “high renewables” scenario that has aggressive growth towards 100 per cent renewable energy by around the middle of the century.

Between these two scenarios is a third scenario, “MID renewables”, that delivers moderate growth of renewable energy.

Through these scenarios, the range of storage requirements for reliability and security in the NEM have been estimated. Some of the factors that will govern the solution and key sensitivities are also considered.

Rather than identifying specific energy storage technologies that could be deployed to meet the requirement, an analysis of cost projections has been undertaken – particularly as cost is one of the key factors when choosing technologies.

Other factors taken into consideration include the suitability of each technology to meet reliability or security requirements; public response to large-scale infrastructure projects; geographical constraints and planning requirements; uptake of energy storage for purposes other than power system reliability; safety; and the availability of alternative solutions that do not involve energy storage.

1.1 Energy Storage Scenarios for Australia

The three energy scenarios chosen to provide an envelope of the potential storage requirements by 2030 are (1) a “low renewables scenario” (LOW RE) scenario; (2) a scenario that delivers moderate growth of renewable energy (MID RE); and (3) a high renewable (HIGH RE) scenario. The overall capacity mix by scenario is shown in Figure 6 and capacities by state shown in Figure 7.

Generation capacity mix in gigawatt (GW) has been used as *input* to the scenario modelling. The amount of renewable electricity generated (GWh) is a modelling *output*, as it depends on both the hourly demand and the order that different generation types are used

or dispatched. In the three scenarios (LOW RE, MID RE and HIGH RE) the modelled output of renewable energy, including energy from variable and dispatchable renewable sources, accounts for, respectively, approximately 35 per cent, 50 per cent and 75 per cent of electricity generation at 2030. Individual state percentages vary from 20 per cent to 100 per cent in the LOW RE scenario, and from 54 per cent to 100 per cent in the HIGH RE scenario.

The **LOW RE scenario** has been derived from the AEMO generation information for each state, including committed and proposed projects. In this scenario, it is assumed that 50 per cent of proposed wind, solar, and gas projects proceed, with the exception that in South Australia only the committed wind

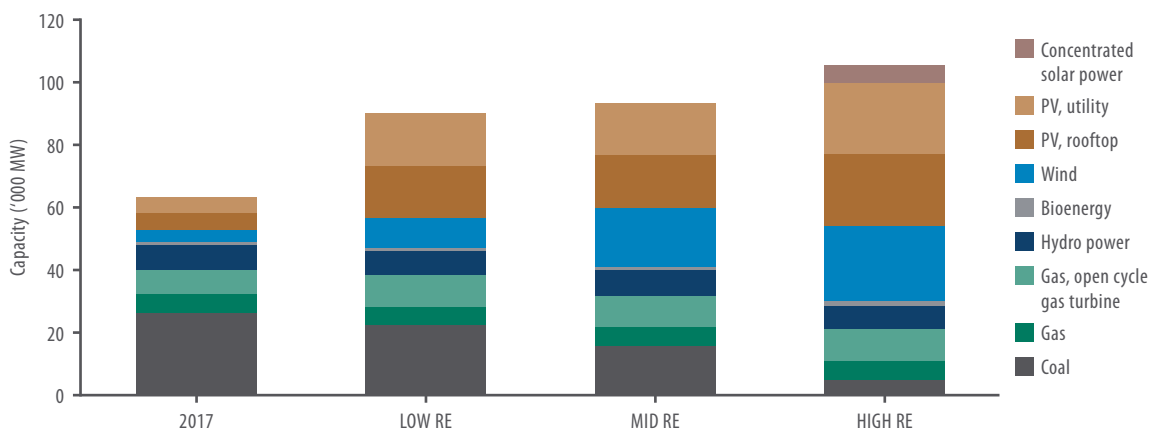


Figure 6: Total generation capacity by scenario in 2030

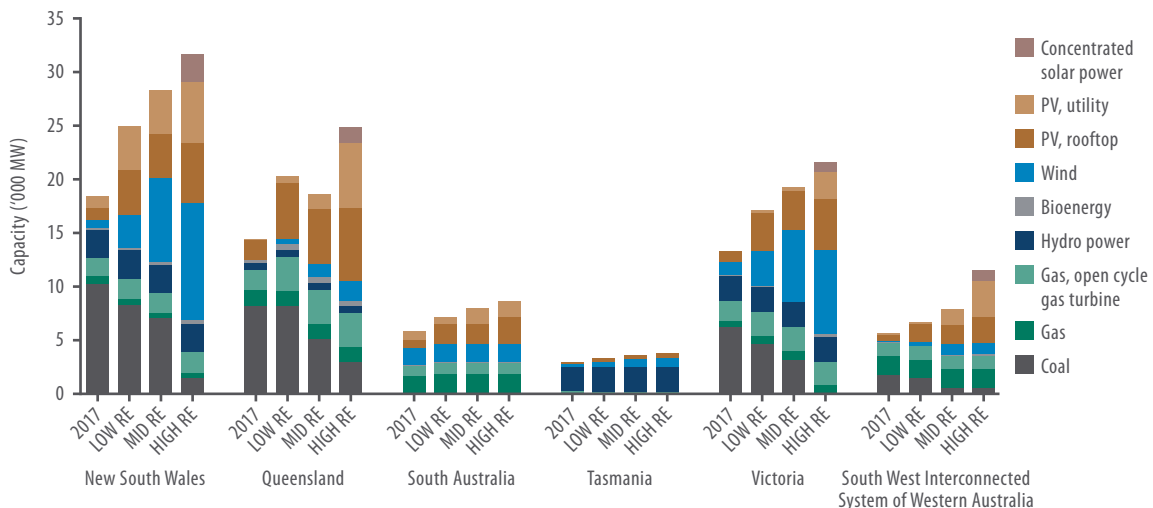


Figure 7: Generation capacity, scenarios by state

farms proceed.⁸ Announced withdrawals of 3940 MW of coal plant are included. Rooftop solar data for each state is taken from the National Electricity and Gas Forecasting report (AEMO, 2016a), using the neutral projection of installed capacity.

The **MID RE scenario** increases the penetration of renewable generation, and retires a number of coal fired generators, sufficient to meet the electricity sector renewable penetration in the lowest cost scenario in the Climate Change Authority (CCA) report (Climate Change Authority, 2016). This presented a range of renewable penetrations from 46–76 per cent corresponding to different policy options. Fifty-two per cent renewable generation was chosen in the CCA report as the likely outcome of an emissions intensity scheme, which the CCA identified as the lowest cost option. This level of approximately 50 per cent was taken as the target renewable percentage for the MID RE scenario for this report. For this scenario, the capacity mix was iterated until it resulted in a 50 per cent renewable generation output.

The **HIGH RE scenario** uses the nationwide generation capacities from a projection of 100 per cent renewable electricity undertaken recently by the University of Technology Sydney, Institute for Sustainable Futures (Teske et al., 2016), and modified to remove the capacity increase projected to cater for a rapid switch to electric vehicles.⁹ In order to arrive at a state-by-state allocation, the nationwide capacities per technology were allocated in proportion to presently proposed projects, and then adjusted to distribute the resulting curtailment more equally between

states. Coal retirements were scheduled with older generators retired first.

Hydro generation is an important variable in the modelling because it can operate as a peaking plant¹⁰. A conservative approach was adopted for potential output from hydro, with a maximum capacity factor of 20 per cent assumed for NEM states other than Tasmania, where a 50 per cent capacity factor is assumed. The 20 per cent capacity factor corresponds to overall hydro output from 2010, which was a low year (Office of Chief Economist, 2016). The Tasmanian hydro maximum capacity factor was set at the minimum average annual capacity between 2011 and 2017 (Hydro Tasmania, 2017)¹¹. The dispatch order in the model puts variable renewables ahead of hydro and bioenergy, so the actual capacity factor depends on the amount of variable renewables. In Tasmania, the modelled capacity factor is less than 50 per cent in the HIGH RE scenario.

Northern Australia, comprising northern Western Australia, the Northern Territory and northwest Queensland, are not included in this assessment because their electricity generation is dominated by gas and diesel. There will be limited demand for storage to provide system reliability for the foreseeable future when supplying local loads. Using batteries to help manage hybrid diesel-renewable or gas-renewable local power stations is already a well-understood proposition. Nevertheless, there is an opportunity to scale up the energy storage industry in Northern Australia in order to facilitate the development of a renewable energy export industry.

8. Energy mix data between states was revised after the first modelling runs, which resulted in an unrealistically high potential curtailment in South Australia in the HIGH RE scenario.

9. The storage and demand associated with electric vehicles is outside the scope of this work.

10. Peaking plants are power plants that generally run only on the few occasions when there is a high demand, known as peak demand, for electricity.

11. The detailed information available for Hydro Tasmania (2011–2017) was not available for the other states.

1.2 Energy Storage Technologies and their Projected Costs

Six different energy storage technologies were analysed (see Appendix 1). These included three types of batteries (advanced lead acid, lithium-ion (Li-ion) and zinc bromine (Zn-Br)), compressed air energy storage (CAES), pumped hydro energy storage (PHES), concentrated solar power (CSP) molten salt storage, and power-to-gas conversion. This selection is based on the assumption that only very large amounts of energy storage will be useful for power system reliability, so only those technologies with the best prospects of being used for large-scale energy storage in Australia by 2030 have been included.

The biggest challenge associated with performing cost comparisons of energy storage technologies is formulating a metric that can standardise the cost comparison while taking into account the different imperatives of storage that each technology is designed to meet. This is particularly difficult for utility-scale storage solutions such as PHES and CAES, whose costs cannot be generalised because they are site-specific (IRENA, 2012; Luo et al., 2014).

Energy storage specialists have approached costing in two ways – by performing profitability analyses of the technologies (Locatelli, Palermo & Mancini, 2015; Parra et al., 2016), or by calculating a discounted cost per unit of discharged electricity (denominated in \$/kWh or \$/MWh) known as the levelised cost of energy storage (LCOS) (Julch, 2016), which is effectively the levelised cost of energy discharged from storage. **LCOS is used in this study, and is defined as the total lifetime cost of an investment divided by the cumulative energy generated out of the storage medium by this investment**

(Pawel, 2014). While LCOS has been used extensively in recent literature for energy storage cost analysis (Julch, 2016; Pawel, 2014; Zakeri & Syri, 2015) it is believed that this is the first such Australian study published. When considering the energy reliability requirement, LCOS is considered an appropriate metric as it assigns a cost based on energy cycling through the storage medium. Nevertheless, a different calculation may be required to assess and compare the costs of storage for the provision of grid services, such as frequency regulation. The LCOS does not measure the value of energy storage to any given stakeholder group, but provides a method for comparing the costs associated with alternative energy storage technologies. **LCOS cannot be compared directly to levelised cost of energy (LCOE). As such, it is not useful to compare storage options to generation options without additional in-depth analysis.**

The key inputs to the LCOS calculation are the capital cost of the equipment, costs associated with operations and maintenance, the cost of the electricity to be stored, and the technical parameters associated with the technology, such as round-trip efficiency.¹² Many of these parameters vary according to the use case, and in particular, whether the storage is behind or in front of the meter. The comparisons in this report assume storage is in front of the meter.

Data for capital costs and technical specifications were sourced from primary research and literature. Technical data, such as depth of discharge (the degree to which a battery can discharge relative to its capacity) and round-trip efficiency, was obtained from the literature.

12. Energy storage consumes electricity ('charging'), saves it in some manner and then delivers it back ('discharging') to the consumer or electricity grid. The ratio of energy put in (in kWh, MWh or GWh, depending on the scale of the storage plant) to the energy delivered back from the storage plant is the round-trip efficiency, expressed as a percentage (%). The higher the round-trip efficiency, the less energy is lost due to storage and thus the more efficient the system is as whole.

Comparing battery costs is complex, as capital costs may be given with and without inverters, and with or without installation. In order to standardise the comparison, the capital cost for all data sources that excluded the inverter and installation costs was adjusted by adding these costs from CSIRO storage report (Brinsmead et al., 2016). Appendix 2 provides summaries of cost data and technical specifications for the storage technologies analysed.

The LCOS analysis was undertaken with particular emphasis on the application of selected technologies to supplying energy reliability in the Australian market. Thus, the variables were chosen as far as possible for a utility scale application with reasonably frequent cycling. Estimated LCOS values for this application are shown in Figure 8¹³, noting that there is a high degree of uncertainty in these data, as many assumptions are required to undertake the calculation, and the cost is intricately bound up with the use application. For example, the number of cycles per year for the storage and the input electricity price have a high impact on the LCOS (Figure 9),

which may vary significantly according to market dynamics, the purpose of the storage, and the location within the network.

Different technologies also have distinct characteristics, and finding a suitable technology for the purpose may be much more important than the cost.

Some technologies are suitable for storing electricity from any generation source, while others, such as molten salt, are paired to a particular generation type (i.e. concentrated solar thermal power). Compressed air energy storage (CAES) also can be cost competitive, but its LCOS is highly dependent on the interaction between gas and electricity prices – expensive gas and cheap electricity will result in a higher LCOS, and vice versa. Deployment potential is also varied, with pumped hydro energy storage (PHES) and CAES dependent on suitable sites and each has a long development and construction lead-time, while batteries may be deployed quickly virtually anywhere. The LCOS is directly proportional to the price of electricity for all the energy storage technologies shown in Figure 9.

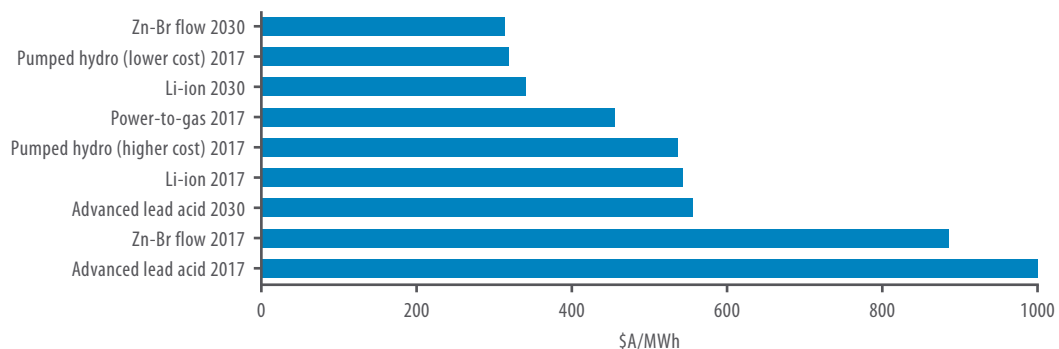


Figure 8: Indicative levelised cost of energy storage for bulk energy storage by technology (\$/MWh)

Note: Only those batteries where sufficient evidence exists of future trends have been included in this figure. The assumed electricity price is \$A100/MWh. A full list of input assumptions used to calculate the levelised cost of energy is provided at Appendix 2.

13. Constant costs are assumed for all non-battery technologies. Power-to-gas does not exist yet at scale so there is no credible present cost. Pumped hydro is mature and costs are not anticipated to change materially between 2017 and 2030. This is a constant-dollar analysis (no inflation) so costs in 2017 and expected costs in 2030 can be directly compared.

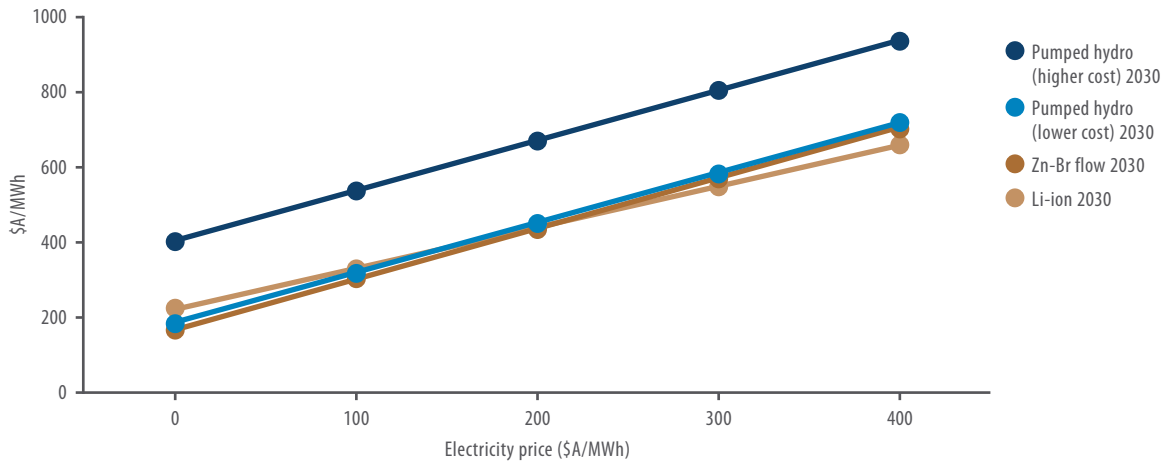


Figure 9: Changes in levelised cost of energy storage (LCOS) plotted against changes in electricity price. As shown, LCOS (2030) is proportional to the price of electricity for the energy storage technologies included.

1.3 Modelling of System Reliability and Security

The modelling was designed to provide the minimum credible analysis to estimate an energy storage requirement for reliability, accounting for:

- The characteristics of the technologies
- The existing energy mix in Australia and its potential changes until 2030
- Major interconnectors between states (which are separate market regions).

The distinctly different approaches taken by each jurisdiction means that this report must apply a separate analysis to each in order to gauge the reliability and security requirements for energy storage.

1.3.1 Reliability and security requirements

Understanding reliability, the ability to meet demand, requires a time-series model of available energy sources and energy demand.

A model with minimum complexity to study power system reliability is based on an hourly analysis of supply and demand in each state. The key sources of variability are wind generation and solar generation. Demand-controllable

generation sources, along with energy storage, are dispatched to meet any demand that is not supplied by wind and solar generation. Hourly resolution is sufficient to resolve mismatches in supply and demand that would influence energy reliability, and, if sustained, would make it difficult to meet demand.

Because system reliability is limited by any supply constraint, the analysis of storage requirements depends on statistical extremes and is sensitive to the selection of input data, in particular the choice of year for wind and solar data. To model the storage requirement for system reliability, the year with the most extended period of low wind – 2010 – was selected from the available data set (2003–2010). This was done by calculating the longest period for which wind output was lower than 20 per cent of the rated capacity (see Figure 10).

The low wind output should result in the greatest requirement for energy reliability storage. Given that solar irradiance is influenced by the same weather systems that determine the wind, solar energy output is partially correlated with wind energy output. Hence, the same year of data was used for both resources to ensure that the model accounted for this correlation.

Security is about the ability of the power system to transition quickly from one supply–demand balance to another. Australia’s power system relies principally on the inertia of large spinning steam and hydro turbines to maintain a steady frequency. This spinning inertia helps to ensure there is sufficient time (seconds to a few minutes) to respond to sudden changes in electricity generation, transmission or demand (see Box 2).

As renewable energy sources increase their share of capacity, the amount of inertia in those systems tends to decrease. Of the major sources, solar PV generation lacks inertia entirely, while wind generation has inertia that can only be used through explicit control. Considering the changing energy mix from now until 2030, the requirement for fast frequency response was estimated to keep frequency stable as system inertia declines.

The fast frequency response requirement can be met in a number of ways, including the inertia of fossil-fuel generation and some forms of renewable generation. Using ‘synthetic’ inertia from wind turbines is another way to meet this requirement. This form of inertia can be provided with present technologies. However, these forms of fast frequency response are only available when the generators are operating, and this may not be the case at times when the renewable fraction is high as it depends on the available

Box 2: Inertia and Australia’s electrical power system

An electrical power system is designed to run at a nominal frequency, typically 50 or 60 Hz. If energy security cannot be maintained, the system may collapse. Such a collapse may arise when a sudden generator outage occurs and the rate of the subsequent frequency change is not managed. Historically, in the NEM, this rate of change of frequency has been managed by the resistance to frequency change provided by the plentiful system inertia, a by-product of energy production by thermal and hydro generators.

Increasing penetration of renewable generation, which does not provide any or only limited system inertia, raises questions about whether this previously free, essential system inertia has an emerging value and how best to manage rate of change of frequency in the future.

The changing generation mix also affects other aspects of power system security. These include frequency regulation, availability of resources, fault level and transient stability. (Gannon, Swier & Gordon, 2014)



Figure 10: Continuous hours of low wind production where less than 20 per cent of the state’s overall capacity for wind was generated

energy mix of each region. Batteries have the advantage that they do not have to be charging or discharging to offer this service – they just have to be ready for immediate operation with their power electronic systems energised.

Batteries are cost-effective if installed with a high power-to-energy ratio and are now widely considered to provide a new means for stabilising the grid. Having invested in fast frequency response batteries, the incremental cost of adding more power capacity via batteries could be lower than other options, including pumped hydro, even when pumped hydro would otherwise be the cheapest stand-alone solution.

1.3.2 Overview of storage calculation process

Figure 11 provides an overview of the storage calculation process. Key inputs are:

- The generation capacities by type for the three scenarios (LOW RE; MID RE; HIGH RE)
- Demand projections and load curves for each state

- Interconnector capacities
- Meteorological data to calculate hourly solar and wind power generation.

The installed capacities are derived from published sources, and the resulting annual generation in MWh is calculated on the basis of meteorological data (in case of solar and wind) or dispatch requirements.

The model does not include possible intra-state restrictions due to transmission or distribution constraints, so it is assumed generation in a state can meet demand anywhere within that state. Potential interstate export is limited by the capacity of the interconnector, and is only allowed if all demand within the state is met.

The model identifies excess renewable production, defined as potential wind and solar PV generation greater than the actual hourly demand in MW during a specific hour. To avoid curtailment, the surplus renewable electricity must be exported via an interconnector, or stored in some form of energy storage technology.

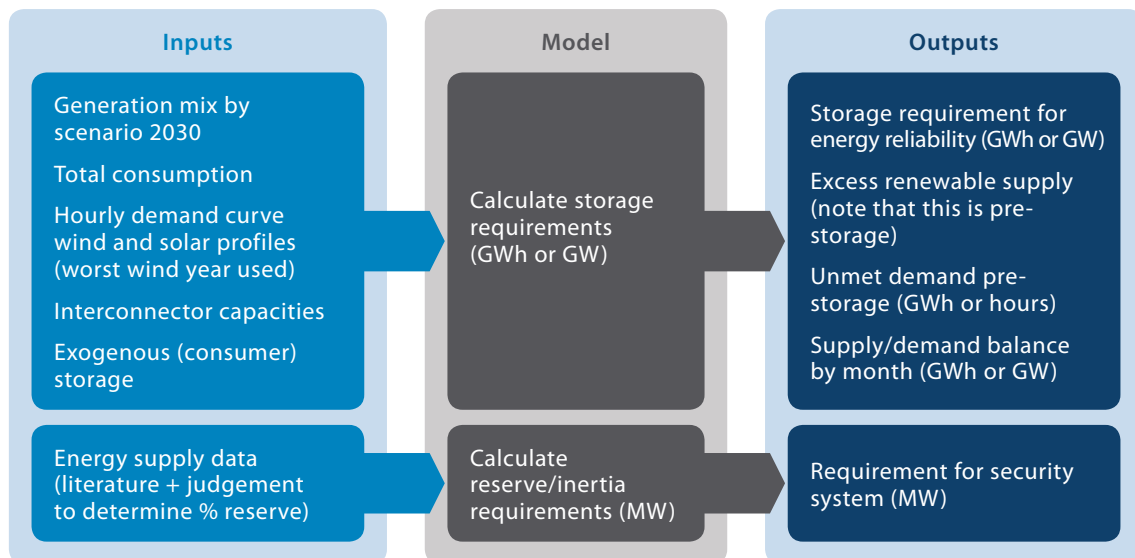


Figure 11: Storage calculation overview

Within the model, excess renewable production accumulates through the dispatch order. If storage is present, it will charge within the limits of the input capacity. If no storage is included, this potential excess renewable production is reported as “potential curtailment” (pre-storage).

Although not brought explicitly into the modelling, energy storage installed for other uses is considered as potentially available to meet a storage requirement for power system reliability or security. For example, it has been assumed that a large amount of behind-the-meter consumer battery storage will be installed by 2030, independent of NEM system requirements. As another example, while electric vehicles are likely to create considerable electric energy demand by 2030, they come with storage. Provided their charging regimes are managed to some degree, their impact on energy supply and additional energy storage requirement can be ignored at a first level of approximation. Nevertheless, manufacturers should consider this issue as they are designing grid-support functions into their vehicles and charging stations.

1.3.3 Modelling limitations

The model developed for this report is not a power system model of Australia’s electricity grid and cannot simulate consumer or generator behaviour. Nevertheless, it does carry out an hour-by-hour calculation of the energy supply balance and calculates the storage required to compensate for extended low supply periods. Key limitations are:

- The model does not take account of distribution or transmission constraints. If there is variable renewable generation in the system, it can go into any utility scale storage in front of the meter, providing the storage is not fully charged.

- For those dispatchable technologies (namely hydro and bioenergy) where a maximum capacity factor over the year is imposed, this is achieved by reducing the effective load continuously until that capacity factor is achieved. This is a simplification, but would tend to increase any storage requirement.
- Interconnectors can only connect one step (e.g. surplus wind from South Australia coming into Victoria cannot supply New South Wales).
- All scenarios have been calculated with the same dispatch order¹⁴ to achieve comparable results, but in order to calculate the storage requirement, storage (other than consumer storage) has been put last in the dispatch order. In the real world, storage is likely to overlap considerably with dispatchable generation, as increasing cycle numbers reduce the levelised cost of energy storage. This means curtailment should be lower in the real world compared to model results.

1.3.4 Modelled results – storage requirements for system reliability and security

Table 3 shows the energy storage requirements indicated by this study for the NEM as a whole. Quantity of energy (GWh) (highlighted in red) is most important for system reliability, while system security requires near-instantaneous delivery of power (GW) to compensate for sudden shocks to system operation. A summary of Australian Energy Market Operator generation information for system reliability and security on a state-by-state basis in the NEM is provided in Appendix 3.

¹⁴. An instruction issued by system management to an electricity generator.

The reliability requirement is due to a mismatch between the times of variable renewable generation and variable demand – as overall there is sufficient energy generation.

While demand response and demand management could contribute to meeting the reliability requirement, it is likely that the majority of demand will need to be met by stored energy within the given supply mix.¹⁵ Multiple storage technologies could meet this requirement, with different costs and characteristics.

The reliability requirement has been defined by examination of an unfavourable year for wind generation, with extended periods of low output.¹⁶ The unmet demand is unlikely to occur in a single period, so the same energy storage resource can be reused multiple times to meet the total unmet demand. That is, unmet demand is a performance

shortfall requirement, and the ratio of storage requirement to demand shortfall requires fewer than ten full discharge cycles from storage. As stated earlier, the year 2010 was selected because it was the year of the longest period of low wind in almost a decade. In any other year of that decade, the unmet demand and storage requirement would have been significantly less. The storage requirement was modelled without the inclusion of any storage associated with concentrated solar power in the energy mix.¹⁷

The summary of storage requirements (Table 3) shows that the requirements for system security exceed the requirements for reliability until very high renewable penetrations. In the HIGH RE scenario, system security energy requirements fall well short of energy reliability requirements. However, the scale of the fast response capacity needed at this level of renewable penetration may

		2017	LOW RE (2030)	MID RE (2030)	HIGH RE (2030)
Total annual grid demand	GWh	216,955	239,134	239,134	239,134
Total capacity	GW	60	79	85	102
Renewable	GWh	37,836	86,787	125,326	180,225
Coal, gas & diesel	GWh	179,118	152,345	113,795	58,040
Via interconnectors ⁽¹⁾	GWh	90	15	46	1,766
Total			239,147	239,167	240,031
Renewable percentage of generation		17%	35%	50%	75%
Emission intensity	tCO ₂ /MWh	0.82	0.47	0.35	0.16
Storage requirement for energy reliability	GWh	0.00	2	5	105
	GW	0.20	0.4	2	10
Storage requirement for system security ⁽²⁾	GWh	0.10	0.5	1	3
	GW	1.30	5.8	16.8	35.2

Table 3: Summary of storage requirements in 2030: LOW RE, MID RE, & HIGH RE scenarios

Note 1: The total net amount that is imported into all states.

Note 2: Although described here as a requirement for storage, system security requires a fast frequency response, that can be provided by storage or by some other means.

15. Demand response can be expected to shift load by some hours, but a shortfall of some days is unlikely to be avoided by demand response unless load is curtailed altogether.

16. The scope of modelling resulted in a short period of weather data being interrogated (seven years) – there may well be more adverse years for wind generation.

17. While it is highly unlikely that concentrated solar power would be installed without storage, the modelling has been undertaken assuming zero storage, in order to ascertain the raw storage requirement.

mean a relatively small additional investment would enable storage for security to provide a significant contribution to meeting the reliability requirement. Assuming batteries meet the security requirement, scaling those to provide an hour of storage (a common configuration) could reduce the need for energy reliability by a third.

Energy security can be met by several means. The traditional approach is to maintain a sufficient level of generation by turbines continually rotating in synchrony with the grid frequency. Through the inertia of their spinning masses, they resist rapid changes in frequency that are caused by contingency events. This synchronous generation can be provided by fossil fuels and some renewable technologies (hydro, biomass, geothermal, or concentrated solar power). Wind turbines can also apply the inertia from their spinning blades to frequency support, called 'synthetic' inertia because it is mediated by power electronics.

Batteries can make an important contribution to replacing inertia with fast frequency response that performs the same function. They are cost effective in this role because the energy requirement is small. Table 3 shows the power requirement for system security, assuming it is entirely provided by energy storage. The corresponding energy capacity requirement allows that fast frequency response should be provided for only five minutes, by which time regular "recovery" frequency control ancillary services resources are online (see Box 3).

Fraunhofer Institute (Pape et al., 2014) also concluded that the requirements for fast response dominate in Germany until very high penetrations of renewable energy generation, and that energy reliability storage is relatively low even at penetrations of 50 per cent renewable energy. Australia is fortunate, compared to Northern European countries, in

Box 3: Would batteries have prevented the South Australian blackout on 28 September 2016?

It's reasonable to ask whether fast frequency response resources such as grid-scale batteries would have prevented the blackout that followed storm damage to the SA transmission system in September 2016. The resulting voltage disturbance caused 315 MW of wind generation to disconnect, and the flow on the Heywood interconnector from Victoria increased to between 850 and 900 MW to make up the difference. This flow exceeded the design limit of 600 MW, and the interconnector's protection system opened the circuit to prevent damage, resulting in rapid frequency collapse.

Wind generation could have been part of a solution. Had the correct fault settings been in place to ride through the voltage disturbance, the more recently installed wind turbines could themselves have provided synthetic inertia with suitable control settings.

Other forms of fast frequency response would have bought time for other generation resources to come online. With 600 MW of fast responding batteries, corresponding to the interconnector as the largest single component of SA supply, the loss of generation would have been almost instantly compensated. Conversely, the loss of the interconnector at any other time could also be compensated. At today's storage prices, some \$A800 million would provide up to two hours of supply from these batteries, ample time to respond to the contingency by ramping up reserve generation. So, it is likely that with sufficient fast responding batteries, the blackout would have been prevented or much less widespread.

that the seasonal mismatch between supply and demand is slight. This means that energy storage for reliability may be required for a matter of days or weeks, rather than months.

1.3.5 The effect of interconnectors

Interconnectors play an important role in providing system reliability. The option of doubling the existing interconnector capacities rather than installing storage was tested for the HIGH RE and MID RE scenarios by running the energy reliability model with existing interconnector capacities doubled. The storage requirement went down by 15 GWh (14 per cent) in the HIGH RE scenario, and by 1 GWh (less than 1 per cent) in the MID RE scenario.

Increasing interconnectors would be a capital-intensive undertaking, and this report has not attempted to compare the costs with installing storage. Nevertheless, in the HIGH RE scenario, curtailment is a significant issue prior to installation of storage. This may be more effectively addressed by bulk storage technologies rather than interconnectors, because there may be a large overlap in periods of over- and under-production from renewable energy generators in adjacent states.

1.4 Technology Options for Storage Requirements

There are many alternatives for meeting the storage requirements in each of the scenarios, and the actual mix of storage or other technologies used will depend on market dynamics, policy settings and consumer preferences.

Considering the LCOS estimates provided, it is likely that larger scale options, such as PHES, will be the lowest cost for bulk energy storage. There is approximately 128 GWh of PHES potential identified in the NEM – 98 GWh within the lower cost range. These

technologies could make a large contribution to reducing potential curtailment, although this could also be achieved through power-to-gas storage.

If concentrated solar power is to make up any of the generation mix, molten salt storage is likely to also contribute, as the additional cost of adding storage is low. This has not been factored into the calculations in this report, as the objective was to determine “raw” storage requirements.

Assuming the entire energy **reliability** requirement was to be met by PHES, costs to meet this requirement for the HIGH RE scenario would be in the order of \$A43 billion (noting that this does not allow for the contribution from whatever solutions are used for system security). However, it is highly likely that a proportion of this requirement will be met by batteries for quick response (i.e. security requirements), or by molten salt storage associated with concentrated solar power, which is cheaper on a per MWh LCOS basis.

Should the entire requirement for system **security** be met by two-hour batteries, costs at 2030 prices would be \$A22 billion for the HIGH RE scenario. For context, network capital spending in the NEM is \$A5–6 billion each year based on the current Regulatory Investment Notices, equating to approximately \$A70 billion total if this level of expenditure is continued annually to 2030.

Solutions required for system security will also mitigate some of the need for energy reliability, and vice versa. Assuming that two-hour batteries are used to meet the security requirement, and the remaining reliability requirement was met by PHES, the total cost would be \$A36.5 billion.

There are other ways to meet both of these requirements, and the costs provided for these technologies are merely an example

of one alternative (see Figure 12 for cost comparisons). However, as a reference, network capital spending in the NEM is \$A5–6 billion each year based on the current Regulatory Investment Notices. This equates to approximately \$A70 billion total if this level of expenditure is continued annually to 2030.

Some storage will be installed entirely independent of the system requirements, particularly behind-the-meter consumer-driven battery storage. The current AEMO forecast for uptake of small-scale storage systems is 4.3 GWh by 2030 (Jacobs Group, 2016), although some studies put this estimate considerably higher (Wilton, 2017).

Consumer storage could potentially make a significant contribution to the LOW RE requirements for system security. Present regulatory settings allow this service provision through aggregation as a market load, while individual market participation by customers is not presently available. It remains to be seen whether the market provides sufficient signals for consumers to allow their storage systems to be used in this manner.

At least one technical solution has been demonstrated (ARENA, 2015).

In the LOW RE and MID RE scenarios, consumer storage would theoretically be sufficient to provide the entire energy reliability requirement, although behind-the-meter storage is unlikely to interact with utility scale renewable energy. The reliability requirement in these two scenarios is small, respectively requiring 1.5 and 5.0 GWh in total, and could be managed by demand responses, such as load shedding. The reliability requirement in the HIGH RE scenario is significant with 105 GWh and it is hard to imagine how this could be met other than by utility scale bulk energy storage.

1.5 Policy and Regulatory Implications

The modelling conducted for this report is not equivalent to comprehensive system reliability or cost optimisation modelling. It provides indicative results that can guide policy and

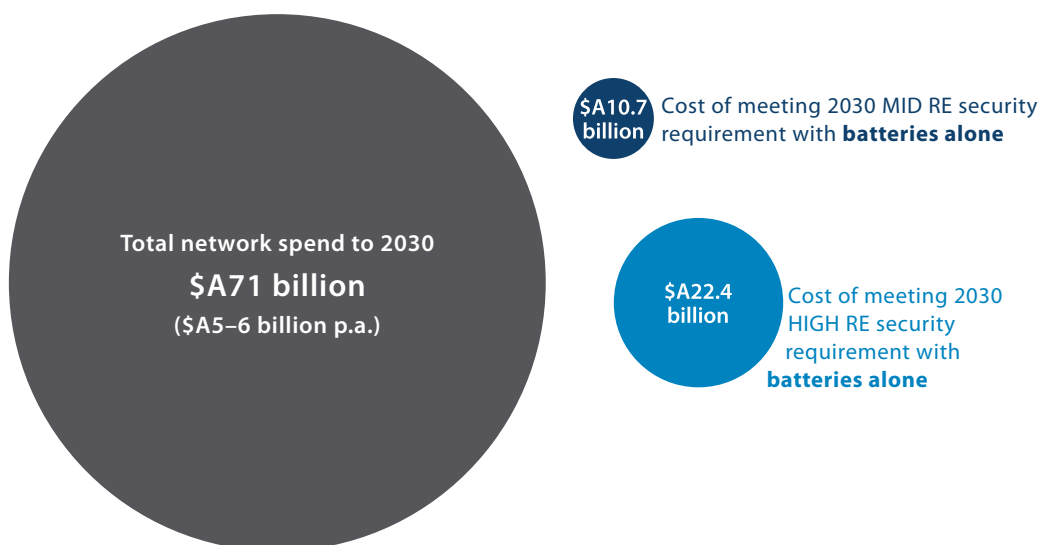


Figure 12: Cost comparisons

regulatory development and further studies¹⁸ to ensure the most cost-effective system outcome for Australia.

The modelling provides reassurance that both reliability and security requirements may be met with readily available technologies. The outputs (Figure 13) show that system security requirements will dominate until very high (50+ per cent) renewable energy penetrations are reached. Nationally and regionally, the electricity system can reach penetrations of renewable energy close to 50 per cent without significant requirements for energy reliability storage.

Reliability problems, such as those that recently occurred in South Australia and New South Wales, can be responded to quickly and effectively with appropriate storage.

The projected cost for meeting the security requirements at 2030 in the MID RE scenario by batteries alone, for example, would be approximately \$A11 billion at 2030 prices. This would also easily meet the reliability requirements.

In the short-term, it is important to provide a regulatory environment that is suited to a distributed energy future, as the potentially significant contribution from consumer storage could otherwise be lost.

This regulatory environment would seek to improve the market by breaking down barriers to prosumers accessing additional value streams from their systems.

In the longer term, it is important for energy storage policy to promote market growth, while also managing risk. Australia's energy sector is not an easy one for new entrants. It is inherently and necessarily complex, given the regulatory structures in place to govern a non-integrated market. There is a role for government to incentivise ways to reduce risk for traditionally risk-averse businesses and help direct investment towards the best long-term energy storage mix that provides the suite of services our future energy market will need. Before embarking on policy changes, it is critical to understand the market landscape prior to embarking on policy action to ensure that measures address the barriers to an industry while also capitalising on growth opportunities.

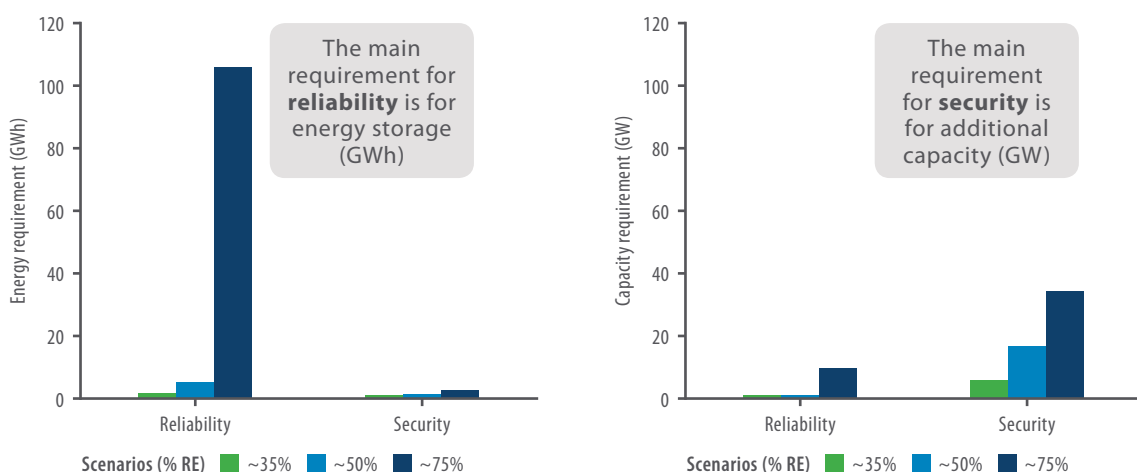


Figure 13: Reliability (GWh) and security (GW) requirements at 2030 across the three scenarios

18. Cost optimisation between generation mix and storage, together with a quantitative market impact analysis, factoring the requirements for both energy security and energy reliability, are required. This would best be undertaken for renewable penetration levels delivering compliance with the MID RE targets, and for an electricity system approaching zero emissions to ensure that policy makers consider the most efficient long-term outcome.

1.6 Key Findings

1. **There is a near-term requirement to strengthen energy security¹⁹ in NEM jurisdictions. Maintaining acceptable energy security levels for customers will dominate energy reliability²⁰ requirements until well in excess of 50 per cent renewable energy penetration.²¹**
 - Batteries are cost-effective for system security when installed with a high power-to-energy ratio, noting that there are other ways to strengthen system security (e.g. installation of more fast start gas turbines use of spinning reserve in wind turbines, and demand response or load shedding measures).
2. **At an aggregated national level²², Australia can reach penetrations of 50 per cent renewable energy without a significant requirement for storage to support energy reliability.**
 - Installing the levels of storage power capacity (GW) required for security creates the opportunity to expand energy stored (GWh) capacity for reliability at a lower marginal cost than would otherwise be the case.
 - Despite significant development and construction time, pumped hydro energy storage (PHES) is presently the cheapest way to meet reliability requirements. Projections indicate that the most cost-effective energy storage options available in 2030 will be PHES, lithium-ion batteries and zinc bromine batteries. These all have similar levelised cost of storage, depending on the PHES sites selected and uncertainty in reduction of battery costs.

19. "System security" is the ability to deliver near-instantaneous power (GW) for short periods (seconds to minutes) as fast frequency response to withstand sudden changes or contingency events in electricity generation, such as failure of a large generator or loss of a transmission line.

20. "System reliability" is the ability to meet electrical energy demand (GWh) at all times now and in future.

21. Ensuring system reliability and system security is a core function of the Australian Energy Market Operator. (AEMO).

22. The storage requirements differ at a state level.

CHAPTER 2

OPPORTUNITIES FOR AUSTRALIA IN GLOBAL AND LOCAL ENERGY STORAGE SUPPLY CHAINS

2 Introduction

The global market for energy storage in electricity systems²³ is growing rapidly, with Australia proving to be one of the fastest growing markets – notwithstanding that it is far from the largest. This chapter identifies and discusses the array of challenges and growth opportunities for Australian research and industry at each stage of the global and local energy storage supply chain framework (Figure 14).²⁴

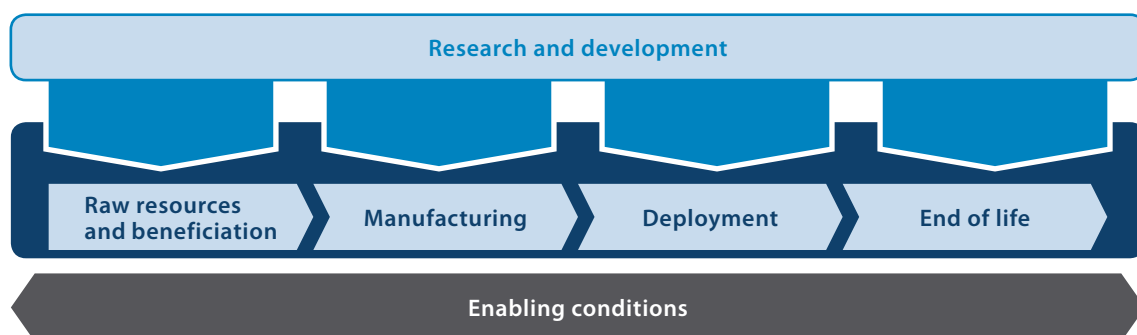


Figure 14: Energy storage supply chain analysis framework

23. Energy storage for transport purposes, portable electronics, and technologies that are not applicable to the storage of electrical power, including thermal storage for heat processes, are out of scope.

24. Evidence gathered from publicly available literature together with information received from more than 80 stakeholders and experts from the energy and energy storage sectors informed this work.



2.1 Research and Development

2.1.1 Emerging energy storage technologies and Australia's research strengths

Research is very active in the energy storage field – globally and locally. Current trends include high-volume production of clean hydrogen and ammonia, optimising concentrated solar thermal storage, improving batteries, and developing new battery technologies.

Australia has research strengths and there are industry opportunities in some of the most promising emerging energy storage technologies including:

- *Hydrogen*, which can be sustainably produced by using electricity generated via renewable energy to split water (electrolysis).
 - There is strong, but as yet unfulfilled, demand for clean hydrogen in countries such as Korea and Japan that have limited domestic energy resources (Cross-ministerial Strategic Innovation Promotion Program, 2015).
 - Hydrogen production using Australia's abundant renewable resources (particularly our high levels of sunshine) provide a significant export opportunity as well as absorbing excess power production from renewable resources when system demand is low.

- Opportunities will also be created for new technologies to more efficiently produce, store, and use hydrogen and ammonia²⁵. While ammonia synthesis and cracking are established processes, they are inefficient and expensive.
 - Australian researchers are working on high efficiency electrochemical approaches to ammonia synthesis, improvements to the efficiency and cost of hydrogen synthesis and transport processes, and the direct combustion of ammonia.
 - *Next generation batteries*, where Australia is competing with well-funded international programs²⁶. Nonetheless, Australian research groups are performing at or above world standard in this field and with strategic investment and prioritisation could capitalise on market opportunities.
 - As the market and technologies develop, opportunities are arising for batteries that are cheaper, safer, more sustainable, and have better performance characteristics than current technologies.
 - Lithium-ion is the most popular battery chemistry. Australian researchers²⁷ are developing new generations of lithium-ion batteries as well as emerging technologies including metal-air batteries, sodium-based batteries, and next-generation flow batteries.
- Research is also underway on the use of metals such as aluminium, magnesium and calcium.
- Ionic liquid and solid-state technologies appear to hold promise for next generation batteries.
 - Significant research activity is underway in Australia – both public sector and industry – and Australian researchers are established international leaders in the ionic liquids field as applied to next generation battery technologies.
 - First generation lithium metal solid-state batteries based on solid polymer electrolytes are commercially available through the Bolloré Group²⁸. Australian researchers have established strengths in polymer chemistry and polymer electrolytes that could contribute to next generation solid-state batteries.
 - *Advanced thermal energy storage systems*, where Australian companies Vast Solar, Graphite Energy and 1414 Degrees have developed novel thermal energy storage systems that can be used to supply industrial grade heat or generate electricity. The round-trip efficiencies are much lower than batteries or pumped hydro energy storage systems,²⁹ but thermal energy storage is expected to be

25. To ensure safety and reduce volume, hydrogen can be converted to ammonia for transport. It is subsequently converted back to hydrogen (ammonia cracking) for use in fuel cells or electric vehicles.

26. The United States' Advanced Research Projects Agency-Energy (ARPA-E) Program, and the German Government's energy transition program.

27. ANSTO's Australian Centre for Neutron Scattering, CSIRO's Centre for Hybrid Energy Systems and Stored Energy Integration Facility (CSIRO, 2016a), and the Deakin-CSIRO BatTRI-Hub.

28. For deployment in vehicles (Jolly, Cres & Dimitriadis, 2015) and also in hot climates such as Australia and Africa for stationary energy storage due to increased safety and stability compared with Li-ion.

29. The 1414 Degrees prototype, which builds on IP developed by CSIRO and stores energy in molten silicon (1414 Degrees, 2016) achieved 31 per cent efficiency for electricity (1414 Degrees, 2017).

cheaper than batteries, highly scalable in capacity and power, and not have the location constraints of pumped hydro energy storage.

- Although purely thermal energy storage is outside the scope of this report, improved thermal energy management in domestic, commercial and industrial applications has great potential to improve energy productivity and reduce greenhouse gas emissions from the broader energy sector³⁰.

Australia's strength in research and development in these fields, and particularly its world-leading electrochemistry researchers, is recognised as providing excellent opportunities in the energy storage supply chain³¹. Public sector organisations that work in energy storage technologies include:

Australian National University
The Australian Centre of Excellence for Electromaterials Science
The Australian Nuclear Science and Technology Organisation (ANSTO)
The Australian Solar Thermal Research Institute
CSIRO
Curtin University
Griffith University
Monash University
Queensland University of Technology
University of Adelaide

University of Melbourne
University of New South Wales
University of Queensland
University of Sydney
University of Technology Sydney
University of Wollongong

Information on the energy storage research conducted by these organisations is provided in Appendix 4.

2.1.2 Australia's R&D success stories and challenges

Australia has had a number of successful energy storage R&D outcomes (see Box 4). Although these are mostly small scale, particularly in economic terms, it is notable that they have occurred where there has been collaboration between research groups and industry.

Nevertheless, evidence gathered during consultations indicated a number of challenges to overcome if energy storage R&D in Australia and commercialisation of resulting intellectual property (IP) are to continue to be successful. These include:

- A need for greater collaboration between researchers and industry – for example, new models for IP ownership, flexibility of business models to incorporate new technologies, and establishment of domestic and international sector hubs to facilitate collaboration.

30. Monash University is developing IP on intermediate temperature (100–200 °C) phase change materials that can store large amounts of roof top solar-thermal for use in domestic and small commercial use.

31. The Excellence in Research for Australia (ERA) evaluation identifies 11 Australian universities involved in energy storage research as having engineering and materials chemistry research performance that is above or well above world standard (ERA score 4–5; Australian Research Council, 2015).

Box 4: Successful energy storage R&D outcomes

The UltraBattery – this CSIRO-developed hybrid battery combines a super-capacitor and lead-acid battery in a single unit and has been successfully commercialised by Australian company Ecoulit (CSIROpedia, 2005).

A commercialisation agreement between Redback Technologies (an Australian energy storage company) and the University of Queensland (UQ) that enables direct access by Redback to UQ researchers and their energy storage technologies (Swan, 2016).

Commercialisation by SupraG Energy (a Monash University spinout company) of graphene super-capacitors that allow a three-fold increase in energy storage capacity (Monash University, 2016).

Development of batteries for submarines by PMB Defence Engineering – including main storage batteries for the Collins Class submarines (PMB Defence, 2017).

BatTRI-Hub (Deakin University and CSIRO) – a world class research centre focused on the development of next generation battery technologies with the aim of growing the battery manufacturing industry in Australia (Deakin Research, 2016).

Aquahydrex – a spinout company from the Australian Centre of Excellence for Electromaterials Science – formed to develop a technology using solar energy to produce hydrogen from seawater (Goldie, 2012).

- Systemic issues in research-industry collaboration (not specific to energy storage alone) impeding commercialisation of technologies in Australia³². For example, the vanadium redox flow battery was invented in Australia in 1985 (Skyllas-Kazacos, Rychick, & Robins, 1988), but was commercialised and manufactured in China, Germany, Japan, the United Kingdom and the USA because there was limited interest in commercialising the technology in Australia.
- Analysis of the optimum size, location, and operation of energy storage, as applied to Australia's energy grids, is necessary to improve cost effectiveness of these systems, (Australian Academy of Science, 2016). This includes improving energy efficiency transfer into and from storage.
- A lack of funding to take developments to full commercial potential. Although several grant funding schemes exist in Australia, the high failure rate of applicant companies with non-commercial technologies delays development of research to a stage that attracts commercial involvement³³.

2.2 Raw Resources and Beneficiation

2.2.1 Mineral resources and beneficiation (value-adding)

Due to the abundance of natural Resources, Australia has the opportunity to contribute to the supply chain for a number of energy storage technologies. Increased demand for mineral resources required for energy storage will, however, largely be dependent on the technologies that are most successful in end-use markets over the coming decades.

³². These issues are being targeted via Australian Government initiatives such as the National Innovation and Science Agenda (NISA).

³³. The Small Business Innovation Research program in the US is a mechanism that specifically identifies and targets this gap. Australia is piloting a similar scheme as the Business Research and Innovation Initiative (Commonwealth of Australia, 2016a).

A range of mineral resources is required for the production of energy storage technologies. Those used in current generations of batteries include lithium, lead, cobalt, nickel, and zinc, while those identified as essential for emerging energy storage technologies include vanadium, manganese, aluminium, iron, magnesium, phosphorous, potassium and graphite. Australia holds the world's largest economic demonstrated resources (EDR³⁴) of iron ore, lead, nickel, and zinc. Its bauxite (aluminium oxide), cobalt, lithium, magnesite (magnesium ore), manganese ore, tin, and vanadium EDR are all ranked in the top five worldwide (Britt et al., 2016). Details on Australia's mineral resources and the companies involved in their production and processing are provided in Appendix 5.

The most significant raw material opportunity for Australia is in lithium. Should car manufacturers invest heavily in electric vehicles and demand rises in distributed and behind-the-meter energy storage markets (Navigant Research, 2016a), lithium-ion batteries will be a key technology for at least the next decade. Forecasts by Goldman Sachs estimate the lithium-ion battery market (electric vehicles only) to be worth US\$40 billion by 2025 (Sanderson, Hancock & Lewis, 2017). Tesla's decision to significantly increase production to 35 GWh/year of lithium-ion battery cells by 2018 (Tesla, 2017) together with growth plans of Chinese, Korean and Japanese lithium-ion battery manufacturers demonstrates the increasing demand for lithium over the coming years. Australia is currently the biggest supplier of lithium (Britt et al., 2016).

Secondary processing of raw materials has been declining in Australia, with one of the major contributing factors being the high cost of energy. Nonetheless, a small number of Australian companies are involved in lithium processing and opportunities for value-adding for export of higher value products (e.g. lithium salts, lithium metal, electrode materials) are being pursued .

2.2.2 Pumped hydro resources

The viability of pumped hydro energy storage is strongly dependent on locating sites with suitable geographic characteristics, including upper and lower reservoirs that have an appropriate elevation difference (Hearps et al., 2014). These can be river-based or off-river at locations such as hilly regions, along coastlines, or even at decommissioned mine sites (Blakers, 2015). Land use and water requirements for PHES have the potential to negatively influence the social license for the technology if environmental and water use impacts are not appropriately managed.

In addition to three sites in the Snowy Mountains and Queensland, many locations in Australia have been identified as suitable for PHES (see Box 5). The Australian Renewable Energy Agency (ARENA) funded *Atlas of Pumped Hydro Energy Storage* study currently being developed by ANU, ElectraNet, and VTara Energy Group, aims to identify more potential sites for off-river pumped hydro projects (Vorrath, 2016a).

34. EDR includes Joint Ore Reserves Committee Proved and Probable Ore Reserves as stated in company annual reports and reports to the Australian Securities Exchange, as well as indicated and measured resources.

Box 5: Examples of Australian pumped hydro energy storage projects

The Kidston PHES Project (250 MW) is an example of an off-river pumped hydro site. This project uses the disused Kidston Gold Mine in northern Queensland, which has large suitable pits (Genex Power, 2016). Construction of the project is expected to commence in late 2017, pending financial arrangements.

Energy Australia has proposed a 100–200 MW coastal PHES project for South Australia that would use the ocean as its lower reservoir thus alleviating potential environmental and social concerns of its water dependency. ARENA has awarded \$A450,000 to Energy

Australia to fund the feasibility study (Reid, 2017).

In March 2017, the Commonwealth Government announced that it would invest up to \$A2 billion dollars into the expansion of the Snowy Mountains Hydro Scheme. Badged as Snowy Mountains Scheme 2, the expansion proposes the addition of 2,000 MW of renewable energy to the scheme's current output of 4,100 MW. Four options, using existing dams, are under consideration – these include use of the Tantangara and Talbingo reservoirs. (Coorey, 2017)

2.3 Manufacturing

The 2016 Global Manufacturing Competitiveness Index shows Australia's manufacturing competitiveness ranking declined from 16th to 21st over three years (Deloitte, 2016). This decline has been attributed to issues such as high labour and energy costs, distance from key markets, and lack of access to growth capital – issues which are just as relevant to the manufacture of energy storage and associated technologies.

2.3.1 Local energy storage manufacturing

Battery cell manufacturing is developing at a rapid pace globally. Attempts to compete against global manufacturers in established technologies will pose great challenges for Australian industry. Australia should look for opportunities in manufacturing where it has competitive strength such as in high-value, low-volume energy storage solutions for niche applications as well as technologies and software for system integration and control.

Manufacturing of high-value, low-volume energy storage solutions can provide opportunities for Australian industry³⁵. The only battery manufacturing currently underway is by PMB Defence in South Australia, which manufactures batteries for submarines, including the Collins Class battery system (PMB Defence, 2017).

Opportunities also exist for local assembly using imported cells to build battery packs (including balance of system management) required for electricity network applications operating under Australian ambient conditions.

Other high margin opportunities include customised solutions for niche applications or novel technology developments commercialised from Australian IP, such as the concentrated solar power system developed and demonstrated by Vast Solar (Vast Solar, 2016) and the silicon-based thermal energy storage system developed by 1414 Degrees for industrial and grid applications (1414

35. CSIRO's Advanced Manufacturing Roadmap recognised customised high-margin solutions as a growth opportunity for Australian businesses (CSIRO, 2016b).

Degrees, 2017). Energy storage solutions that address issues specific to Australian conditions may also facilitate creation of markets in the electricity grids of developing nations (e.g. high temperature environments, fringe of grid or off-grid systems).

A lack of confidence³⁶ in achieving commercial manufacturing success in Australia reflects a somewhat common attitude across many knowledge-intensive industry sectors – that is, Australia has a challenge in translating R&D and IP strengths into commercial applications. The most recent audit of the innovation system has found that there is no inherent or fundamental reason why this should be the case (Innovation and Science Australia, 2016), but given the historical systemic difficulty in this area, a suite of policy and cultural changes will be required to facilitate improved performance.

Notwithstanding the challenges of competing against global manufacturers there is still

interest in the development of a local battery-manufacturing sector. Australian Vanadium and its subsidiary, VSun Energy, have expressed an intention to develop a vertically integrated vanadium flow battery operation in Australia. If successful, they will mine vanadium and produce vanadium electrolyte for use in their own batteries. This project is currently in a capital-raising phase.

2.3.2 Participation in global supply chains

Incremental improvements in established energy storage technologies are unlikely to offer significant local manufacturing opportunities. Australian companies have demonstrated success in commercialising Australian IP through international partnerships and through contributing their technologies and IP to different components of energy storage systems (see Box 6).

Although most examples provided have been small scale, identifying opportunities in global

Box 6: Commercialisation through international partnerships

Ecoult has partnered with international manufacturing companies in key markets including the USA and India to produce the CSIRO developed UltraBattery (an advanced lead acid battery technology) (ARENA, 2017a).

RedFlow has commercialised a zinc bromide flow battery technology. Despite basing their R&D operation in Australia, Redflow has outsourced the manufacture of their products to a global company to allow for scalable manufacturing and the ability to have greater proximity to key markets (Redflow, 2017).

Gelion – a spin off company from the University of Sydney – has partnered with Armstrong Energy (a London headquartered

company) focused on solar energy at utility scale. The initial target market for Gelion batteries (which differ from zinc bromine in that they use a gel instead of a liquid) is for storage in residential and commercial buildings (Vorrath, 2016b).

Australian company Nano Nouvelle has developed a tin anode for lithium-ion batteries that uses nanotechnology to improve battery performance. A key design goal for the electrode was its compatibility with existing battery technologies and manufacturing processes to make it easy for manufacturers to adopt the technology (Nano-Nouvelle, 2016).

36. Stakeholder interviews.

energy storage value chains will be essential for most companies in the Australian energy storage industry.

2.3.3 Technology for energy storage integration and control

Australia is widely viewed as a test bed for the impacts and benefits of distributed energy storage due to its rapid energy storage market growth – 356 per cent growth between 2014 and 2015 (China Energy Storage Alliance, 2016). Developing technology solutions that allow for the integration and coordination of energy storage and other distributed energy resources provide a key opportunity for Australian industry and researchers.

Australia has greater competitive advantages and potential for manufacturing success in the hardware and software systems that will be required for smart management and integration of energy storage systems³⁷.

A number of industry stakeholders consulted noted the potential for improved use of data, data analytics and system modelling to manage Australia's energy systems. The application of modern information and communications technologies including cloud computing, machine learning, and the internet-of-things is allowing the creation of smart systems that can optimise customers' energy use and provide benefits to the electricity grid by reacting to price signals from energy utilities. Australian companies such as Reposit, GreenSync, Redback, Selectronic, and Evergen are leading the development and deployment of smart technologies for the integration and control of distributed energy systems (e.g. solar and storage) in Australia. The technologies developed by these companies, typically allow for greater transparency and control

of energy and storage use (e.g. Evergen, 2016; GreenSync, 2016; Reposit, 2017).

The energy storage market is competitive, and although systems integration and design have been identified as a significant opportunity for Australia, the industry will need to act quickly to compete with international companies such as AutoGrid and Sunverge Energy in the USA, Sonnen in Germany and multinational technology companies such as ABB, GE and Siemens.

2.4 Deployment

Energy storage is recognised as a key enabling component of future energy grids with high penetrations of renewable energy (Australian Academy of Science, 2016; IRENA, 2017). The deployment of energy storage systems within Australia's energy sector offers significant scope for economic and environmental benefit. Companies that retail and install energy storage solutions (usually batteries coupled with solar PV systems) for residential and commercial customers are an early example of industry growth in the energy storage sector. Another key growth area is in off-grid deployments, where high costs of diesel generation are providing an economic incentive to install solar PV and energy storage solutions. As discussed in Chapter 1, there is also a growing appreciation of the importance of grid-scale energy storage deployments to support system reliability and security.

2.4.1 Distributed energy storage and system integration

Australia is seeing rapid uptake of energy storage systems. This is predominantly due to the high penetration of solar PV and the end of a number of feed-in tariff schemes.

³⁷. Stakeholder interviews.

Australia is expected to have one of the highest penetrations of energy storage globally (China Energy Storage Alliance, 2016; IHS Markit, 2016). It also has weakly connected networks spread over vast distances. Because of these factors, opportunities exist for the deployment of new grid solutions that integrate energy storage and distributed energy resources to help address the energy trilemma. The design of smart grids, microgrids, embedded networks and off-grid solutions provide an opportunity for Australia to contribute to the energy storage supply chain.

Due to their high efficiencies and relatively small size, batteries are expected to remain the dominant technology for distributed and behind-the-meter energy storage solutions. Lithium-ion batteries are the most popular technology for these markets (Navigant Research, 2016a).

The Essential Services Commission (2016) in Victoria has analysed the electricity network to assess the energy and network value of distributed generation. This research indicates that distributed energy generation could provide value to the network by alleviating network congestion and that network value can be optimised with the addition of storage and smart control systems.

Network businesses and utilities are considering the opportunities and challenges that energy storage technologies pose to their business models. Grants and allowances have enabled utilities and network businesses to undertake trials and demonstration projects to develop expertise in distributed-energy-resources-based systems and improve their ability to adapt to the transforming market (see Box 7).

Box 7: Utility and network businesses – demonstration and trials

AGL's virtual power plant trial in SA: aims to demonstrate the ability to centrally manage and monitor 1,000 solar PV and battery systems (a total of 5 MW/7 MWh energy storage) for both consumer and network benefit (AGL, 2016).

Microgrid trials undertaken by AusNet Services and other distribution networks: demonstrate the feasibility for communities to generate, store and share their renewable energy using local grid infrastructure (AusNet Services, 2016).

Fringe of grid solutions: Ergon Energy has developed an energy storage system (Grid Utility Support System) to improve reliability for fringe of grid customers serviced by single wire earth return (SWER) networks. This system is able to reduce the load on a SWER and improve the voltage at the end of the network at significantly lower cost than traditional augmentation (Ergon Energy, 2016).

SA Power Networks' battery storage trial: 100 batteries installed in a three-year trial in Salisbury in Adelaide's northern suburbs.

The trial uses smart systems to manage power generated by household solar panels, and supplies the grid with excess energy to manage network issues, especially those caused by adverse weather conditions (SA Power Networks, 2016).

Microgrids and standalone power systems are anticipated to be an important energy supply solution especially for remote and fringe-of-grid communities in Australia. There is also interest in applying energy storage with solar PV systems to offset the high costs of diesel generation in remote areas³⁸. Expertise

³⁸ Sandfire Resources successfully commissioned a solar and storage system at the DeGrussa mine in June 2016. The project which includes 6 MW of lithium-ion battery storage is expected to cut approximately 20 per cent off their annual diesel consumption (Sandfire Resources NL, 2016).

developed from the design and integration of storage and renewable generation for standalone off-grid systems is expected to be of interest to small and remote communities in the Asia-Pacific region.

2.4.2 Grid-scale energy storage

The Renewable Energy Target (RET) is driving increased penetrations of variable renewable energy in Australia's electricity networks, yet there is no significant policy driver to provide firm and dispatchable energy from renewable sources. Recent energy security issues have, however, driven increased interest and growing recognition of the potential of energy storage to contribute to the reliability and security of Australia's electricity market³⁹.

Pumped Hydro Energy Storage (PHES) – Australia has over 1.5 GW of PHES connected to the NEM. Although no large-scale PHES facilities have been built in Australia in the past 30 years (AECOM, 2015) it is expected to remain the most cost effective option for large-scale energy storage (>100 MW) for some time. PHES projects are estimated to create between 2.75–5.5 full time equivalent jobs per MW in direct job creation for the length of the project (Navigant Consulting, 2009).

The challenge to PHES deployment is the perception of competing land and water usage issues (social licence); and the large costs and length of time required for their development, making private investment in PHES unlikely without risk mitigation efforts by government (see Box 8).

Compressed Air Energy Storage (CAES) – There are just two underground CAES deployments in operation globally and there appears to be little interest in the development of CAES or liquid air energy storage in Australia.

Box 8: Major Expansion of the Snowy Hydro Scheme – “Snowy Hydro 2”

In March 2017, the Commonwealth Government announced that it would invest up to \$A2 billion dollars into the expansion of the Snowy Mountains Hydro Scheme. Badged as Snowy Mountains Scheme 2, the expansion proposes the addition of 2,000 MW of renewable energy to the scheme's current output of 4,100 MW. The extra capacity, to be pumped into the national electricity market, will be enough to power 500,000 additional homes. It will employ pumped-hydro technology that involves using water to drive turbines and then pumping the water back up a hill to a storage dam.

The original snowy scheme was built between 1949 and 1974. It currently comprises 16 dams, 145 km of tunnels, 80 km of pipes and aqueducts. It is operated by Snowy Hydro Limited, an unlisted public company which is 58 per cent owned by NSW, 29 per cent owned by Victoria and 13 per cent owned by the Commonwealth.

A feasibility study expected to conclude at the end of 2017 will examine various sites, following which a detailed cost estimate will be prepared. The Australian Government has suggested that work would commence on the scheme shortly after conclusion of the feasibility study. (Coorey, 2017)

Underground CAES requires specific geological structures and above ground compressed air storage has been abandoned by the USA-based start-ups who were leading its development (St. John, 2015).

³⁹. In February 2017, ARENA and CEFC were asked to focus on encouraging the development of flexible capacity and large-scale storage projects in Australia (ARENA, 2017b).

Concentrated Solar Power (CSP) – The deployment of CSP provides an opportunity to capitalise on Australia’s significant research investments (the ASTRI program, Vast Solar, 1414 degrees) and its abundant sunshine. Deployment of a large-scale demonstration plant will be an important step for any of these new CSP technologies to demonstrate their operational and economic viability.

Grid-scale Battery Storage – Government supported trials are helping to develop knowledge of this form of energy storage, which will help to improve the economics of grid scale battery deployments. These include:

- The Victorian government recently announced that it intends to run a tender for deployment of a 20 MW battery system to support the network and enhance opportunities for the integration of new solar and wind generation (Minister for Energy Environment Climate Change, 2017).
- Australian solar and storage company ZEN Energy intends to develop a large-scale (50 MW, 50 MWh) battery project in Port Augusta (SA) to support their solar developments. The company is also exploring the potential for a 100–150 MW plant to address grid security issues (ZEN Energy, 2017).
- SA has outlined plans to spend \$A510 million to “keep the lights on”. The plan includes \$A150 million to encourage the development of a 100 MW battery storage plant and \$A360 million to build and operate a new gas power plant to help stabilise its electricity system (CNBC, 2017).

Global energy storage projections by Navigant Research suggest that deployments of energy storage for grid and ancillary services will reach more than 20 GW by 2025. Companies such as AES Energy Storage, Tesla, RES Group, S&C Electric, Siemens, GE, and LG are amongst global leaders supplying grid scale battery storage solutions (Navigant Research, 2016b).

2.4.3 Renewable hydrogen and ammonia

Australia’s abundant sunshine makes it an optimal environment to produce hydrogen using solar energy. Synthesis and export of hydrogen from renewable sources is a major opportunity for Australia. This opportunity is partly driven by Japan’s recent investment and national economic strategy directed towards hydrogen projects, including hydrogen-powered vehicles and fuel cells (Cross-ministerial Strategic Innovation Promotion Program, 2015).

Hydrogen gas is difficult to transport due to its low density; instead, it is proposed that hydrogen is converted to ammonia for transport, and then converted back to hydrogen for use. Australia possesses significant expertise and infrastructure from the export of liquefied natural gas (LNG), which could be used or converted for ammonia transport. The export of renewable hydrogen is reliant on improving the efficiency and cost of hydrogen synthesis and transport (discussed in 2.1.1).

Australian industry promotion body Renewable Hydrogen is driving the creation of a pilot plant to generate solar energy in the Pilbara region of Western Australia (Turner, 2015). The solar energy generated will be stored as hydrogen and could then be shipped in the form of liquid hydrogen, ammonia or liquefied synthetic gas to Japan, Korea, and other parts of Asia (Renewable Hydrogen, 2014).

Ammonia production is already taking place in Australia. Yara Pilbara Fertilisers operates an ammonia production plant in the Burrup Peninsula, Western Australia. Ammonia at the Yara plant is produced using natural gas as a hydrogen source, rather than renewable sources, and ammonia is exported primarily for fertiliser production (WA Country Hour, 2017).

2.5 End of Life

The scenarios in Chapter 1 for utility scale storage to meet security and reliability requirements predict a strong uptake of batteries. This uptake together with significant behind-the-meter battery storage (approximately 4.5 GWh) and batteries from electric vehicles (which this report did not address) has led to the identification of end-of-life recycling and repurposing as a potential opportunity for Australia, in particular for lithium-ion batteries. The Australian Energy Storage Roadmap states *“appropriate arrangements for the safe disposal or recycling of end-of-life [energy storage] systems – product stewardship – is vital to maintaining community support and industry integrity”* (Clean Energy Council, 2015). Despite the growing number of batteries being used, only lead-acid batteries are recycled in Australia.

2.5.1 Strengths and opportunities

Increased battery recycling and repurposing is promoted by the Australian Battery Recycling Initiative, and was identified as a potential opportunity in Australia during consultation with industry stakeholders. Apart from lead-acid batteries, used batteries are being collected in Australia and sent overseas for recycling. Several valuable components,

including metals, can be extracted from retired batteries and the export of these components to battery-manufacturing countries could add significant value to the energy storage supply chain (see Box 9 for Australian companies working on recycling).

2.5.2 Challenges

The lack of recycling regulations for batteries, the relatively small number of batteries available for recycling and the current economics of material recovery are the primary reason for a lack of battery recycling facilities in Australia. As the battery industry in Australia grows, so too will the opportunities for local recycling and repurposing. The economics of material recovery will benefit from research, technology improvements, an increase in the cost of recoverable materials or the imposition of tariffs on export.

In Australia, batteries lighter than 5 kg were listed as a priority for consideration of possible product stewardship approaches in 2015, but have not yet been regulated (Department of the Environment and Energy, 2015). Battery recycling regulations would decrease the environmental impact of toxic battery chemicals in landfill, and may lead to the establishment of a battery recycling or re-use market in Australia.

Box 9: Australian companies working on recycling

PF Metals commenced a trial project in resource recovery from lithium-ion batteries in August 2015. From the trial, they developed a method of extracting 95 per cent of the batteries' valuable components, but are not yet recycling these batteries commercially. (PF Metals, 2017)

Relectrify is working on technology to repurpose retired electric vehicle batteries for use in household energy storage to deliver more affordable residential energy storage solutions (Relectrify, 2016). Its financial viability is dependent on an increase in electric vehicle uptake.

2.6 Enabling Conditions

A key focus of stakeholder consultations undertaken for this report was to identify the enabling conditions that would underpin economic, social and environmentally beneficial growth for the Australian energy storage industry, and successful research outcomes in Australian research institutions.

Recurrent themes amongst the responses included strategic governance, improved energy market design and regulation, driving investment and improving access to capital, and enhanced coordination and collaboration between stakeholders.

2.6.1 Energy market design and regulatory frameworks

Energy markets around the world are seeking solutions to the energy trilemma of energy security, equity and sustainability. The Independent Review into the Future Security of the National Electricity Market aims to address these issues (Finkel et al., 2016).

Increasing the amount of energy storage in the electricity system should not be a primary goal of an electricity market's design. However, increased energy storage is seen as a likely outcome of implementing mechanisms that incentivise least cost decarbonisation of the electricity system while maintaining system security and reliability.

The Independent Review's report notes the potential of energy storage technologies to contribute to the security and reliability of Australia's national electricity market in a number of ways.

2.6.2 Government policy and initiatives

Stable and integrated energy and climate change policy – policy uncertainty (e.g. climate policy and energy policy are not sufficiently linked) is a barrier to attracting investment in energy technologies generally. A unified climate and energy policy, informed on the basis of independent expert evidence, is an essential enabler of investment in Australian energy storage applications.

Strategic government leadership – A number of countries have recognised the importance of energy storage to their energy systems, and have implemented long-term strategic plans and targeted support for research and industry development. A national, long-term strategic plan focused on resolving the energy trilemma in the Australian electricity sector will support such investment.

Government support for industry development and innovation – Australian governments have implemented a number of initiatives to support industry development. Those with particular relevance to energy storage include grant funding (ARENA), subsidies for energy storage installation, support for start-ups, direct procurement, and the R&D tax incentive. Funding programs and incentives that exist to support industry development and research opportunities in energy storage would benefit from national leadership and enhanced coordination.

2.6.3 Access to venture capital and finance

Limited access to capital during the growth stage of a company is seen by industry as a key reason for high growth technology companies leaving Australia (Fitzsimmons, 2015). Access to early stage venture capital

can be challenging in Australia based on a sentiment that Australian investors have a low appetite for risk. The introduction of tax incentives for investors in early stage innovative companies announced in the Australian Government's National Innovation and Science Agenda (Commonwealth of Australia, 2016b) is seen as a mechanism to support early stage ventures in Australia, albeit at a smaller scale to the UK's successful Seed Enterprise Investment Scheme. On the other hand, the finance sector suggests that there is no shortage of finance for projects with appropriate risk and return profiles. However, projects that require large investments and have significant development times – such as PHES – are particularly challenging to finance.

Government efforts to mitigate investment risks can help to enable greater private investment in high capital projects, such as PHES systems. The 2017 International Renewable Energy Agency (IRENA) report, *Rethinking Energy*, notes that: *“limited public funds need to be used in a way that maximises the mobilisation of private finance ... this means a shift from traditional public financial instruments (e.g. grants and loans) toward risk mitigation instruments such as guarantees that cover political, currency and power-offtake risks”* (IRENA, 2017).

The Clean Energy Finance Corporation (CEFC) is a positive initiative with great potential to stimulate growth in the energy storage sector. In September 2016, the CEFC made a \$A10 million commitment to help establish a Clean Energy Seed Fund to be managed by Artesian Venture Capital. The fund aims to invest a total of \$A20 million in 30–50 high growth potential startups over the next 4–5 years. Energy storage is one of the sectors that this fund intends to target (Clean Energy Finance Corporation, 2016).

2.6.4 Strategic coordination and collaboration

Challenges with industry-research collaboration are not unique to the energy storage sector. It is widely recognised that Australia has strengths in research and knowledge creation, but does not perform as well in the transfer and application of knowledge (Innovation and Science Australia, 2016).

Greater value and impact from Australian energy storage research initiatives could be achieved through establishment of collaborative research hubs (BatTRI-Hub, ACES and ASTRI are examples of successfully operating hubs) targeting industry collaboration; strategic international collaborations; and funding with major international programs.

2.7 Key Findings

3. Australia is well placed to participate in global energy storage supply chains. Business opportunities will arise, given appropriate policy decisions at State and Commonwealth levels, and incentives for actors across those supply chains.

- Australia has abundant raw mineral resources for batteries (most notably lithium), but could capture greater value through beneficiation (i.e. value-adding to the raw mineral resources).
- Australian companies and researchers are commercialising their energy storage intellectual property (software and hardware for battery integration, design and deployment of off-grid energy supply and micro-grids, and battery technology and components) through international and global partnerships.
- Australia has abundant resources (e.g. solar), appropriately skilled workforces and established supply chain relationships to generate renewable hydrogen and ammonia at the volumes required to supply potential export markets, such as Japan and Korea.

4. Australia's research and development performance in energy storage technologies is world class; but it would benefit from strategic focus and enhanced collaboration.

- Australia is recognised as conducting world-leading research in several energy storage disciplines including electrochemistry, materials development and materials processing for advanced batteries, and power system design and modelling.
- Deriving the full return-on-investment from this research requires improved research translation through national and international industry-research collaboration and commercialisation.

5. The availability of private sector risk capital and profitable revenue streams for Australian energy storage start-ups and projects is a challenge for new ventures, as is policy uncertainty.

- Profitable revenue streams from energy markets together with consistent, stable and integrated energy and climate policies will be essential to drive investment in energy storage and other technology solutions that support decarbonisation of the electricity system while ensuring system security and consumer equity.
- Technology-neutral market-based reforms will be required to address these challenges at least cost.

CHAPTER 3

ENVIRONMENTAL BENEFITS AND RISKS FROM ENERGY STORAGE UPTAKE

3 Introduction

Low-carbon technologies in energy systems provide climate change mitigation and reduce pollution. It is important to assess the full lifecycle of any new technology to identify potential negative impacts, including unforeseen negative environmental and social consequences.

Energy storage technologies are considered essential to future renewable energy systems. However, they may have high resource requirements and significant environmental and social impacts that need to be appropriately managed before a sustainable energy system can be realised.

Five stationary energy storage technology groups were reviewed for this report:

- Battery technologies: lithium-ion, lead-acid, sodium-based chemistries and flow batteries
- PHES
- CAES
- Hydrogen energy storage
- Concentrated solar power with thermal energy storage (CSP TES).

3.1 Impact Assessment Framework

An impact assessment framework was developed based on a streamlined lifecycle approach to identify environmental and social impact “hotspots” along the supply chain (Ellingsen et al., 2016). The criteria are defined according to the environmental, social and safety impact categories.

The framework is intentionally broad to enable a comparison of the diversity of energy storage technologies, which are at different levels of maturity. Impacts along the entire supply chain have been examined.

A detailed techno-economic assessment is outside of the scope of this report. Hence, the impacts that are highlighted as “hotspots” require additional research or intervention. The full Impact Assessment Framework is provided as a table in Appendix 6.



3.1.1 Environmental and social impacts

The aim was to identify key “hotspots” rather than quantify the environmental impacts. Thus, a traditional environmental life cycle assessment (E-LCA) was not considered appropriate in the context of this report. A strong emphasis on qualitative impacts was considered, for example where an E-LCA has a value for water use or human toxicity. A deficiency of E-LCA is that it does not provide location specific information – such as the impact of water use on the environment or the human health effects that may occur at mining sites in various regions.

In the framework, resource depletion is considered in the impact categories of *material intensity* and *recyclability*. Climate change impacts are considered in the category of *lifecycle GHG emissions*, while the *environmental health*⁴⁰ category looks at

damage to ecosystems and human health, including typical Life Cycle Assessment (LCA) criteria of land use, water use, human toxic effects, biodiversity and other pollutants. Importantly, lifetime energy efficiency, recyclability and supply chain criticality categories – environmental and economic impacts associated with vulnerability to shortages of raw materials – have been added to the scope of the LCA (see Box 10 for definitions).

The main impact categories of Social Life Cycle Assessment (S-LCA) have been simplified to focus on the categories of *human rights* and *health and safety* (see Box 10 for definitions), where the main stakeholder groups considered are workers, consumers and local community. Where appropriate, supply chain stakeholders and society as a whole are also considered (Benoît & Mazijn, 2009).

40. The environmental health category includes health impacts on workers and communities, for example those arising from heavy metal contamination during mining.

Box 10: Definitions for S-LCA

Lifetime energy efficiency – different efficiency measures vary in their importance depending on the application of the technology. Thus, no single measure is universally appropriate. For example, for long-duration storage (weeks or months) the self-discharge rate (how quickly a storage device loses its stored energy when not in use) is very important. For efficiency when in use the round-trip efficiency (a measure of the ratio of the energy retrieved from the battery to the energy put into the system) is important because a higher round-trip efficiency reduces the technology uptake requirement and emissions. It is also important to consider the expected lifetime of a storage technology as this, coupled with round-trip efficiency, determines the total energy that can be stored and released over the lifetime, with implications for minimising total resource requirements and associated impacts.

Recyclability – For recyclability, the end-of-life recycling rate of products, current technical recycling potential and material value for recycling have been considered. A material with a lower recycled content compared to end-of-life recycling rate reflects growing demand for the material and shows the limit to recycling's ability to contribute to meeting total demand (UNEP, 2011).

Supply chain criticality – Material "criticality" can be measured in various ways. Supply risk is based on a combination of substitutability,

end-of-life recycling rate and the proportion of producing countries that have poor governance. Criticality is dynamic over time in response to changes in technology and geopolitics. Qualitative aspects of the supply chain have been reviewed, including the major uses of materials and the potential impact this could have on supply for energy storage technologies. Where information exists, the major countries and corporations involved and their share of the global supply chain are included.

Human rights – This category is focused on workers and the local community as the main stakeholder groups. For workers, the main issues included child labour, a 'fair' salary, working hours, forced labour, equal opportunities and discrimination, and social benefits or security. For the local communities, the focus was on access to resources, cultural heritage, safe and healthy living conditions, respect for indigenous rights, community engagement, local employment and secure living conditions.

Health and safety – This focus is on impacts for workers along the supply chain (particularly in manufacturing, installation, maintenance and end-of-life) and consumers. Health and safety impacts during the mining phase are addressed in the human rights criteria, as they relate to broader issues of working conditions and child labour.

3.2 Impact Assessment

It is challenging to make direct comparison across the technology groups – owing to different technology characteristics, technical maturities, and potential applications at different scales. Nevertheless, a comparison is useful to flag impact "hot spots", to help

inform future research, and to support the development of priority mitigation and management strategies.

3.2.1 Lifecycle energy efficiency

Lifecycle energy efficiency is important because a high efficiency maintained

over a longer than expected lifetime minimises energy losses, technology uptake requirements and associated impacts.

Lithium-ion batteries perform well with a high average round-trip efficiency (~90 per cent) compared to lead-acid (~80 per cent) and flow batteries (~75 per cent). For comparison, the efficiency of conventional electricity transmission and distribution systems in Australia is approximately 90 per cent on average.

PHES has the highest round-trip efficiency (75–80 per cent) of high-volume bulk energy storage technologies and also has the longest lifetime of all technologies: between 50 and 150 years. The expected lifetimes for lithium batteries are also slightly longer than, for example, lead-acid and flow batteries, but are still short in comparison to bulk storage technologies.

Hydrogen-to-power performs poorly (20 per cent) against other technologies when considering lifecycle energy efficiency.

3.2.2 Lifecycle greenhouse gas emissions

The carbon intensity of the energy mix in the use phase of its lifecycle has the biggest impact on overall lifecycle GHG. However, as energy systems transition to more renewable sources, the emissions contributed by material extraction and manufacturing processes become more significant.

In terms of the current high carbon-intensity of Australia's energy grid, the technologies with a high round-trip efficiency, such as lithium-ion, perform relatively well. For bulk energy storage, PHES performs the best whilst CAES does not perform as well as other technologies as it is typically integrated with natural gas combustion resulting in CO₂ emissions that impact on lifecycle GHG emissions. Hydrogen-to-power is also not highly ranked when considering impact on

lifecycle GHG emissions, but the flexibility of hydrogen in terms of end-use could support the decarbonisation of heat, power, transport and industrial processes. There is also potential for large-scale long-distance renewable energy export.

It is difficult to directly compare CSP with TES lifecycle emissions because these systems generate electricity as well as provide energy storage, but within the system the thermal storage component contributes a very small amount to the overall emissions.

3.2.3 Supply chain criticality

Supply chain criticality not only considers geological availability of resources, but also potential supply chain vulnerabilities and risks associated with economic, technological, social or geopolitical factors. It provides insights for understanding technology development trends and enabling new opportunities for industry and research.

Lithium-ion batteries have the highest level of supply chain criticality owing to the use of cobalt, natural graphite, fluor spar, phosphate rock and lithium. The different lithium-ion battery chemistries, in particular nickel manganese cobalt oxide (NMC) chemistry, have a higher level of supply chain criticality owing to the supply risk of cobalt. Half of world cobalt production is from the Democratic Republic of Congo (DRC) and the vast majority of the world's resources are in the DRC and Zambia.

The security of supply of antimony used in certain lead-acid batteries and vanadium for Vanadium Redox Flow batteries (VRB) are also potentially of concern. Polymer Exchange Membrane (PEM) electrolysis technology for hydrogen production uses platinum catalysts that are identified as critical on the basis of supply chain constraints. For CSP TES plants, there are no issues in terms of material

criticality of the Thermal Energy Storage (TES) materials (nitrate salts) although there are potential constraints on supply of silver and cerium for CSP. None of the materials used for PHES or CAES is considered critical to supply chains.

3.2.4 Material intensity

Material intensity is an important metric owing to the high use of non-renewable resources in energy storage technologies. In general, battery storage technologies have a higher material intensity compared to the other technologies reviewed. Lithium-ion batteries have a relatively high energy density that makes them less material intense than the alternative battery technologies (there are significant differences between the lithium-ion chemistries). The material intensity of CSP is relatively high compared to other renewable generation technologies, however the molten nitrate salts used for thermal storage are abundant.

3.2.5 Recyclability

With energy storage technologies, there is the potential to alleviate high material intensity through recycling, reuse, or remanufacturing. Low recyclability highlights a need to develop new infrastructure and technology and stewardship approaches. Lead-acid batteries are the only battery technology to have a high level of recycling in Australia (90 per cent) as recycling offers a return to recyclers. New batteries are typically manufactured with 60–80 per cent recycled content.

While most lithium-ion batteries are technically recyclable, there is neither the economic driver nor a policy incentive for recycling in Australia. As the market grows for energy storage batteries, so will the hazardous waste stream that – as with

lead-acid batteries – can become a resource recovery opportunity. There are other niche resource recovery pathways for batteries under development, for example the potential for ‘rebirthing’ batteries from electric vehicles at the end-of-first-life, for use in stationary energy storage. For hydrogen storage, there are established pathways (although not located in Australia) for platinum catalyst recycling capable of achieving high recovery efficiencies (greater than 95 per cent).

Recycling is well established for the major materials used for PHES, CAES and CSP with TES and the long lifetimes for these bulk storage technologies reduces the need for recycling.

3.2.6 Environmental health

Damage to ecosystems or human health along the supply chain can undermine the benefits of moving to a renewable energy system. As batteries are a material intense technology they have the most significant impacts. These impacts vary depending on the location of mining, processing, end-of-life management, and differences in technology, production pathways and local environmental and social standards. The most significant impacts from mining can include contamination of air, water and soil. The cobalt mining area of the DRC is one of the top ten most polluted places in the world due to heavy metal contamination of air, water and soil, leading to severe health impacts both for miners and surrounding communities (Narendrula et al., 2012).

In the case of bulk storage technologies, whilst PHES has a relatively large land and infrastructure footprint the impacts can be minimised through location in areas that have already been modified (for example existing reservoirs, away from conservation

areas and with closed loop systems that reuse water). CAES has a lower visible impact on the landscape. However, creating salt caverns for compressed air storage involves the removal and processing of large volumes of salt water. Hydrogen storage has a relatively low land-footprint (for electrolysis technology) and there is strong potential to use existing infrastructure. On the other hand, as it is a feedstock, water availability is an important consideration in dry or arid locations.

3.2.7 Human rights

There are significant human rights impacts associated with the material demand for lithium-ion batteries, particularly lithium and cobalt. The mining of cobalt in the DRC is often done by artisanal and small-scale miners who work in dangerous conditions in hand-dug mines without proper safety equipment (Tsurukawa et al., 2011; Frankel, 2016). There is also extensive child labour (Tsurukawa et al., 2011). While there is a lack of published research on the impacts of lithium mining, investigations by journalists and NGOs highlight water-related conflicts and concerns over lack of adequate compensation for the local communities, with many people remaining in poverty despite decades of lithium mining in Chile, and recently in Argentina.

For bulk storage technologies, the major impact is the potential conflict over land use that could arise from new PHES, CAES or CSP TES developments in Australia.

3.2.8 Health and safety

Inadequate management of health and safety risks has the potential to jeopardise the viability of the emerging stationary battery industry and highlights a need to engage all relevant stakeholders to adhere to best safety-

practice. The potential for thermal runaway leading to fire and explosion is considered a significant safety issue for the dominant lithium-ion chemistries (e.g. NMC) and has received a lot of public attention with the recall of Samsung Galaxy Note 7 smartphones.

For hydrogen storage, the high flammability and mobility of hydrogen that can penetrate and damage internal structures, or create hard-to-detect leaks, present the main potential health and safety impacts. No high-order safety impacts are identified for PHES, CAES and CSP TES, all of which use mature technologies that are typically operated by trained workers.

3.3 Maturity of Mitigation Strategies

Table 5 provides a high-level overview of the environmental and social impact ratings across the storage technologies reviewed for this report that will need to be addressed should a particular technology or technologies be adopted. The degree of environmental and social impact was derived from a comprehensive literature review and expert stakeholder interviews, as well as characterisation of the 'maturity' of the mitigation and management strategies with maturity affecting the overall ranking of the impact:

- *Immature* – R&D agenda, absence of policy and incentives
- *Maturing* – mitigation exists but not deployed at scale
- *Mature* – well-established mitigation strategies demonstrated in industrial context

For example, a potential high-level impact may be identified for a technology, but if there is an established mitigation strategy in

	Li-ion	Li-ion LFP	Lead-based	Flow batteries	Sodium-ion	Hydrogen	CAES	PHES	CSP with TES
Environmental impact									
Lifetime energy efficiency	Yellow	Yellow	Orange	Orange	Orange	Orange	Orange	Yellow	Yellow
GHG emissions	Yellow	Yellow	Orange	Orange	Orange	Orange	Red	Yellow	Yellow
Supply chain criticality	Red	Orange	Yellow	Orange	Yellow	Orange	Yellow	Yellow	Orange
Material intensity	Orange	Orange	Yellow	Orange	Yellow	Yellow	Yellow	Yellow	Yellow
Recyclability	Orange	Orange	Yellow	Orange	Orange	Yellow	Yellow	Yellow	Yellow
Environmental health	Orange	Orange	Orange	Yellow	Yellow	Yellow	Yellow	Orange	Yellow
Social impact									
Human rights	Red	Orange	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Health and safety	Red	Orange	Orange	Yellow	Yellow	Orange	Yellow	Yellow	Yellow
Overall	Red	Orange	Orange	Yellow	Yellow	Orange	Orange	Yellow	Yellow

Impact levels ■ Higher ■ In between ■ Lower

Table 5: Risk matrix comparing the “order” (low-medium-high) of environmental and social impacts across the storage technologies

place that is considered “mature”, then the final impact level is appropriately adjusted.

The analysis of energy efficiency and lifecycle GHG emissions criteria shows that the dominant lithium-ion battery chemistries – nickel, manganese, cobalt oxide (NMC); lithium iron phosphate (LFP); PHES; CSP with thermal energy storage (TES) perform well compared with other technologies.

For material intensity and recyclability, the potential for adverse environmental impacts associated with materials used in batteries is highest, with the exception of lead-acid batteries where used lead-acid batteries (ULAB) recycling is considered “mature”. The supply chain criticality for the NMC chemistry is highlighted owing to the use of cobalt (for the cathode) which is supplied predominantly from the DRC and graphite (for the anode) which comes from China, India and Brazil.

Impacts on local environmental health are most significant for the battery technologies (largely associated with the material intensity). While the potential for adverse environmental impacts is also flagged for PHES, management and mitigation strategies for PHES are easier to implement as they occur in Australia compared to offshore jurisdictions.

Adverse human rights impact for battery technologies arise due to issues associated with the mining and manufacturing in jurisdictions such as the DRC that lack adequate health and safety standards. With its abundant mineral resources, Australia can participate in (and encourage) the establishment of sustainable supply chains. While the fire risk of lithium-ion chemistries is flagged as an impact ‘hot-spot’, mitigation and management strategies are under development to offset that risk. For the larger storage technologies, human rights

impacts revolve around competing land use. Mitigation strategies to offset this risk need to consider the economic, social and cultural impacts of developments to local communities.

3.4 Risk Analysis and Interventions

Figure 15 represents the risks evaluated and prioritised for mitigation and management against the relative frequency and exposure ratings for each of the technologies. It should be noted that anything that stores energy (chemically) has an associated risk factor. As such, the introduction of energy storage using chemicals as a medium or interface is not considered a new concept.

Impact colours align with the overall impact ratings presented in Table 5. The vertical axis

provides a range of likely deployments from niche to exclusively utility scale to broad domestic deployment, and is considered a proxy for level of exposure (i.e. more stakeholders are exposed for technologies likely to be deployed in residential and small commercial markets).

The horizontal axis provides a range of likelihoods of deployment consistent with the scenario modelling presented in Chapter 1 and as such is a proxy for frequency. On this basis, technologies clustered towards the top-right quadrant represent the greatest risk. Because of their likely higher rate of deployment, lithium battery technologies should be a priority for mitigation and management for likely environmental and social impacts.

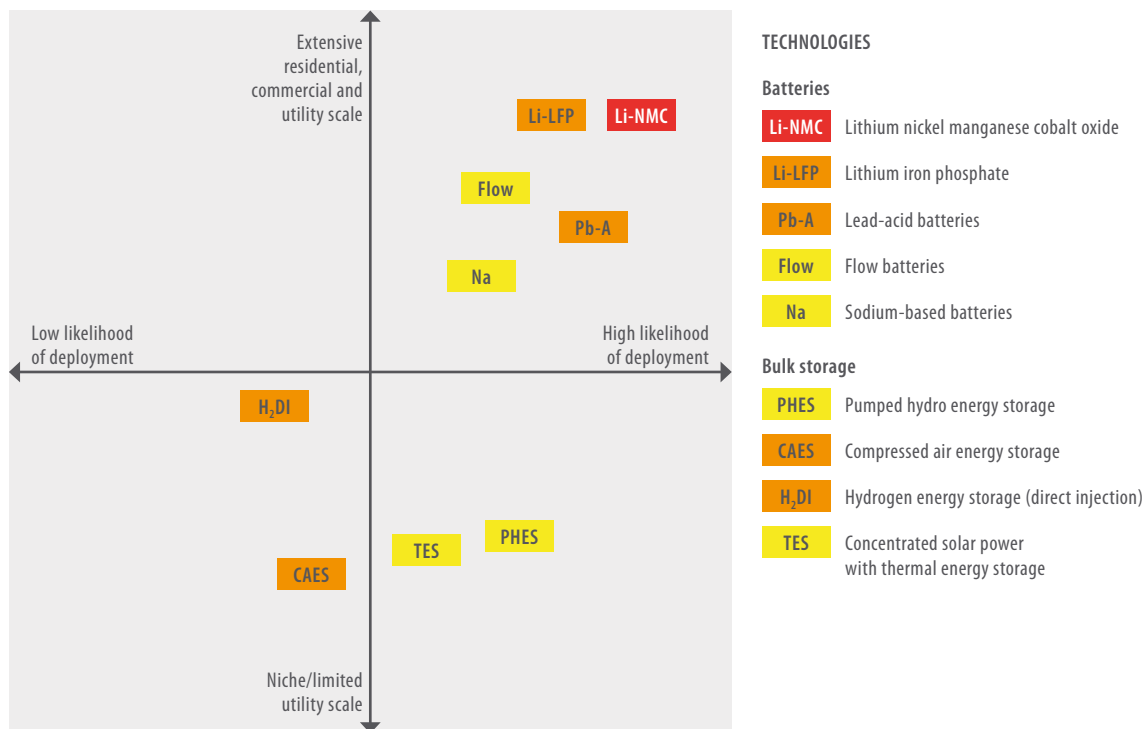


Figure 15: Quadrant diagram showing relative risk and exposure ratings for energy storage technologies

Priority focal points for intervention include:

Engage the emerging battery energy storage industry stakeholders to ensure their adherence to best practice for safety.

- The current focus of safety risk mitigation strategies prioritise installation, which is logical given the status of the emerging battery energy storage industry. The main initiatives include the development of installation guidelines, installation standards, efforts towards establishing a national energy register, and efforts to align Australian initiatives with international product standards.
- Engage with the industry to adopt best practice as a standard is developed and evolves. In the absence of any regulatory levers, the Clean Energy Council has implemented “battery endorsement” for PV accredited installers. Some industry stakeholders are advocating for changes to state and territory electrical safety standards to ensure a more enduring (potentially regulatory) solution that encourages industry engagement and adherence to safety standards.

The development of stewardship approaches for responsible end-of-life management.

- Stationary storage batteries could present a significant waste management challenge or resource recovery opportunity in the coming decades. As there is no economic or policy driver in place, encouraging investment in end-of-life management infrastructure is a priority. Chapter 2 identifies that opportunities for the creation of a recycling and repurposing industry will grow as the battery energy storage industry grows.
- Establishing a product stewardship scheme requires multiple points of intervention along the supply chain (retail, installation,

deinstallation, end-of-life) highlighting the need to engage a range of stakeholders. A stakeholder with expertise in this area (and consulted as part of information gathering) identified the opportunity to align efforts to improve end-of-life management with complementary ongoing efforts to ensure safety:

- Installation and deinstallation represent a shared opportunity for ensuring safety and establishing pathways for responsible end-of-life management;
 - Making the cost of end-of-life transparent at the point of sale (as opposed to the point of disposal) leads to better end-of-life management outcomes; and
 - Consistent approaches to stakeholder engagement and awareness-raising through, for example, protocols for information transmission along the supply chain and consistency in signage and labelling.
- There is a strong rationale for action now rather than in ten years when the first installations reach end-of-life.

Encourage the development of sustainable supply chains for metals.

- Australian governments and companies can take a leading role in putting sustainable supply chains on the global agenda by supporting initiatives, including ethical sourcing and corporate social responsibility, mining and chain-of-custody standards such as that developed for the steel industry (Australia led the development of the Steel Stewardship Forum), national sustainable supply chain legislation, increased rates of recycling and reuse, and new research to address the lack of data characterising supply chain impacts, criticality, and the best approaches for mitigation.

3.5 Key Findings

6. A high uptake of battery storage has a potential for significant safety, environmental and social impacts that would undermine its net benefits.

- The development of safety standard is required given anticipated rapid uptake of batteries.
- As an early market “test bed” for batteries, Australia has an opportunity to promote and lead development of sustainable supply chains from mining to disposal. This would use Australia’s expertise in sustainable mining to lead and support the development of international standards.
- There are opportunities for consumers to influence commercial behaviour globally through improved awareness of the environmental and social impacts of battery development.

7. Unless planned for and managed appropriately, batteries present a future waste management challenge.

- Australia has an opportunity to play a product stewardship role to ensure the sustainable repurposing of used electric vehicle batteries and recycling of all batteries.
- Focused development of recycling infrastructure and technology will be crucial and provides an opportunity for industry development and job growth.

CHAPTER 4

SOCIAL DRIVERS AND BARRIERS TO UPTAKE OF ENERGY STORAGE

4 Introduction

Over the past decade, Australian households, utilities, investors and governments have spent some \$A40 billion, in nominal terms, on clean energy investment (Bloomberg New Energy Finance, 2016). This investment contributed to solar PV installations growing from 8 MW to 5,400 MW, or approximately 9 per cent of current electricity generation capacity (Australian PV Institute, 2016). The growth has occurred largely in the residential sector and has been supported through various state and commonwealth schemes including generous feed-in tariffs and Renewable Energy Certificates.

The absence of long-term renewable energy targets and a widening social inequality has raised concerns about the distribution of solar energy production. Uniform tariffs that are not means tested or that might regressively tax low socio-economic and vulnerable groups are seen to, in effect, provide subsidies or “middle class welfare” for more affluent demographics (Nelson, Simshauser & Nelson, 2012; Simpson & Clifton, 2016).

There is concern that electricity prices will become an increasing financial burden for households. The cessation of several generous feed-in tariff schemes has led to concerns about increased electricity prices. In response to these concerns, Australians are beginning

to consider energy storage opportunities such as batteries (Agnew & Darguschm, 2017; Colmar Brunton, 2015).

With the large-scale deployment of energy storage still in its infancy, it is timely to consider and understand how consumers, industry and policy makers are responding to energy storage technologies. The growing international trend to move towards clean reliable energy – most often supplied by renewables – indicates that the emergent energy storage industry is poised for a transformation. Responses to storage technologies will be location specific (see Box 11) and will be influenced by a range of factors.

Box 11: Responses to deployment of energy storage technologies

In **New Zealand**, concerns over energy security and increasing demand for electricity have resulted in growing support for in-front of meter solutions. Due to the negative perceptions of battery storage as an emergent and untried technology, and with insufficient power, energy capacity and perceived high costs, battery storage is considered to have low likelihood of deployment compared with conventional thermal generation (Kear & Chapman, 2013).

In the **United Kingdom**, there has been strong support for energy storage – both behind and in front of the meter. Drivers of this support includes both avoided distribution network costs and reduced consumer bills (Grünewald et al., 2012).

In **Germany**, the addition of a battery system is seen as a social obligation, contributing to the success of the nation's energy system transformation. Other drivers include higher

independence from energy suppliers and increased self-consumption (Gähns et al., 2015). In contrast, another German study investigated perceptions of hydrogen storage. Batteries were perceived as familiar, but 'dirty' compared to other energy storage technologies such as fly wheels (traditional, simple and clean); and hydrogen storage (clean, modern and fascinating), (Zaunbrecher et al., 2016).

In **Fukushima**, following the nuclear disaster, domestic battery storage adoption has generally been viewed favourably and as a necessary component of emergency preparedness (Abe et al., 2015).

In **South Australia**, in response to an extreme weather event in September 2016 that resulted in a state-wide blackout, the state government announced investment of up to \$A150 million in energy storage projects to support system security (March 2017).

There is considerable uncertainty facing the energy storage sector. In Australia, this uncertainty includes the energy policy discord between national and state jurisdictions as well as the lack of a national standard for residential lithium-ion batteries, in particular regarding system design, battery enclosure ventilation, maintenance testing performance and system documentation (Standards Australia, 2016).

The uptake of energy storage has the potential to blur distinctions between the once clear boundaries of 'products' and 'services' for the energy and other sectors.

This may result in the creation of further complexity for consumers, where the risk of rapid market development could possibly *"erode existing ombudsman jurisdiction, effectiveness and reputation"* (Benevenuti, 2016). This is in contrast with the Australian Energy Market Commission's (AEMC) view that battery storage and *"the functions it performs are not different to other types of technology and can be accommodated within the existing regulatory framework"*, where *"competitive market frameworks currently in place will allow consumer preferences to drive how the sector develops"* (AEMC, 2015). Notwithstanding these mixed messages and policy uncertainty, the development and implementation of energy storage solutions is already underway globally and is expected to see strong similarities in adoption with other smart grid enabling technologies.

4.1 Socio-technical Uptake of Other Smart Grid Technologies

A number of lessons can be drawn from the previous roll out of energy related technologies and initiatives – solar PV cells,

smart meters, changing tariff structures through cost reflective pricing and energy efficiency – when considering the potential uptake of energy storage in Australia. Each of these has relevance as they represent new technologies and innovations that have challenged the way that householders use and interact with their home energy⁴¹. Lessons can also be learned from the different financial structures that have incentivised or constrained market penetration. A summary of the key findings from research documenting societal responses to these issues follows.

4.1.1 Solar PV

The path dependency of societal solar uptake has changed significantly within Australia in the past two decades and can be characterised into three eras – Pre-FiT (feed-in tariff), Premium FiT and Low FiT – where each is influenced by different demographic variables and attitudes towards solar (see Figure 16). The influence of the various incentive schemes that promoted PV can help to inform considerations regarding finance options for energy storage at both the individual and community level.

Understanding the drivers and uptake of solar PV helps to inform considerations for storage uptake in a number of ways. Many respondents believe the early market for battery storage in Australia will mostly benefit households with existing solar PV that are:

- experiencing a recent loss in their premium FiTs and are now facing the true cost of electricity within their jurisdictions.
- early adopters of technology who invested in solar and are therefore likely to be interested in the emergent battery technologies.

41. Just as consumers were challenged by the introduction of motor vehicles onto roads that had been established for the horse and cart.

Explanatory variables		
	Demographic profile	Attitude profile
Pre-FiT era		
1992	Low solar penetration; mainly off-grid non-domestic applications where economic factors are secondary considerations (Watt 2009). 66 % of all successful applicants for the PV Rebate Program (PVRP) for the period 2000–09 are from medium-high or high socio-economic postal areas. Large upfront costs excludes many low to medium income households from the program (Macintosh & Wilkinson 2011).	Solar has high acceptance with educated males and households with children. Early grid-connected adopters are motivated by self-sufficiency, energy-independence and environmental values (CSIRO 2009; Gardner, Carr-Cornish & Ashworth 2008). Higher levels of education and skilled occupations allow greater access to internet enabling easier access to information on PV systems and options for rebates (Macintosh & Wilkinson 2011).
2007		
Premium-FiT era		
2008	Large grid connected domestic solar uptake by predominately educated individuals aged 35–74 (with a significant percentage over the age of 53) living in detached/semi-detached owner occupied dwellings and employed in a wide range of industries with moderate gross household income (ACIL Allen 2013; Seed Advisory 2011).	Strong support for solar from all demographics. Payment preferences similar between age, income and gender. Actual objective knowledge of solar is much lower than perceived subjective knowledge (Romanach, Contreras & Ashworth 2013). Attitude-behaviour gap exists towards purchases of products because consumer ecological values and attitudes do not necessarily materialise into green product purchases (Claudy, Peterson & O'Driscoll 2013).
2012		
Low-FiT era		
2013	A slowdown of domestic capacity uptake characterised by families where the number of bedrooms and the type of dwelling are significant explanatory variables; age (over 55); tertiary education and financial capacity become less significant compared to previous eras (Sommerfeld et al. 2017). Declining domestic volumes offset by growth in business solar (Origin Energy 2016).	Solar is almost unanimously accepted as a social good and the most popular option towards achieving clean energy policies (Cass 2016). Mixed opinions on supporting renewables through electricity tariffs (Simpson & Clifton 2016). Growing disbelief in solar as a cost-effective solution to reducing electricity prices. (Colmar Brunton 2015).
2017		

Figure 16: Summary of solar PV deployment in Australia

4.1.2 Smart meters

Advanced metering infrastructure or smart meters, enables two-way communication of information about energy use. It is considered to be critical infrastructure for successful deployment of battery storage, cost reflective pricing and support for energy reliability within distribution networks.

Despite their potential, the forced government roll out of smart meters in Victoria resulted in the deployment of this technology being less positive than experienced in other jurisdictions. This was complicated by growing compatibility, privacy, security and cost concerns post implementation (Hess, 2014; Lamech, 2014).

In contrast to this local, and similar USA experience, a UK Department of Energy & Climate Change survey indicated that the majority of customers with smart meters held little to no concern about them, with only a few indicating that they had been disadvantaged enough to desire changes to their devices (DECC, 2015). Feedback also indicates that after an early engagement period with devices, long-term usage dropped off considerably as they lost their novelty factor, indicating that for smart meters to have long-term impact, consumers would have to adopt behind the meter automation software.

4.1.3 Cost reflective pricing

A key element that may facilitate battery storage uptake is the adoption of cost reflective pricing and changing patterns of demand⁴². Recent evidence suggests that there is growing support among Australians for more cost-reflective pricing (Deloitte, 2013;

Hall, Jeanneret & Rai, 2016) even as large differences exist in support of different tariff structures depending on demographic factors such as income, education, household type and rental status (Stenner et al., 2015).

Irrespective of perceived support and interest for cost reflective pricing, electricity consumption for most of the Australian population still remains price inelastic and relatively unresponsive to price signals (Hobman et al., 2016). With the institution of different tariff structures – irrespective of demand response – this price inelasticity ultimately produces winners and losers across households that may create social inequality concerns for policy makers (Simshauser & Downer, 2014).

4.1.4 Energy efficiency measures

Energy efficiency measures across Australia have been critical in reducing electricity consumption nationwide (Energetics, 2016). Although there has been a strong drive by governments and utilities around the world to promote energy efficiency behaviours, this has met with mixed results that have mainly stemmed from gaps between “actual” and “expected” financial benefits derived from those measures. This is because rising energy prices often outweigh expected savings; or the scope of the intervention is insufficient to significantly relieve worries about fuel costs (Chan & Ma, 2016). Unlike other enabling technologies, household attitudes can often be predictors of adoption of energy efficient behaviours, whereas perceived social pressures to engage or not engage in a particular behaviour, together with the extent

43. With existing flat rate tariffs there is little motivation for shifting load with batteries (Khalilpour & Vassallo, 2016).

to which an individual believes that they have control of their energy efficiency intentions (Scott, Jones & Webb, 2014) are generally found to be weak predictors of intentions to conserve energy.

In the USA, there are large demographical distinctions based on gender, political affiliation and socio-economic status between perceptions and attitudes to government and utility-led energy efficiency campaigns (Craig, 2016; Craig & Allen, 2014).

A similar divide between government and utility-led initiatives may also occur for energy storage initiatives in Australia, particularly where individuals hold low levels of trust in either institution.

4.1.5 'Prosumers' and energy cultures

Rooftop solar, energy efficiency, cost-reflective pricing, and smart metering all embody new cultural valuations and practices for electricity generation and use that will shape energy storage in the future. Households have become more than consumers of electricity – indeed the term 'prosumer' (meaning both a producer and consumer) has been used in the energy sector since the uptake of PV.

New forms of consumer behaviour are emerging (Bulkeley et al., 2016). This includes an increasing awareness of the ability to self-produce electricity, consumer interaction with technology to manage consumption, and localisation of energy production – whether at a community or regional scale. This has resulted in the philosophical questioning of the foundations of the electricity system (Strengers, 2013) and the drawing of insights from historical and cross-cultural experiences (Maller & Strengers, 2013).

4.2 Models of New Technology Acceptance

There are numerous published theories about the uptake and acceptance of new technologies and innovations. Possibly the most well-known is Rogers' (1962), which shows that adoption tends to fit a bell curve that compartmentalises individuals by their speed of adoption into one of five groups: innovators, early adopters, early majority, late majority and laggards. Further, diffusion of new technologies into a market typically occurs through a socialisation process that follows an S-curve (Figure 17).

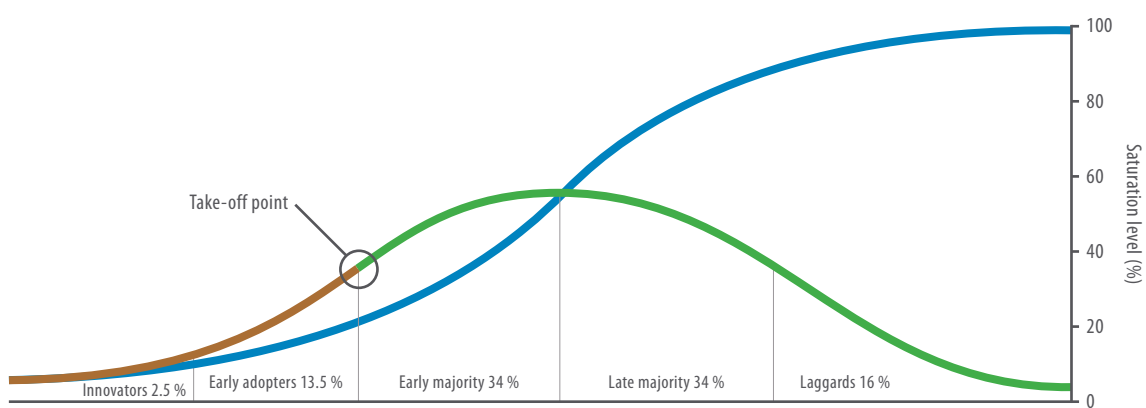


Figure 17: Graphical representation of Rogers' Theory (1995) of technology diffusion to market which describes that different consumer types will adopt or reject the new technology with varying ease (shown by the brown and green bell curve). A rapid "take off" occurs as the 'early majority' begin to adopt the new technology. Overall adoption or market share (blue S-curve) will eventually reach full saturation.

Willingness to adopt a technology is influenced by a number of characteristics including awareness, interest, evaluation and trials of the technology. Based on these evaluations – either positive or negative – individuals choose to accept or reject a technology. If they choose to adopt and implement the technology, they will seek supportive statements to confirm that their choice is a good one (continued support for the technology reinforces further adoption). If, however, an individual receives negative messages, they are likely to discontinue with that technology – while if an individual first rejects a technology and finds supportive messages relating to their decision, that rejection will continue. However, in the absence of support for rejection, the individual may ultimately adopt that technology.

More recently, social psychology has been used to explain and predict the social acceptance of pro-environmental innovations. Understanding why consumers support or resist sustainable technology during the early phase of introduction can lead to more acceptable designs and implementation (Huijts, Molin & van Wee, 2014) and more effective, targeted information and communication strategies (Huijts, Molin & Steg, 2012; Zaunbrecher et al., 2016).

One of the more advanced theories on the identification of causal links between intention and acceptance is the technology acceptance framework (TAF) (Huijts et al., 2013; Huijts, Molin & Steg, 2012; Huijts, Molin & van Wee, 2014). This model has shown that a person's normal behaviour is the strongest predictor of intention to act in favour of or against a technology, highlighting its importance in determining pro-environment action.

The next two strongest determinants for intention to act favourably are the perceived costs and benefits. Those negative determinants of an intention to act are the perceived negative effects of risk, and lack of trust in the industry. The TAF model provides useful insights that can be applied at the householder level to understand likely attitudes towards energy storage, in particular battery storage. A number of the variables explained in the TAF model were used to inform the national survey undertaken as part of this report (see Section 4.3).

4.3 Methodology

A mixed methodology was used to better understand societal attitudes towards storage in Australia.

- Interviews were undertaken with stakeholders who had background knowledge and experience with energy storage.
 - Overall 17 telephone interviews with 19 participants were undertaken with representatives from government, industry, academia and community service organisations (CSO).
- Focus groups were conducted with a cross section of the public.
 - 58 participants (40 per cent male).
- A national survey⁴³ was undertaken (Q & A Research)⁴⁴ across a representative sample of the Australian public (N=1,015).
 - Key characteristics of the sample matched those of the Australian population including age and gender, proportion of the sample from each state and territory and employment status (ABS 2011). There was an equal split across gender and across three age brackets of 18 to 34 years, 35 to 54 years and 55 plus years.

43. Survey questions are available in the Consultant's Report on the ACOLA website <www.acola.org.au>.

44. <<https://qandaresearch.com.au>>.

- The survey comprised 43 questions over four areas – demographics, current energy use and living arrangements that might influence energy use, variables associated with socio-psychological theories of technological acceptance, and preferred renewable energy scenarios.
- The survey questions were informed by a literature review, interviews, focus groups and the scenarios established in Chapter 1.

Gender, age, level of education, belief in climate change and an individual’s view on the likelihood of rising electricity costs were all significant predictors of preferences towards a higher or lower mix of renewable energy. For example, older males tended to expect a lower renewable scenario as did those who believed that the cost of electricity would continue to rise. Equally, those with post-graduate level education and a belief in climate change felt a higher renewable energy scenario was likely.

4.4 Results

4.4.1 Preferred renewable energy scenario

The survey confirmed (as have other surveys) that Australians prefer renewable energy (59 per cent) to non-renewable energy, but generally associate increased costs with its deployment. When presented with a choice between higher and lower renewables as the more *likely* scenario in 2030, respondents were split with 39 per cent indicating that a lower mix of renewables was likely in 2030; 35 per cent that a higher mix was likely; and 26 per cent unsure.

When asked their preferred scenario in 2030, the response was very clearly for a future with higher renewable energy penetration (see Figure 18).

4.4.2 Battery technologies

While current perceptions of battery technology suggest they are financially out of reach, solar PV has met with such strong support that the introduction of energy storage options adds to its appeal. On this basis, the continued uptake of various battery technologies across Australia is more likely.

“[Storage is] more flexible...., it just takes all that risk away from you because you know what your input costs are. It’s interesting on so many levels. It’s such an interesting development and I think that’s why it’s coming forward so fast, because it’s not just of interest to people who are thinking about reducing emissions, it’s just such a liberating technology in so many ways. (Interview 012)

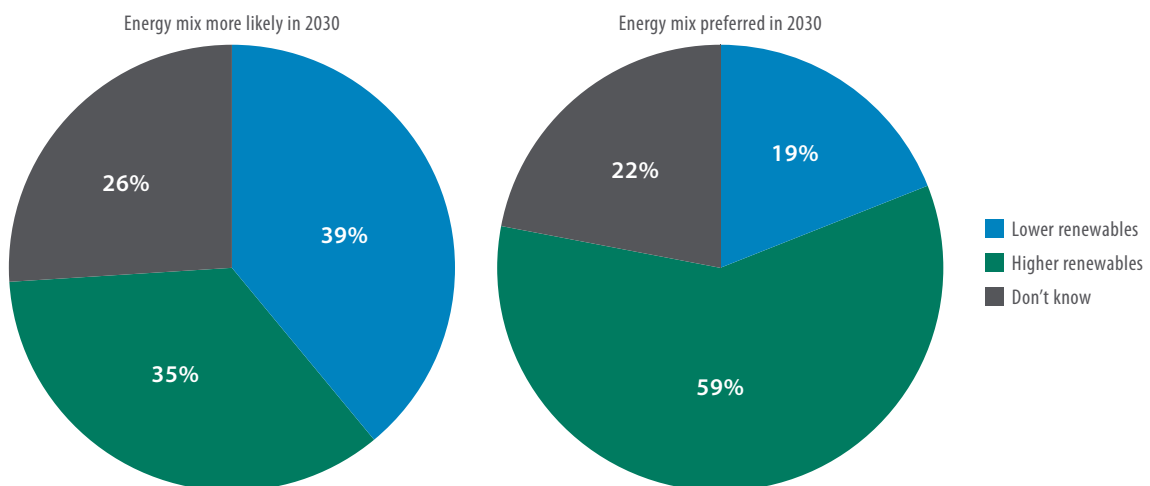


Figure 18: 2030 energy mix, likelihood versus preference

Safety

The major concern that arose across all interviews was the safety of energy storage across the storage supply chain. This included expressed concerns for the environment if batteries were not responsibly recycled (see Chapters 2 and 3) with the general concern expressed that an early negative incident may have serious ramifications for deployment.

Respondents considered such an occurrence would be similar in outcome to the earlier failure of the Commonwealth Government's home insulation program that ultimately resulted in four deaths. This theme also arose in the focus groups and national survey.

"Recent events in South Australia have clearly proven that "Renewable" Energy sources as a stand-alone do not work and do not have the capacity for storage. Battery storage is dangerous, as most consumers have no idea on both maintaining and storing these items. Replacement costs will be exorbitant, with limited warranty on the items. Initial costs may be cheaper via subsidies however, those subsidies will not allow for replacement. This is very similar to the ceiling insulation issues during the Rudd Government Stimulus Programme in 2008/2010." (Identification number 581)

"There was a lot of talk when we first spoke to Standards Australia about which standard we should focus on, and the reason we did installation rather than product was that we don't really do much in the market. So as more batteries come into the market, the more critical thing is to make certain that we actually have these batteries installed appropriately, safely and by skilled people, and we actually understand where they're installed." (Interview 002)

Financial considerations

Another common theme revolved around the financial considerations that might enable or impede energy storage for householders.

Many Australians have been affected by the sharp rise in electricity prices that have occurred over the past five years. These increases, together with deregulation of the electricity retail market, changes to FiTs and time of use (ToU) pricing, have led many Australians to develop an underlying mistrust of governments and the energy industry.

"So the fact that prices are so high and also the poor behaviour of retailers – with all the stories about gold plating for networks..... it breeds this sort of mistrust in the energy sector and flows onto wanting independence, like 'I just want to go off grid because I don't want to give my money to those companies, I don't trust them.'" (Interview 009)

Legacy issues that emerged from the interviews, focus groups and survey suggest that many individuals are cautious about trusting both government- and industry-led initiatives. Energy storage sits firmly in the middle of this – presenting an opportunity for individuals to become independent of the established regimes – but necessitating a significant investment of capital without a guaranteed return.

Directly coupled to the value proposition for home battery storage units will be the availability of various pricing structures. ToU pricing will help to drive energy consumption behaviours off peak and allow individuals who have flexibility to capitalise on their alternative use of electricity while also supporting energy reliability. This highlights the need for proactive collaboration between government and industry to ensure benefits can be achieved, while also ensuring those from low socio-economic groups are not disadvantaged.

There was an expectation among survey respondents that consumers, who can afford home battery storage units, may simply elect to become independent of the grid as a way of managing costs and gaining more control over their home energy use.

However, there was also some recognition that not everyone would be likely to have the technical knowhow, motivation or interest in being so involved in their personal electricity supply.

Technology adoption

Individual responses to technology adoption⁴⁵ were compared with intention to purchase a battery storage unit. Of the responses received, 30 per cent of those who own, or intend to own, a battery storage system are likely to classify themselves as early adopters. Whereas of those who see themselves as part of the late majority, 30 per cent were not interested in purchasing a battery storage unit.

Most participants believed that early battery storage deployment will likely correlate with solar PV ownership and the loss of premium FiTs. Nonetheless, there was recognition that the current price of battery storage units was still prohibitive for most, but that an emerging downward trend in the retail price which, coupled with the opportunity for incentives

at both government and retail levels, presented a promising outlook for the future.

Knowledge and awareness

What is evident is that most Australians do not understand much about energy storage and how it relates to energy generation more broadly, although most are familiar with the concept of electric cars and commonly used lithium-ion batteries in computers and mobile phones. When asked what they knew or had heard about energy storage, the most common response was “batteries” with many responding “Tesla” and the “Powerwall”.

“....I think we can't underestimate the, I suppose, the Tesla implications. People have got excited about.... Tesla batteries are the sexy looking batteries.... Digital media is becoming more and increasingly prevalent, so people want the new gismo as part of their household future.” (Interview 002)

Factors that influence a decision to purchase a home battery storage unit included the ability to reduce electricity costs, the purchase cost and safety features (Figure 19).

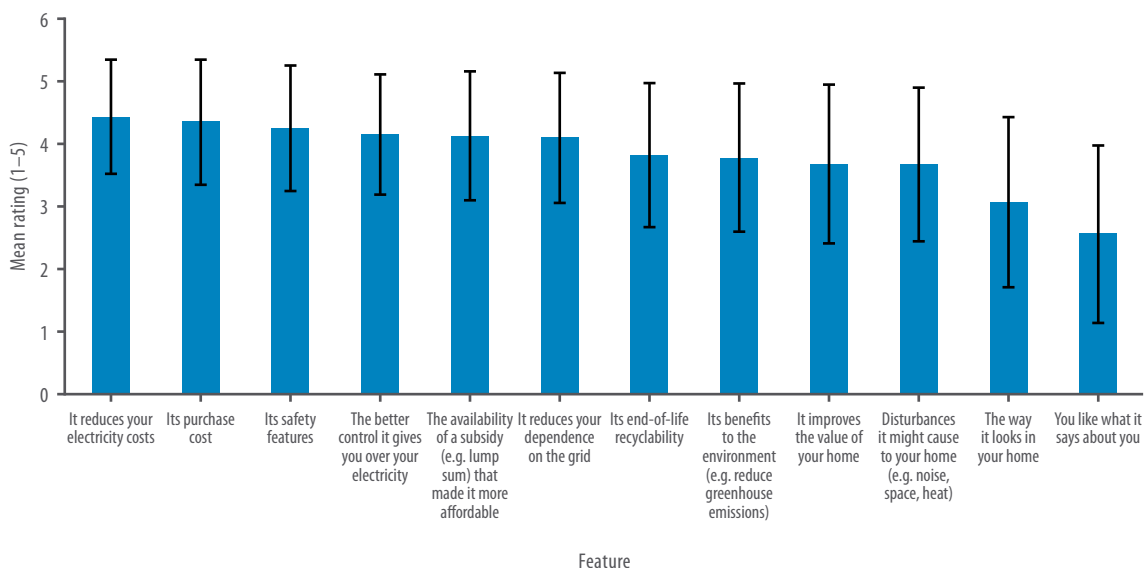


Figure 19: Factors influencing purchase of storage

Note 1: Error bars are standard deviation amounts

Note 2: Likert scale of 1 = not trustworthy and 5 = extremely trustworthy

45. Building on Rogers' (1962) "Theory of Diffusion".

4.4.3 Utility scale storage

Utility scale storage was less commonly referred to than battery storage, but when it arose, the discussion tended to focus on the role of PHES as an established technology that was relatively cheap when compared to all other forms of storage. Nevertheless, as a location specific technology there were mixed feelings about whether the issues of competing land and water use could create social licence issues that may prevent its ultimate deployment (Chapters 2 and 3).

The interviews and survey revealed that some industry and government representatives saw opportunities for utility scale storage across Australia that could ultimately help address security of supply issues in specific geographic locations.

“...unless you can build chunks of 1, 2, 3 GWh who cares, and let’s face it, there’s lots of really big batteries being built around the world... that’s where the synchronous machines, particularly like pumped storage make sense, not only do you deal with the intermittency of renewables but you also start to deal

with the ability to provide inertia because there is a big rotating machine...”
(Interview 015)

4.4.4 Trust, education and communication

Trust

The national survey included the question, “If there is a large increase in the use of home battery storage in Australia, to what extent would you trust the following groups to act in the best interest of the consumer?” The responses indicated low of trust in the Commonwealth and state governments and electricity sector organisations (see Figure 20). This low level of trust in government is likely linked to the frequent and substantial changes to electricity policy over the past decade.

If Australians are to regain trust in governments and the energy industry more broadly, then the politicisation and debate on energy security and Australia’s transition to a low carbon future must be replaced with policy certainty, communication and engagement of all Australians on the range of opportunities available – including energy storage.

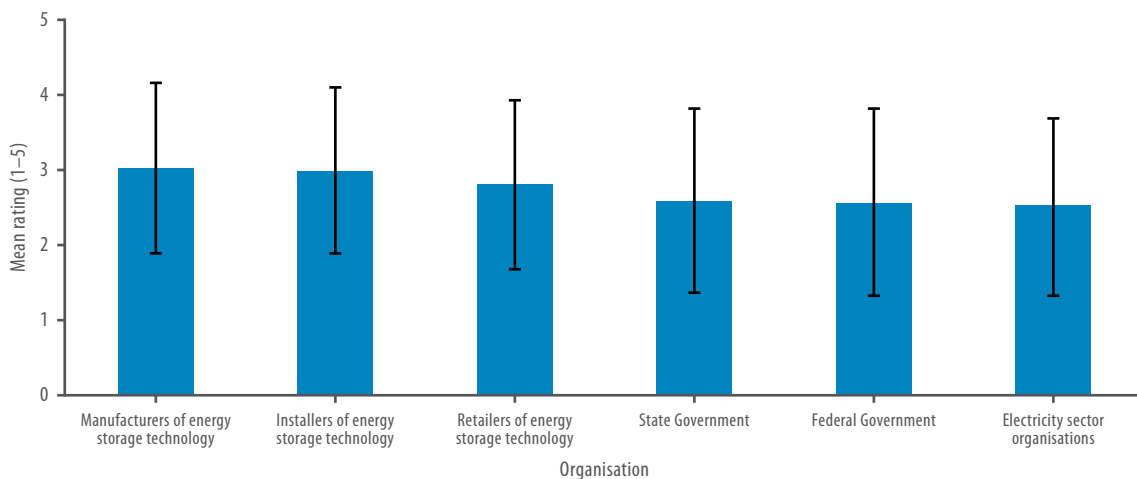


Figure 20: Levels of trust in organisations to act in the best interest of the consumer

Note 1: Error bars are standard deviation amounts. Note 2: Likert scale of 1 = not trustworthy and 5 = extremely trustworthy.

*“Government needs to stop ripping people off like the current reduction of tariff buy-back reduced from \$0.33 to now \$0.08. **** they cannot leave anything good alone. It was working out so well for us now it is hardly worth having the solar panels. Don’t trust any government project as it always turns to ****. Not very happy at all”.*
(Identification number 247)

Education and Communication

Overall there was significant interest in information about the various options available to consumers when purchasing a battery – whether that purchase would benefit them financially or whether there would be a reasonable payback period. Most acknowledged they had limited knowledge about energy storage.

This was confirmed in the survey results that indicated a majority of individuals had very limited knowledge of home battery storage (Figure 21). This correlated to a hesitancy to purchase, with 38 per cent of respondents noting they felt they did not know enough about battery storage to make a decision.

They also indicated they would actively seek out information from trusted sources that included friends, family and others in the community whom they expected to be knowledgeable on the topic. A lack of credible information and political leadership were noted as challenges to be addressed.

“...wide range of sources, you’d want to hear it from people you knew, advertisements, articles in many newspapers, to almost change the culture to be more welcoming of the technology”
(Focus group 4)

There is an opportunity for improved communication on the role that energy storage can play in Australia’s energy future – at residential, community and utility scale. This could be enhanced if combined with more concerted efforts to improve the energy literacy of the Australian public more broadly.

If Australian governments (Commonwealth, state and territory) believe that energy storage has an important role in securing a part of Australia’s energy future, then communication on how it works, the benefits and the investment required will be important for successful deployment.

“We literally have a twentieth century regulatory framework system in a world that’s twenty-first century, where a whole range of possibilities are not only possible, but inevitable and beneficial for everybody involved.” (Interview 006)

“...I don’t think there will be any one solution. I suspect you will find that all the solutions will be deployed. You will find behind-the-meter, you will find in front of the meter. The early adopters will go behind-the-meter because they want to...” (Interview 015)

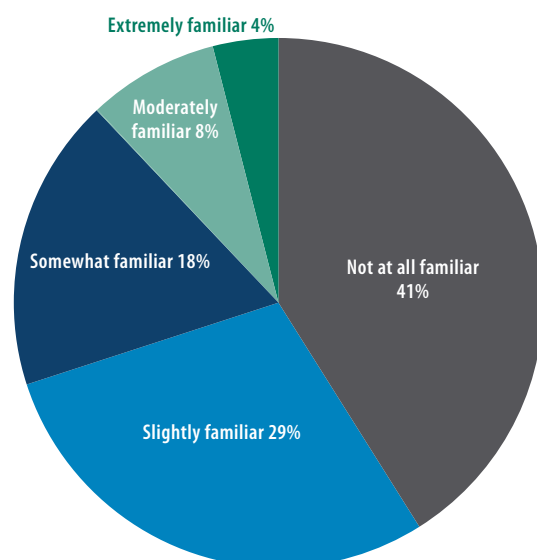


Figure 21: Knowledge of home battery storage

4.5 Case Studies

Examples of deployment of energy storage in Australia are presented in three case studies – commercial deployment, residential deployment and community deployment.

4.5.1 Commercial deployment – Bundaberg, QLD

Bundaberg Christian College is an independent day school for students from K to Year 12. The school's mission of equipping students to make a positive impact on the world around them is most evident with their April 2016 installation of 732 solar panels (194 kW) around the school to reduce their electricity consumption from 330 MWh to 130 MWh/yr.

"Schools are perfectly made for solar, in the sense our usage starts to climb at 8, and starts to decrease at 3, perfectly correlating with our solar production."

Business Manager, Bundaberg Christian College

The college has also installed 30 Hitachi lead-acid batteries (250 kWh) for storage, to

become the largest hybrid solar installation in Australia.

"We have a lot of sun in Queensland and a lot of roof space and schools, so if we can install more solar and use it more broadly, there are opportunities there, it just has to become viable." Business Manager, Bundaberg Christian College

The entire endeavour has cost the school approximately \$A650,000, but has reduced their electricity costs by 80 per cent, giving them a payback of around seven years. For purposes of energy security during extended periods of low solar exposure, the system remains connected to the grid. The project has also led to strong interest from several other schools across Australia.



Figure 22: Bundaberg Christian Colleges' extensive solar array (Source: GEM Energy)

4.5.2 Residential deployment – Melbourne, VIC

Jayne and Cathy are a couple who live in the north east of Melbourne. For many years, they had been battling with constantly unpredictable and inconvenient grid 'drop-outs' resulting from their single wire earth return (SWER) line connection. To combat electricity reliability concerns, in February 2016 they paid for the installation of 6.6 kW solar and 32 kWh of lead-gel batteries system on their property.

To accommodate the batteries, they have had to upgrade their carport into an insulated double car garage to house the temperature sensitive lead-gel batteries. During the summer, the household air conditioning cools the garage so that the batteries do not overheat. Alongside their initial energy security drivers, they also attribute a desire to become more self-sufficient, mitigate against rising power costs as well as becoming more environmentally conscious.

"Having control of where our power comes from has made us extremely aware

of our own energy consumption. It was also satisfying to watch our TV and see everyone around us in darkness". Cathy

Their choice of battery technology came after extensive research. They found that although the newer technologies were superficially impressive, concerns regarding space requirement, cost and maintenance, as well as a lack of experience, were significant factors against adopting these new technologies. Salt-based batteries were considered unsuitable due to load characteristics. Lithium-ion batteries were much more expensive than lead, and were thought by them to have too many associated safety problems.

Although it was an expensive and time-consuming experiment for both of them, Jayne and Cathy are extremely satisfied with the outcomes as it has improved their daily lives significantly knowing they are no longer at the mercy of electricity 'drop-outs' and future price rises.



Figure 23: Jayne and Cathy's house with solar panels, inverter and battery system (Source: Jayne and Cathy)

4.5.3 Community deployment – Perth, WA

On the surface, Alkimos Beach is a typical northern suburb of Perth, not too dissimilar from the numerous community developments across Australia, thriving with young families and working households.

The Alkimos Beach battery storage trial is led by Synergy in collaboration with Alkimos Beach development partners Lendlease and LandCorp with additional funding from ARENA. These organisations have collaborated to trial an innovative approach to community battery storage at Alkimos – virtual energy storage (Figure 24).

Residents are not directly connected to the shipping-container sized battery (1.2 MWh of lithium-ion batteries) that abuts their

community, but they virtually deposit and withdraw credits in the battery through excess rooftop solar production for a small subscription cost of \$A11/month (36 cents per day) by participating in the specifically designed time-of-use peak demand saver plan trial. This allows them to bank excess rooftop solar production when the sun is shining, that would otherwise flow to the market. These banked production units can then be withdrawn during the evening when household consumption generally peaks, but the solar panels are not producing electricity. The facility allows residents to virtually increase their self-consumption of solar and reduce their overall electricity bills.



Figure 24: Alkimos community storage battery container (Source: Synergy)

The 'virtual account' is reset at the end of each day. Excess solar credits do not roll over, but are accumulated and settled at the Renewable Energy Buyback scheme rate (7 c/kWh) at the end of the billing period. Where credits are exhausted prior to the end of the peak period, residents are charged the relevant time-of-use rate of 48 c/kWh during peak events (4 pm – 8 pm). This is considerably higher than the Peak Demand Saver Plan off-peak rate of 26 c/kWh that they would be charged during any other part of the day.

By comparison, customers on the standard home plan tariff are charged 26 cents all day, every day. The Peak Demand Saver plan model provides a financial incentive to match excess solar production during the day with evening electricity consumption.

Cost saving was a significant factor in participating in the trial. We have been able to save 50 per cent on our electricity bills. At the same time, we have learnt how to use our appliances around the new rules, because it is a little different now with a battery as opposed to before. But luckily for us, the big behaviour change was actually when we got the solar panels, with the battery you have a little bit more flexibility, but obviously you have to know how it works. It's not just set and forgot, there are rules behind it, mostly coming from the power provider.

Alkimos Beach Resident 1

The project has not been without challenges. Last year, Perth experienced an atypically long, cold and rainy winter, which affected the residents' solar credit production. This meant that residents often were not producing enough credits to offset their increased energy consumption. As a result, some residents noticed their bills had increased.

Last winter we noticed that our electricity bill had gone up almost 80 %. But we weren't surprised because we had noticed that our heating had gone up because of the long cold winter. It also rained a lot, so we were not producing a lot of solar, unfortunately. But that's something you can't control. Other than that, we have been satisfied with the trial.

Alkimos Beach Resident 2

It might seem counterintuitive for Synergy, as an electricity gentailer (a company that is an electricity generator and retailer), to participate in a trial that reduces customers' electricity bills. However, it is part of a bigger plan to save money by reducing infrastructure spending, which can then be passed on to the customer as well as trialling innovative and relevant products to meet customer needs.

Key Findings

8. Australians are deeply concerned by the sharp rise in electricity prices and affordability. They hold governments and energy providers directly responsible for the perceived lack of affordability.

- Deregulation of the electricity market, changes in feed in tariff schemes (fits) and other time of use (ToU) tariffs have led to an underlying general mistrust of the government and energy providers. Focus group participants believe that individual consumers who can afford home battery storage units may elect to become independent of the grid to avoid rising energy costs.


9. Energy storage is not a well-known concept in the community and there are concerns that a lack of suitable standards at the household level will affect safety.

- A majority of respondents surveyed said they did not know enough to make an informed decision about whether to purchase a home battery storage unit.
- Although a battery storage installation standard is currently under development, there is concern that an early negative incident may have serious ramifications for household deployment, with many in focus groups referring to the “Home Insulation Program” failure.

- “Pumped hydro” was recognised by some of those surveyed in the general community as an established utility scale technology, but that possible “social licence” issues may arise due to the perception of competing land use and a potential lack of available water.
- There is an opportunity for governments to increase the Australian public’s knowledge and awareness of energy systems (from energy generation through to storage – at utility and consumer levels).

10. Australians favour a higher renewables mix by 2030 particularly PV and wind, with significant energy storage deployed to manage grid security.

- The majority of those surveyed suggested they would look to government to play a role in the future energy mix but lacked confidence that their preference for higher renewables would be achieved without consistent energy policies.



Australians favour a higher
renewables mix by 2030,
particularly PV and wind,
with significant energy
storage deployed to
manage grid security

CHAPTER 5

CONCLUSIONS

Australia is undergoing an unprecedented transformation in the electricity sector. Encouraged by Commonwealth, state and territory technology-specific energy policies since the mid-2000s, Australian consumers and businesses have already invested in new generation technologies (principally renewables), taking control of their energy use and supply and supporting action on climate change. In this decentralised, yet integrated, 21st century energy future, storage provides a vital link between generation and consumption that allows for greater penetration of utility scale and distributed renewable energy generation.

There is a legitimate role for governments to provide strategic direction by ensuring the right policy settings are enacted to drive growth in energy storage in the national interest. Leadership in energy policy and the deployment of energy storage can promote innovation, investment, the establishment of new (and growth of existing) high technology industries and increased or new energy exports. A proactive approach will provide the opportunity for Australia to lead and facilitate re-skilling of workforces and employment across all levels of the value chain from mining and manufacturing through to consumer spending.

Recent extreme weather events have led to acknowledgement by governments, industry and consumers of the role of battery storage in ensuring energy security.

This report has identified that:

- There is a near-term requirement to strengthen Australia's energy security in NEM jurisdictions and maintaining acceptable energy security levels for customers will dominate over energy reliability requirements until well in excess of 50 per cent renewable energy penetration.
 - Pumped Hydro Energy Systems (PHES) are expected to remain the most cost effective option for large-scale energy storage (greater than 100 MW) for some time. In addition to the announcement that the Snowy Mountains scheme will be expanded, a number of sites have been identified throughout Australia as suitable for PHES.



- Due to their high efficiencies and relatively small size, batteries are expected to remain the dominant technology for distributed and behind-the-meter energy storage solutions. While not the only way of strengthening system security they are cost-effective when installed with a high power-to-energy ratio.
- The differential between current tariff structures for buying grid electricity and selling self-generated (rooftop PV) electricity is strongly encouraging investment in battery systems by consumers and industry.
- Australia is well placed to participate in global energy storage supply chains and business opportunities will arise, given appropriate policy decisions at state and Commonwealth levels.
 - Australia has abundant raw material resources for batteries, but could capture greater benefits through value adding.
 - Australian companies and researchers are seeking opportunities to commercialise their energy storage technologies.

- Australia has abundant renewable resources (solar), appropriately skilled workforces and established supply chain relationships to generate renewable hydrogen and ammonia at the volumes required to supply export markets, such as Japan and Korea.
- Australia can play a leading role in product stewardship in the development of standards for battery storage, sustainable supply chains from mining to manufacturing, and the sustainable repurposing and recycling of all batteries.
 - The development of recycling infrastructure and technology will support industry development and jobs growth.
- Australians are deeply concerned by the sharp rise in electricity prices and affordability and hold governments and energy providers responsible for the perceived lack of affordability.
- Energy storage is not a well-known concept in the community and concerns exist at the lack of suitable standards at the household level.
- Australians favour a higher renewables mix by 2030 – particularly PV and wind, with significant energy storage deployed to manage grid security.

This work provides reassurance that both reliability and security requirements can be met with readily available storage technologies. Notwithstanding, the market and technologies for energy storage and its

integration into electricity networks continue to evolve. With additional time and resources, the findings of this report would be strengthened by further work into, for example:

- The optimum balance of generation, storage and interconnection, taking into account both cost optimisation and the long-term strategic opportunities for Australia.
- The role of ‘prosumers’ including their effects on the market, the system (equity and pricing concerns) and on their potential contribution to the energy transformation that is underway.
- The broader question of public literacy, as Australians’ knowledge of, and attitudes towards, energy storage will shape its acceptance and adoption.
- A deeper analysis of opportunities for growth of a substantial energy storage industry in Australia.

Using a traditional strengths, weaknesses, opportunities and threats (SWOT) approach to review the internal and external environments for energy storage in Australia, a preliminary analysis, based on the findings in this report is summarised in Table 6.

Given these internal and external environmental factors, it is important for energy storage policy to promote market growth to capitalise in strength and opportunity, while also managing risk to mitigate against weaknesses and threats.

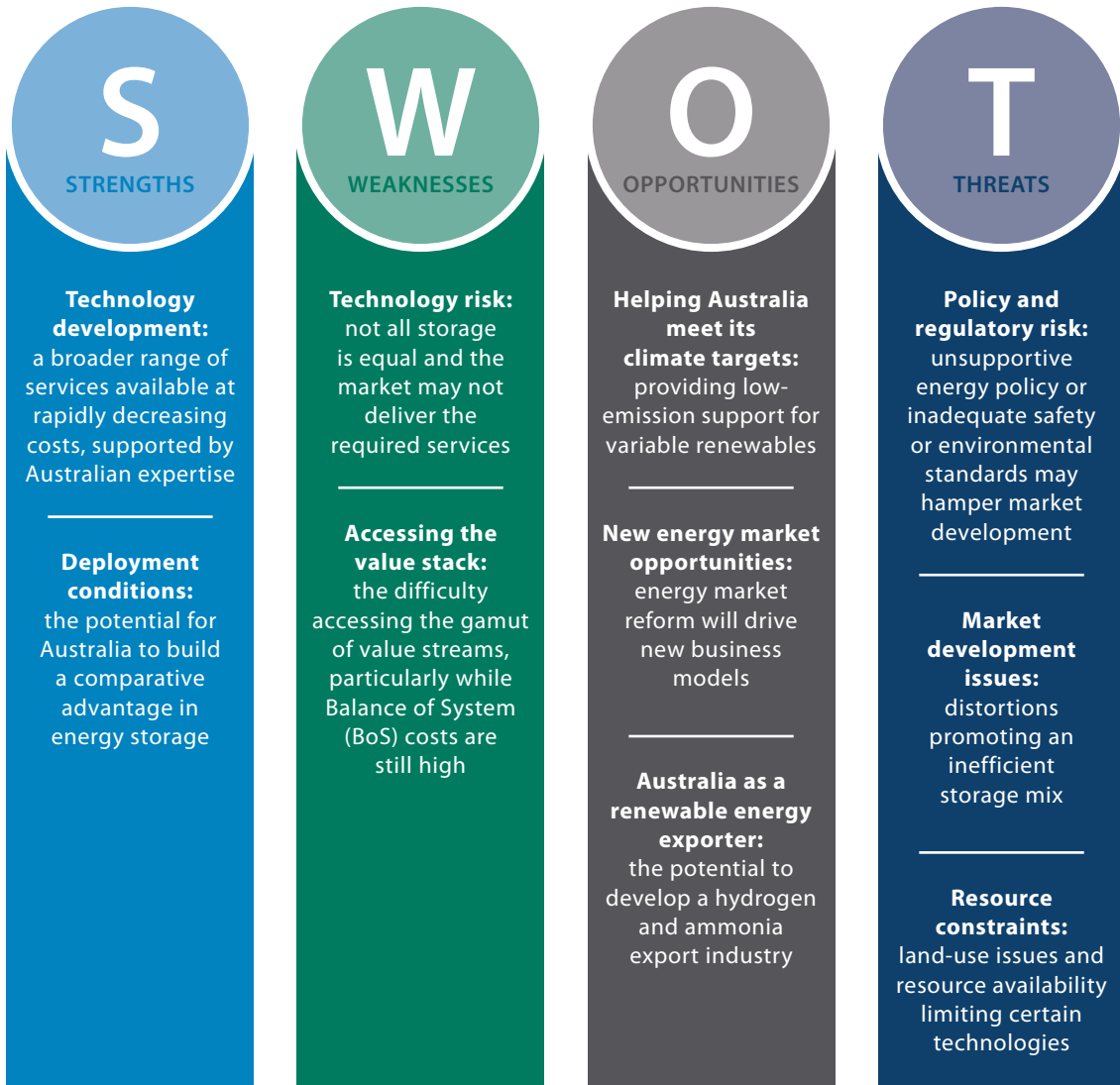


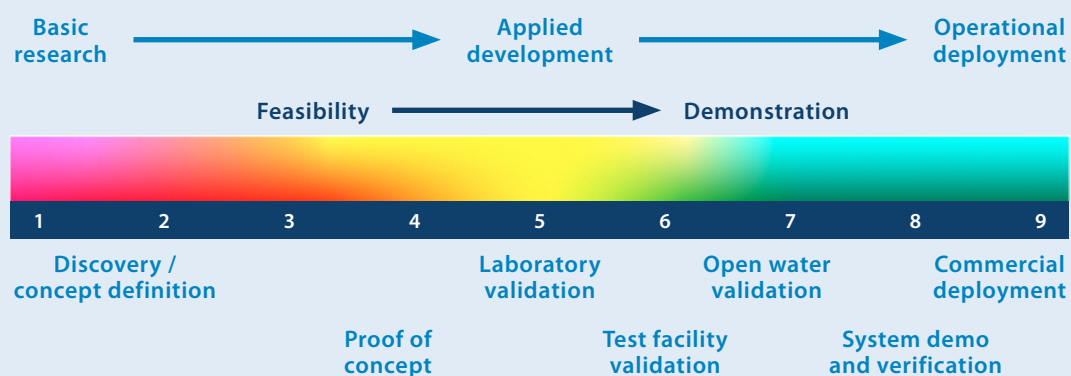
Table 6: Summary of outcomes of SWOT analysis for energy storage

APPENDIX 1

REVIEW OF CURRENT AND EMERGING ENERGY STORAGE TECHNOLOGIES

Box 12: Technology readiness levels

Technology readiness levels (TRL) are a measurement system used to classify the maturity of technologies. Technologies are assessed against a set of criteria assigned for each technology level and are then rated with a TRL based on the project's stage of development. There are nine technology readiness levels with TRL 1 being the lowest and TRL 9, the highest.



From <http://coet.fau.edu/ocean-energy/ocean-energy-industry.html>

TECHNOLOGIES CONSIDERED IN DEPTH IN THE BODY OF THIS REPORT

Electrochemical Storage (Batteries)

Battery technologies have existed for decades and are ubiquitous in modern society. They use reversible chemical reactions to convert stored chemical energy into electricity and vice versa. There are a wide variety

of battery technologies available with different maturities, strengths, opportunities, weaknesses and challenges.

Lead-acid battery

Invented over 150 years ago, traditional lead-acid batteries are the oldest type of rechargeable battery (AECOM, 2015) and are therefore a well-established technology (TRL 9). Historically the most common battery used for transport and off-grid power supply

applications, lead-acid batteries are quickly losing ground to modern technologies such as lithium-ion (Li-ion) batteries. Lead-acid batteries have been coupled with solar, wind and off-grid systems and are considered a cheap and reliable storage source.

More recently, advanced lead acid batteries have been developed with new electrode materials, such as replacing one of the lead electrodes with a carbon electrode to enable extended use at an intermediate state of charge. These batteries are well suited to both charging and discharging, which is appropriate for supply-demand balancing applications in power systems, such as system stability services. It is possible to use advanced lead acid batteries for simultaneous bulk energy shifting and fast balancing. Nevertheless, it is still desirable to operate the battery within a 50 % range of state of charge, for example between 25 % and 75 %, to avoid premature ageing.

Weaknesses and Challenges

The technology has a markedly lower cycle lifetime and depths of discharge compared with other battery types. Lead-acid batteries have low energy density compared with competing technologies, and need to be kept in a charged state. Lead-acid batteries also use toxic heavy metals and corrosive acids (Cavanagh et al., 2015, AECOM, 2015). Typical batteries have 70–90 per cent round-trip efficiencies and have a lifetime of around 5–15 years (AECOM, 2015). However, emerging hybrid technologies, such as the UltraBattery developed by CSIRO, are increasing efficiencies, lifetimes and improved partial state-of-charge operability.

Strengths and Opportunities

Lead-acid batteries are cheap, have wide commercial availability and low self-discharge. They also have a rapid recycling rate (Cavanagh et al., 2015).

Lithium-ion (Li-ion) battery

Lithium-ion (Li-ion) batteries are the dominant technology for small-scale energy storage such as phones and laptops, and are increasingly being used for electric vehicles, back-up power supplies and domestic storage (AECOM, 2015). Increasing scale and volume of manufacturing by major companies is driving large cost reductions, which are expected to continue. Li-ion technologies are becoming a common replacement for lead-acid batteries and are soon expected to be the dominant battery technology for most applications (AECOM, 2015). The technology is still developing and has considerable potential for applications. Research is focused on the improvement of lifetime and cycling.

There are many Li-ion variants with different characteristics and with varying levels of feasibility for widespread use. Some of the different chemistries used are:

- Li-iron phosphate (LiFePO₄)
- Li-titanate (LT)
- Li-cobalt oxide (LiCoO₂)
- Li-manganese oxide (LMO)
- Li-nickel manganese cobalt (NMC)
- Li polymer
- Li-metal polymer (LMP)
- Li-Air
- Li-sulfur (Li-S)

The different types of Li batteries have varying technology readiness levels (TRLs); some of these, such as Li-air and Li-S, are still in research and development stage.

Conversely, the LMP battery is a mature technology (TRL 9) that is being used in electric vehicles, including public transport, in Europe. This has been commercialised by companies such as Bolloré, who have also developed LMPs which are broadly used for stationary applications.

Weaknesses and Challenges

A major challenge for the technology is that only one-third of lithium reserves are economically recoverable. Safety is the other serious issue in Li-ion technology. Most of the metal oxide electrodes are thermally unstable and cells can overheat and ignite. To minimise this risk, Li-ion batteries are equipped with a monitoring unit to avoid overcharging and over-discharging. Operating temperatures for these batteries must be kept below 60 °C, and battery performance significantly declines at higher temperatures.

Strengths and Opportunities

Li-ion batteries have high round-trip efficiencies, ranging from 85–98 per cent and have lifetimes of 5–15 years depending on manufacturing and treatment (Cavanagh et al., 2015, AECOM, 2015). They are rechargeable, have high energy density, low self-discharge and high charging efficiency. Li-ion batteries have plummeted in cost over the last decade, making this technology competitive with lead-acid batteries. Nearly any discharge time (from seconds to weeks) can be realised, which makes them a very flexible storage technology. Lithium can also be completely recycled, and considerable opportunity exists for developing more economically viable recycling technologies (AECOM, 2015). There is considerable opportunity for Australia to adopt Li-ion battery technology for use in transport to reduce carbon dioxide (CO₂) emissions.

Flow batteries

Unlike conventional batteries, the energy in flow batteries is stored in one or more electroactive species, which are dissolved in liquid electrolytes that are stored in tanks external to the battery and pumped through

electrochemical cells, which convert chemical energy to electricity (Cavanagh et al., 2015). The power capacity of a flow battery is controlled by the area and design of the electrochemical cell, and the energy capacity is dependent on the volume of the storage tanks.

Flow battery technology has several utility applications, including time shifting, network efficiency, and off-grid use. These batteries are also suitable for connection to renewables and time-shifting at the industrial and residential scale.

There are two main types of flow batteries: zinc bromine (Zn-Br) batteries and vanadium redox batteries (VRB).

- Zinc bromine (Zn-Br) batteries consist of two electrode surfaces and two electrolyte flow streams that are separated by a micro-porous film. These batteries were developed in the 1970s by NASA and have recently been commercialised in Australia by Redflow. This technology is mature (TRL 9).
- Vanadium redox batteries (VRB) store energy using vanadium redox couples, which are permanently dissolved in sulfuric acid electrolyte solutions. The first vanadium redox battery was demonstrated in the late 1980s, and they have been used commercially for over eight years (Energy Storage Association, 2016), making them an established technology (TRL 8).

Weaknesses and Challenges

These batteries have environmental and safety issues associated with the toxicity of vanadium and leaching of bromine. The higher voltage and oxidative V⁵⁺ electrolyte in VRBs puts chemical stress on the cell electrodes, membranes, and fluid handling components of the battery cell. Expensive

ion-exchange membranes are needed to reduce losses from cross-membrane transport (Energy Storage Association, 2016).

Zinc bromine technology requires regular maintenance of mechanical parts, such as pumps, throughout the battery lifetime. These batteries have a lower energy density than other batteries, are costly, and require external power to operate.

Strengths and Opportunities

An advantage of flow batteries over conventional batteries is that while the converter stays the same size for a given power density, additional storage tanks can be added to hold more electrolyte. This allows the duration of power supply to be readily extended from a hours to a day or more. (Aneke and Wang, 2016).

Zinc bromine batteries can theoretically be 100 per cent discharged every day, for more than 2000 cycles. Vanadium redox batteries have a high cell voltage, which creates a higher power and energy density, making these systems useful for grid storage. Vanadium is readily available, and can be recovered from various waste products (Energy Storage Association, 2016). There is opportunity to optimise the design of the membranes used in these batteries. These batteries are scalable, tolerant to overcharge and over-discharge, and are safer than Li-ion batteries.

Mechanical Storage

Pumped Hydro Energy Storage (PHES)

PHES accounts for over 99 per cent of bulk energy storage capacity worldwide (Energy Storage Council, 2015). Australia has over

1.5 GW of PHES connected to the NEM and it is a well-established technology (TRL 9); however, no large-scale pumped hydro facilities have been built in Australia during the last 30 years (AECOM, 2015). Among the largest PHES facilities are the 600 MW Tumut-3 and 240 MW Shoalhaven facilities in New South Wales, and the 500 MW Wivenhoe facility in Queensland (Hearps et al., 2014). In PHES systems, large volumes of water are pumped from a lower to an upper reservoir, thus converting electrical energy into gravitational potential energy. When energy is required, the water is allowed to flow from the upper to the lower reservoir and drive a turbine that generates electricity.

Weaknesses and Challenges

PHES is limited by the availability of suitable geological structures. There is potential for environmental impact and social license problems with PHES developments. Depending on the location and water source, PHES can also be affected by drought and evaporative water losses.

Strengths and Opportunities

PHES is the most mature form of bulk energy storage technology available and it is also the cheapest. Electrical energy from PHES is synchronous with the grid, which has inherent benefits for network security and stability. It is suitable for centralised large-scale storage applications. There may be potential for salt-water based applications of PHES (Hearps et al., 2014) and innovative solutions such as the Kidston Hydro project which intends to repurpose an abandoned gold mine site. Blakers (2015) argues that there are many suitable locations for the development of new off-river PHES systems in Australia.

Thermal Storage

Molten salts

Molten salts are solid at room temperature and atmospheric pressure, but become liquid when heated (International Energy Agency, 2014). Molten salt is often used to store heat in concentrated solar thermal facilities for use in generating electricity (AECOM, 2015). As electricity is required, molten salt is dispatched from the storage tank through a heat exchanger to create steam, which powers a conventional steam turbine (Solar Reserve, 2016).

Molten salt storage is often combined with concentrated solar thermal (CST), which uses reflectors to focus sunlight into concentrated heat energy (Clean Energy Council, 2013).

Concentrated solar thermal is a proven technology, which was first implemented in California in 1984 (Clean Energy Council, 2013). There are several examples of CST operating in Australia, including two large-scale plants: one in Kogan Creek in Queensland, and one that has been added to the Liddell coal-fired power plant in New South Wales (Hinkley et al., 2016).

Weaknesses and Challenges

Molten salt storage is currently limited to concentrated solar power applications; however, the technology is still developing in Australia (AECOM, 2015). The high temperature required for liquefying salts poses technical issues for other components in the system. If salts are allowed to solidify

(below 200 °C), serious mechanical problems arise (International Energy Agency, 2014).

These systems therefore require further development to address this issue. A disadvantage of CST is the hazard associated with the use of reflectors to concentrate sunlight. Incorrect alignment of these reflectors results in focusing the sunlight on the wrong part of the system and has resulted in fires, including one at the Ivanpah Solar Power Facility, California, in May 2016.

Strengths and Opportunities

The benefit of concentrated solar thermal over photovoltaic (PV) solar is that energy stored as heat is a reliable source of electricity that can be used for peak or baseload electricity demand (Clean Energy Council, 2013). An advantage of molten salt systems is that the salts do not need replacing for the entire life of the plant. The salts are a mixture of sodium nitrate and potassium nitrate, allowing application as a high-grade fertiliser following decommission of the plant (Solar Reserve, 2016). Molten salt is relatively efficient for storage of heat and is able to store large amounts of energy for up to 15 hours (AECOM, 2015). These systems have the potential to provide high-density, low cost, and high-cycle energy storage (International Energy Agency, 2014).

Opportunities exist for the development of system materials that are able to perform in the high temperatures required to keep salts molten.

Chemical Storage

Power-to-gas

Chemical storage systems use electricity to produce hydrogen by water electrolysis (Cavanagh et al., 2015b). In these systems, electricity is recovered by using the hydrogen to power a generator or fuel cell. Hydrogen can be stored in bulk or transported as a pressurised gas or a cryogenic liquid. Alternatively, it can be upgraded to higher-order gases, such as ammonia. However, any of these processes for storing or transporting the hydrogen increase costs and reduce the round-trip efficiency.

Power-to-gas technology is useful for storage of energy from variable renewable energy sources, and may therefore be useful for integration of renewable energy into the electricity grid. This storage system is still being developed, and is currently in demonstration (Walker et al., 2016). As part of their successful bid to the ACT Government's Next Generation Renewables Auction, Neoeon Australia in collaboration with Siemens has committed to installing a 1.25 MW hydrogen electrolyser capable of producing enough hydrogen to power up to 1000 vehicles per year by the end of 2018. They are also partnering with Hyundai to deliver a refuelling station and 20 hydrogen fuel-cell vehicles (ACT Department of Environment and Planning Directorate, 2016).

Weaknesses and Challenges

Energy use and conversion losses during electrolysis, methanation (in the case of synthetic natural gas), storage, transport, and power generation, mean that power-to-gas technology has a low round-trip efficiency (Cavanagh et al., 2015b). Another disadvantage of gas storage is the size of the tanks that are required, although technologies

such as solid-state hydrogen storage may address this. Additionally, high pressures are necessary, and discharge times are limited to minutes to hours, meaning this technology is not suitable to applications requiring fast discharge. The significant volumes of water required for the electrolysis process also require consideration.

Strengths and Opportunities

Hydrogen can easily hold large quantities of energy, provided enough storage capacity is available. An advantage of using synthetic natural gas to store energy is that it can be pumped into the existing gas grid infrastructure. Power-to-gas technology has the potential to be developed further for the future use of electrolytic hydrogen for fuel cell vehicles, ancillary services, bulk energy storage, commercial energy storage, bulk energy storage, and utility transmission and distribution (Walker et al., 2016). The development of solid-state hydrogen storage offers a potential compact and safe storage option (Materials Energy Research Laboratory in Nanoscale, 2016). Hydrogen can be stored in metal hydrides, magnesium-based alloys, carbon-based materials, chemical hydrides, and boron compounds by either physical adsorption or by forming chemical bonds (Singh et al., 2015). Hydrogen can be released for use by changing the temperature of the solid (Singh et al., 2015). However, there are not yet any storage materials available that have high hydrogen storage capacity, reversible discharging and charging cycles, and fast discharging and charging rates with minimal energy required for hydrogen release and charge (Singh et al., 2015). The development of solid-state hydrogen storage offers a potential compact and safe storage option (Materials Energy Research Laboratory in nanoscale, 2016).

OTHER CURRENT AND EMERGING STORAGE TECHNOLOGIES MENTIONED IN THIS REPORT

Electrochemical Storage (Batteries)

Nickel-based batteries

Nickel-based batteries are well-developed (TRL 9) and are widely used in a variety of commercial products since their introduction in approximately 1915. Nickel-based batteries are used in computer and medical equipment and electric vehicles, however, they are increasingly being replaced by Li-based batteries in vehicles (Cavanagh et al., 2015b).

Lithium-ion batteries have also largely replaced nickel-based batteries for use in mobile devices. Nickel-based batteries include:

- Nickel cadmium (NiCd) battery
- Nickel metal hydride (NiMh) battery
- Nickel zinc (NiZn) battery

Weaknesses and Challenges

Use of this technology is declining in Australia, due to the introduction of more advanced and affordable Li-ion batteries. Nickel-cadmium batteries are prohibited for consumer use due to the toxicity of cadmium, and are used only for stationary applications in Europe (Cavanagh et al., 2015b). Other disadvantages of these batteries include a high self-discharge rate and environmental issues during disposal.

Strengths and Opportunities

Nickel-cadmium batteries are the only batteries that function at very low temperatures (-20 to -40 °C), and have a higher power density, energy density, and

cycle capability compared to lead-acid batteries (Cavanagh et al., 2015b).

Nickel metal hydride batteries have similar capabilities to Ni-Cd batteries, except they have a significantly lower maximal nominal capacity, much higher energy densities and a quick response time.

Sodium-based batteries

There are several types of sodium-based batteries. The two most common types are summarised below.

- **Sodium-sulfur (Na-S) battery**
Na-S batteries are classified as 'high-temperature' and 'liquid-electrolyte-flow' batteries, which require operation above 300 °C to keep the sodium and sulfur molten. They have been used for large-scale grid support, most commonly in the USA and Japan. This technology is currently being tested (TRL 6).
- **Sodium-metal halide (Na-NiCl₂) battery**
Sodium-metal halide batteries were originally developed for application in electric vehicles, and are used for bulk storage with daily energy cycling (TRL 8).

In Australia, Na-NiCl₂ batteries have been developed specifically for the evolving grid storage market, and a molten salt battery generator has been developed for the mining industry, although it is uncertain whether the latter is currently being used (Cavanagh et al., 2015b). Na-NiCl₂ batteries have also been developed for residential use for time shifting of renewable energy, making energy available to the consumer as required.

Sodium-ion technology is quickly evolving, with developmental projects being run by Fardion in the UK, Aquion in the USA, and at the University of Wollongong (sponsored

by the Australian Renewable Energy Agency (ARENA)). The Aquion battery is a significant advance as it uses salt water as the battery electrolyte. This water-based system is safer than lithium-ion batteries because it is able to self-moderate its temperature; it is not possible for internal reactions to exceed 100 °C because at this temperature the water will evaporate creating open circuit conditions (Aquion Energy, 2016). These Aquion batteries are also environmentally friendly and contain no toxic chemicals (Aquion Energy, 2016).

Weaknesses and Challenges

Contrary to the low temperature conditions required for Aquion batteries, high temperatures are required for sodium-sulfur batteries because the solid-state electrolyte (beta-alumina) is only sufficiently conductive above 300 °C. This creates challenges for encasing materials and sealing (Cavanagh et al., 2015b). Faradion have addressed this challenge by developing a sodium-ion (Na-ion) battery with improved thermal stability which is able to be transported safely. For Na-NiCl₂ batteries, the main inconvenience is that the components take 12–15 hours to heat up and become operational (Gallo et al., 2016). Electric heaters on the inner and bottom side of Na-S batteries are required to maintain temperatures over 290 °C during periods of extended standby, causing self-discharge losses of up to 20 per cent per day (Gallo et al., 2016).

Strengths and Opportunities

The main advantages of these batteries are that they can operate at extreme temperature conditions without the need for air conditioning. They also have a long-life cycle and require little maintenance. The high operating temperature (300 °C for Na-S and 270–350 °C for Na-NiCl₂), recharging

time (9 hours for Na-S and 6–8 hours for Na-NiCl₂), and energy density of these batteries make them useful for storage in large-scale systems (Cavanagh et al., 2015b). Sodium-based batteries are efficient, have a large storage capacity, and provide a prompt and precise response. This technology has been developing quickly worldwide during the past five years; research efforts are focusing on lower temperature operation due to problems the high temperature causes with packaging and sealing. Sodium-ion batteries have potential to be a real competitor for grid storage especially where energy density (size and weight of battery) are less important. Sodium is abundant, which makes these batteries cheaper and ensures security of supply of materials in the longer run.

Metal-air

Metal-air batteries use the oxidation of a metal by air to produce electricity. The batteries can use aluminium, magnesium, zinc and lithium. Metal-air batteries produce electricity when the air electrode is discharged by catalysts that produce hydroxyl ions in the liquid electrolyte (Aneke and Wang, 2016). Currently, the only technically feasible metal-air battery is a zinc-air battery with a theoretical specific energy of 1.35 kWh/kg (excluding oxygen). This technology is still under research and development, therefore there is no active usage of these batteries in Australia (Cavanagh et al., 2015b). The batteries are being optimised by companies such as Phinergy in Israel, and Fuji Pigment in Japan.

Weaknesses and Challenges

Metal-air batteries have low efficiency (50 per cent) and are able to achieve relatively few cycles (currently only one cycle for Mg-air).

The major challenge surrounding these batteries is avoiding damage to the electrolyte and cathode from naturally occurring CO₂, and the formation of Zn dendrite (Aneke and Wang, 2016). Recharging metal-air batteries involves mechanically removing the battery and replacing spent materials, and is therefore difficult and inefficient.

Strengths and Opportunities

These batteries are compact, inexpensive, and environmentally friendly. Metal-air batteries are rechargeable by mechanically replacing the consumed metal, or by electrically recharging in some developers' models. The anodes typically used in these batteries (zinc and aluminium) are commonly available metals with a high energy density.

Hybrid batteries

Hybrid batteries combine batteries and supercapacitors. Supercapacitors are energy storage devices with low specific energy, a high life cycle, and high specific power relative to batteries. Supercapacitors are typically used in battery-powered vehicles in order to increase the battery lifetime and keep the system voltage above a certain value (Hemmati and Saboori, 2016). An example of a hybrid battery is the CSIRO-developed UltraBattery, which combines a supercapacitor with a lead-acid battery (Australian Academy of Science, 2016). This battery has been commercialised by Australian company Ecoul, and is used in wind and solar farms for output smoothing. A hybrid battery has also been developed by Carnegie Mellon University and produced by Aquion Energy.

This device uses ion intercalation (the reversible inclusion of a molecule or ion) in the electrode to allow cells to be

stacked to high voltages without requiring control circuitry (Australian Academy of Science, 2016). A Li-ion capacitor hybrid is also commercially available (JM Energy Corporation, 2016). This is a hybrid electrochemical energy storage device which combines the intercalation mechanism of a lithium-ion battery with the cathode of an electric double-layer capacitor. This results in a higher energy density than a supercapacitor alone.

Weaknesses and Challenges

Combining a battery and supercapacitor makes control and energy management more difficult than for a single energy storage system. These batteries are relatively new, and require further research and electrical engineering to advance their functionality (Hemmati and Saboori, 2016).

Strengths and Opportunities

The supercapacitor deals with sudden and large changes in discharge and charge better than a battery, and the battery is able to store charge for longer than a capacitor (Australian Academy of Science, 2016). Combining the supercapacitor and battery allows for a higher energy density, higher voltage, and higher efficiency.

These systems are designed to be safe and inexpensive.

Emerging battery chemistries

Research is focused on the development of new battery chemistries including Al-, Ca-, and Mg-based energy storage technologies, which employ the conventional electrolytes used in Li-ion technology (Ponrouch et al., 2016). This research is being conducted by industry as well as academia;

Australian energy technology company LWP Technologies began development of an aluminium-graphene-oxygen battery in June 2016, which they predict will compete with Li-ion batteries. However, emerging battery chemistries are unlikely to be commercialised for some time and will face significant challenges in competing with well-established batteries.

Thermal Storage

Liquid air energy storage

Liquid air energy storage uses electricity to cool air until it liquefies, stores the liquid air in a tank, and then returns the air to a gaseous state and uses the gas to operate a turbine, generating electricity. These energy storage systems are a long-duration and large-scale technology that can harness low-grade waste heat or cold from co-located industrial processes such as thermal generation plants and steel mills (Energy Storage Association, 2016).

Weaknesses and Challenges

The efficiency of these storage systems is relatively low (40 – 70 per cent) (Aneke and Wang, 2016). The technology is still developing and further improvement of the liquefaction process and use of compression heat during the power generation stage is required to improve efficiency.

Strengths and Opportunities

An advantage of liquid air energy storage is that liquid air occupies 1/700th of the volume taken up by gaseous air (Aneke and Wang, 2016). This results in the storage of a large quantity of air in small containment. These

energy storage systems have long lifetimes (30+ years) and draw on well-established technologies, with known costs and performance, ensuring a low technology risk (Aneke and Wang, 2016).

Thermo-chemical Storage

Ammonia dissociation-recombination energy storage

Ammonia-based thermochemical storage systems have been developed for use with concentrating solar power systems.

Thermochemical storage involves a reversible reaction to store energy in chemical bonds. In the case of ammonia dissociation and recombination, solar energy is used to dissociate ammonia (NH_3) into nitrogen (N_2) and hydrogen (H_2). When required, these stored gases are recombined to synthesise ammonia, giving off heat to power a turbine and generate electricity. The reaction of nitrogen and hydrogen to form ammonia is the basis of the Haber-Bosch process, which is exothermic.

Weaknesses and Challenges

These energy storage systems are technically ready for demonstration, however, it is unclear if this technology would be economically competitive with other energy storage options, particularly due to the high pressures required for storage (10–30 MPa; Dunn et al., 2016). Ammonia dissociation-recombination storage shows potential for 24-hour baseload operation, but slow ramp rates for the synthesis reactors indicate that the technology would not cope with variable loads.

Strengths and Opportunities

One advantage of this storage system is a simple separation of elements which makes solar reactors particularly easy to control. Also by operating above the ambient temperature saturation pressure of ammonia, the ammonia fraction in storage is present largely as a liquid. Therefore, automatic phase separation of ammonia and the dissociated hydrogen and nitrogen is enabling a common storage volume to be used. Ammonia-based storage is also able to take advantage of the more than 100 years of industrial experience with the Haber-Bosch process.

Hybrid Energy Storage Systems

Compressed air energy storage hybrids

These hybrid technologies combine compressed air energy storage (CAES) with supercapacitors, superconducting magnetic energy storage (SMES) systems, or flywheels (Hemmati and Saboori, 2016). These storage systems are proposed to smooth wind turbine output fluctuations (CAES-supercapacitor and CAES-flywheel), and provide both long- and short-term storage options (CAES-SMES).

Fuel cell hybrids

In addition to fuel cell-battery storage systems, hybrid fuel cell storage systems include fuel cell-supercapacitor and fuel cell-SMES. Fuel cell-supercapacitor storage systems have been proposed for electric vehicles and renewable resources integration (Hemmati and Saboori, 2016).

Fuel cell-SMES combine fast response, low capacity storage with slow response, high capacity storage devices. These systems are proposed for handling large variations in energy storage, which may be suitable for integrating large scale renewable resources into the grid (Hemmati and Saboori, 2016). These storage systems are in research and design stage and have not yet been piloted.

Mechanical Storage

Compressed Air Energy Storage (CAES)

CAES systems store energy by compressing ambient air and storing it at high pressure in underground geological structures such as caverns, aquifers and abandoned mines. The compression of the air generates a lot of heat which must be removed before storage. When the stored energy is required the compressed air is released, re-heated, and used to drive a turbine to create electricity. Current systems use natural gas to heat the expanding gas; however, adiabatic systems are being developed that will store the heat removed from the pressurised air and use it to reheat the expanding air.

Adiabatic CAES systems have the potential to increase the efficiency of CAES and remove the need for combustion of fossil fuels. A pilot plant, planned by a German-led international consortium, is scheduled to start operations in 2018 (Energy Storage Association, 2016).

Isothermal CAES is a developing technology in which the pressure-volume curve of the air during compression and expansion is controlled to resemble an isotherm. This process wastes less energy, increases efficiency, and reduces capital costs relative to adiabatic CAES (Energy Storage Association, 2016). Australia has no deployments of CAES technology (Cavanagh et al., 2015b).

Weaknesses and Challenges

CAES typically requires geological structures suitable for storing high-pressure gas. Conventional CAES systems have low round-trip efficiencies and require the combustion of fuel (typically natural gas) to offset the temperature loss experienced during re-expansion of the air.

Strengths and Opportunities

Conventional CAES is an established technology (TRL 9) that is capable of storing significant amounts of energy. Australia is well-positioned geologically for CAES. Technology improvements such as the development of adiabatic CAES (currently TRL 4) and modular, scalable and above ground CAES have been predicted to drive significant growth in CAES installations worldwide (Navigant Research, 2013).

ENERGY STORAGE TECHNOLOGIES NOT COVERED IN THIS REPORT

Technologies such as flywheels, supercapacitors, superconducting magnetic energy storage are not discussed in detail here as they are only able to store energy for short periods and are beyond the scope of the report. Energy storage technologies that are not applicable to the storage of electrical power, including thermal storage for heat processes, are also not covered.

APPENDIX 2

SUMMARY OF COST DATA AND TECHNICAL SPECIFICATIONS FOR ENERGY TECHNOLOGIES

The following table provides a summary of cost data used to determine the levelised cost of energy for storage technologies (LCOS).

All data sources, references and detailed breakdown of information are provided in other tables presented in this Appendix.

Summary of Cost Data

Technology	CAPEX		Depth of discharge	Cycles/yr ⁵	Annual degradation ¹
	2017	2030			
	\$A/kWh rated		%	Min	%
Advanced Lead Acid Battery	680	320	45 %	220	1.5 %
Li-ion	699	333	100 %	220	1.5 %
Zn-Br Flow Battery	1300	272	100 %	220	1.5 %
Pumped Hydro Storage (lower cost)	408	408	100 %	220	negligible
Pumped Hydro Storage (higher cost)	979	979	100 %	220	negligible
Hydrogen Energy Storage	372	372	100 %	220	negligible

Notes:

1. Annual degradation is the deterioration in quality, level, or standard of performance of a unit over time.
2. Fixed O&M costs represent the costs of operation and maintenance that do not vary with output, such as wages and salaries, asset management and administrative expenses including insurances, other overheads, spare parts and routine maintenance (data from Julch, 2016).
3. \$A/kW fixed O&M is converted from \$A/kW to \$A/kWh storage capacity by using the following storage capacities: 2 kWh/kW for the three battery types, 12.3 kWh/kW and 3.7 kWh/kW for the lower and higher cost hydro respectively, and 5.4 kWh/kW for hydrogen energy storage (derived from Winch et al, 2012).
4. Variable O&M are the operating costs that are dependent upon throughput, such as direct and in-direct fuel costs, unplanned maintenance, and consumables such as water and chemicals (data from Julch, 2016).
5. The number of cycles per year was set at 220 for all the storage technologies. This assumption was based on the number of cycles calculated for a pumped hydro scheme operating with a 20 per cent capacity factor.

Fixed O&M ²		Variable O&M ⁴	Round-trip efficiency	Project lifetime
\$A/kW/yr ³	\$A/kWh/yr ³	\$A/kWh throughput/ year	%	years
4.8	2.4	0.0048	94 %	15
9.8	4.9	0.0030	93 %	15
6.1	3.1	0.0009	75 %	15
6.5	0.5	0.0003	76 %	40
6.5	1.8	0.0003	76 %	40
36.4	6.7	0.0043	40 %	20

Technical Specifications

Product Name	Battery Type	Price	Nominal Storage (kWh)	Price (\$/kWh)
Batteries without inverters				
Redflow Zcell	Zn-Br	\$12,600	10	\$1,260
Leclanche Apollion Cube	Li-ion ¹	\$9,200	6.7	\$1,373
BMZ ESS3.0	Li-ion ¹	\$7,700	6.7	\$1,142
ELMOFO E-Cells ALB52-106	Li-ion	\$8,190	5.5	\$1,489
Akasol neeoQube	Li-ion	\$12,000	5.5	\$2,182
LG Chem RESU 6.5	Li-ion	\$6,600	6.5	\$1,015
Delta Hybrid E5	Li-ion	\$8,500	6	\$1,417
Fronius Solar Battery	Li-ion ²	\$15,550	12	\$1,296
DCS PV 5.0	Li-ion ²	\$5,900	5.1	\$1,152
Pylontech Extra2000 LFP	Li-ion ²	\$1,999	2.4	\$833
Batteries with inverters				
GCL E-KwBe 5.6	Li-ion ³	\$7,500	7	\$1,071
Enphase AC Battery	Li-ion ⁴	\$2,000	1.2	\$1,667
Tesla Powerwall 2 (AC)	Li-ion	\$8,800	13.2	\$667
Panasonic LJ-SK84A	Li-ion	\$11,900	8	\$1,488
Samsung ESS AIO	Li-ion ⁵	\$12,000	7.2	\$1,667
BYD Mini ES	Li-ion ²	\$8,400	3.8	\$2,240
Tesla Powerwall 2 (DC)	Li-ion	\$8,800	13.5	\$652
PowerOak ESS	Li-ion	\$13,050	12	\$1,088
Sunverge SIS	Li-ion	\$26,000	11.6	\$2,241
Sonnenbatterie	Li-ion ²	\$6,700	2	\$3,350
ZEN Freedom Powerbank FPB16	Li-ion ²	\$21,750	16	\$1,359
SolaX BOX	Li-ion ²	\$7,700	4.8	\$1,604
SolaX BOX	Li-ion ²	\$11,385	14.4	\$791
Alpha-ESS STORION S5	Li-ion ²	\$7,200	3	\$2,400
Magellan HESS	Li-ion ⁶	\$13,000	6.4	\$2,031

Notes:

1. Li-ion NMC
2. Lithium iron phosphate
3. Lithium nickel cobalt manganese
4. Lithium ferrite phosphate
5. Lithium manganese oxide
6. Lithium manganese cobalt oxide
7. 93 per cent single phase, 96 per cent three phase

Usable Storage (kWh)	Power (kW)	Cycle Life	Depth of Discharge (%)	Round-trip Efficiency	Warranty (years)
10	3	3,650	100	80 %	10
5.4	3.3	5,000	80	97 %	7
5.4	8	5,000	80	97 %	10
4.4	5	8,000	80	96 %	10
5	5	7,000	90	98 %	10
5.9	4.2	3,200	90	95 %	10
4.8	3	6,000	80	90 %	5
9.6	4	8,000	80	>90 %	5
5.1	5	5,000	100	99 %	10
1.9	2	4,000	80	TBD	5
5.6	3	2,000	80	95 %	7
1.1	0.26	7,300	95	96 %	10
13.2	5	n/a	100	89 %	10
8	2	3,650	100	93 %	10 – 7
6.5	4	6,000	90	95 %	5
3	3	6,000	80	98 %	10
13.5	5	n/a	100	91.80 %	10
9.8	3	6,000	80	TBD	5
9.9	5	8,000	85	96 %	10
2	1.5	10,000	100	93–96 % ⁷	10
14.4	5	6,000	90	TBD	5
3.8	4.6	4,000	80	97 %	5
11.5	5	4,400	80	97 %	5
2.7	5	8,000	90	95 %	5
5.8	5	4,000	90	97 %	5

Calculating LCOS

In order to simplify the calculations, all storage is assumed to be in front of the meter, is not differentiated by use and the residual value of all the storage technologies is set at zero. The impact of this simplification was tested empirically and found to be insignificant relative to the uncertainty in the estimates. The formula used to calculate LCOS is as follows:

$$LCOS = \frac{CAPEX}{\#cycles} * DoD * Crated * n = 1N1 - DEG * n1 + rn + Average$$

$$OPEX * n = 1N1 + rn \# of cycles * DoD * Crated * n = 1N1 - DEG * n1 + rn + Pelectricity / \mu(DoD) + (Pgas * Gasin)$$

where *#cycles* is the number of charging/discharging cycles in a year, *DoD* is the depth of discharge, *Crated* is the rated capacity, *DEG* is the annual degradation in rated capacity, *r* is the discount rate, $\mu(DoD)$ is the charging electricity tariff, is the round-trip efficiency and, needed when modelling conventional CAES, *Pgas* is the gas tariff and *Gasin* is the gas required per kWh of electricity and $\mu(DoD)$ is the round-trip efficiency.

The LCOS is directly proportional to the price of electricity for all energy storage technologies included in the summary table above.

Data sources utilised to determine technology costs

Source	Description	Batteries	PHES	Power-to-gas
CSIRO report on energy storage (Brinsmead et al, 2016)	Review of four storage technologies that are most relevant to NEM with cost forecasting for 2035	✓		
<i>Renewable and Sustainable Energy Reviews</i> (Journal article) (Zakeri and Syri 2015)	Analysis of storage costs based on a review of 27 papers from 2008–2013	✓		✓
<i>Applied Energy</i> (Journal article) (Julch 2016)	LCOS analysis for four storage technologies			✓
ROAM report to AEMO on pumped hydro (Winch et al. 2012)	NEM-wide assessment of PH potential (sites suitable for 500 MW+) for AEMO 100 % modelling		✓	
Primary research (technology providers)	Survey of 30 residential battery retailers	✓		

Cost data for LCOS calculation for batteries

	Advanced Lead Acid	Li-ion	Zn-Br Flow
CAPEX (2017) \$A/kWh rated, including installation and inverter ¹	680	699	1300
CAPEX (2017) \$A/kWh average effective capacity ²	1511	699	1300
CAPEX (2030) \$A/kWh rated, including installation and inverter	320	333	272
CAPEX (2030) \$A/kWh average effective capacity ²	711	333	272
Assumed volume-cost learning rate % ³	9	9	15
Fixed O&M \$A/kW/yr ⁴	2.4	4.9	3.1
Variable O&M \$A/kWh throughput ⁴	0.0048	0.003	0.0009

Notes:

1. CAPEX: Advanced lead acid data from (Cavanagh et al. 2015), Li-ion data from Tesla Motors, 2017 and Zn-Br Flow data from data Redflow, 2017.
2. The cost per effective capacity of advanced lead acid increases as a result of the 45 per cent depth of discharge. This is suggested as a maximum from Cavanagh et al. 2015.
3. Less mature technologies have a higher learning rate, and therefore a steeper decline in capital cost until the technology has matured and capital costs level out.
4. O&M data is taken from the meta-analysis published by Zakeri and Syri, 2015. \$A100 /MWh is assumed price of electricity.

Australian pumped hydro potential and costs according to ROAM

	Storage (MWh) ¹			Average capital cost per MWh storage		
	< \$A500,000	< \$A1,000,000	All	< \$A500,000	< \$A1,000,000	ALL
NSW	45,308	3,441	48,749	\$452,871	\$777,443	\$475,782
QLD	13,078	2,193	15,271	\$509,992	\$952,359	\$573,518
SA	-	2,071	2,071	\$0	\$1,027,964	\$1,027,964
TAS	39,956	19,990	59,946	\$324,827	\$1,011,074	\$553,670
VIC	-	2,009	2,009	\$0	\$990,550	\$990,550
Total	98,342	29,705	128,047	\$408,443	\$979,463	\$540,910

All data derived from ROAM Consulting 2012.

Note:

1. ROAM storage potentials have been de-rated by 20 per cent, assuming a maximum 80 per cent discharge.

Cost data – power-to-gas (hydrogen)

A number of hydrogen pathways exist from renewable energy. With a focus on 2030, the most practical pathway for hydrogen to electricity is likely to be via storage in the gas network, followed by use in an existing gas turbine, which is shown here.



Most power-to-gas systems are compatible with existing infrastructure for natural gas storage, conversion and transmission (Cavanagh et al., 2015). As such, the presence of available natural gas infrastructure needs to be considered when analysing costs associated with power-to-gas.

Data used for power-to-gas was obtained from Zakeri and Syri (2015), which was also the source for fixed and variable O&M.

Cost summary – PHES, power-to-gas

	PHES		Power-to-gas
	Lower Cost	Higher Cost	
CAPEX (2017) \$A/kWh average effective capacity ¹	408	979	372
Fixed O&M \$A/kW/yr ²	0.5	1.8	6.7
Variable O&M \$A/kWh throughput ²	0.0003	0.0003	0.0043

Notes:

1. CAPEX: PHES from Winch et al. 2012; Power-to-gas from Zakeri and Syri 2015.
2. O&M: Julch, 2016.

CAPEX – Pumped Hydro

CAPEX costs for pumped hydro are taken from ROAM 2012 report to AEMO (Winch et al. 2012). The methodology used benchmark costs for dam wall, piping and tunnelling, and mechanical or electrical. It does not include cost associated with land purchase. The averaging of “low cost” and “high cost” is arbitrary and used a threshold of below \$A500,000 /MWh for low cost, and between \$A500,000 /MWh and \$A1,000,000 /MWh for high cost. Figures for a 60 metre deep reservoir have been used.

CAPEX – Batteries 2017

CAPEX includes the cost of the battery, the inverter, and installation.

Li-ion – CAPEX for a battery with inverter is from primary research; TESLA prices were used as they are assumed to form a benchmark. Installation cost is from Brinsmead et al., 2016.

Zn-Br – CAPEX for battery is taken from primary research, but there is only one data point. Inverter and installation costs are from Brinsmead et al., 2016.

Advanced lead acid – CAPEX is the 2017 projection from Brinsmead et al., 2016.

CAPEX – Batteries 2030

The Brinsmead et al., 2016 forward projection (cost reduction) from 2017 to 2030 was used to derive the 2030 CAPEX from current prices.

Cost reduction is a combination of the volume-cost learning rate, and projected installation numbers both globally and domestically. Learning rate is defined as the cost reduction for every doubling in installation. It uses the assumption that technology costs come down very steeply at early stage development, as doubling is relatively easy to achieve when the base level is very low. Zn-Br is at a much earlier development stage than either Li-ion or Zn-Br, and the CSIRO report (Brinsmead et al., 2016) projects much steeper price drops for this technology. It is also plausible that Li-ion has accelerated along the reduction curve because Tesla has reduced their costs in anticipation of sales, which will incentivise other companies to reduce their costs in competition.

CAPEX – Compressed air

CAPEX includes the average cost from Zakeri and Syri (2015), which separates costs into the power conversion system (PCS) and the storage section. Capital costs are separated into the charging system, the discharge system, and the storage section.

Technical input data for the LCOS calculations (all technologies)

	Advanced Lead Acid	Li-ion	Zn-Br Flow	PHES	Power-to-gas
Depth of Discharge (%)	45	100	100	100	100
Round-trip Efficiency (%)	94	93	75	76	32
Average effective capacity (%)	90	90	90	100	100
Project Lifetime (yrs)	15	15	15	40	20
Sources	1	2	3	4	5

Sources:

1. Cavanagh et al., 2015.
2. Tesla Motors, 2016.
3. Zn-Br Flow data from Redflow, 2017.
4. Winch et al., 2012.
5. Julch, 2016; Zakeri & Syri, 2015.

Financial input to LCOS calculations

Discount rate	8 %	
Average electricity price	0.1	\$A/kWh
Average gas cost	0.060	\$A/kWh
1 EUR	\$1.42	AUD
1 USD	\$1.32	AUD

All values are 2017 dollars.

APPENDIX 3

AEMO GENERATION INFORMATION BY STATE

The existing, committed, and proposed generation outputs by state were downloaded from the AEMO website (AEMO, 2016b) in December 2016, using the updates provided by AEMO on 18 November 2016. These are reproduced below, with an additional line of the assumed withdrawal of coal plants under the high renewables scenario. The figures do not include rooftop solar.

NSW	Coal	CCGT	OCGT	Gas other	Solar	Wind	Water	Biomass	Other	Total
Existing	10,240	591	1,530	147	231.1	666	2,745	131	9.1	16,289
Announced Withdrawal	2,000	171	0	0	0.0	0	0	0	0	2,171
Existing less Announced Withdrawal	8,240	420	1,530	147	231.1	666	2,745	131	9.1	14,119
Committed	0	0	0	0	23.0	175	0	0	0	198
Proposed	0	15	500	0	211.6	4,723	0	8	0	5,458
Coal retirement MID RE	-1,320	Vales Point is assumed to close								
Coal retirement HIGH RE	-6,840	Vales Point B, Eraring, Bayswater are assumed to close								

VIC	Coal	CCGT	OCGT	Gas other	Solar	Wind	Water	Biomass	Other	Total
Existing	6,230	21	1,904	523	0	1,249	2,296	53	0	12,276
Announced Withdrawal	1,600	0	0	0	0	0	0	0	0	1,600
Existing less Announced Withdrawal	4,630	21	1,904	523	0	1,249	2,296	53	0	10,676
Committed	0	0	0	0	0	306	0	0	0	306
Proposed	0	500	600	0	164	3,449	34	0	0	4,747
Coal retirement MID RE	-1,450	Yallourn W is assumed to close								
Coal retirement HIGH RE	-4,630	Yallourn W, Loy Yang A, Loy Yang B are assumed to close								



SA	Coal	CCGT	OCGT	Gas other	Solar	Wind	Water	Biomass	Other	Total
Existing	0	419	915	1,280	0	1,595	3	21	129	4,362
Announced Withdrawal	0	0	0	0	0	0	0	0	0	0
Existing less Announced Withdrawal	0	419	915	1,280	0	1,595	3	21	129	4,362
Committed	0	0	0	0	0	102	0	0	0	102
Proposed	0	200	320	0	702	2,951	0	20	0	4,193
Withdrawn	-786	-239	0	0	0	0	0	0	0	-1,025

QLD	Coal	CCGT	OCGT	Gas other	Solar	Wind	Water	Biomass	Other	Total
Existing	8,216	1,213	1,894	187	0	12	664	367	1	12,555
Announced Withdrawal	0	0	34	30	0	0	0	0	0	64
Existing less Announced Withdrawal	8,216	1,213	1,860	157	0	12	664	367	1	12,491
Committed	0	0	0	0	28	0	0	0	0	28
Proposed	0	0	2,545	0	646	990	0	158	0	4,338
Withdrawn	0	-385	0	0	0	0	0	0	0	-385
Coal retirement MID RE	-3,780	Gladstone, Tarong, Callide B are assumed to close								
Coal retirement HIGH RE	-5,240	Gladstone, Tarong, Callide B, Stanwell B are assumed to close								

TAS	Coal	CCGT	OCGT	Gas other	Solar	Wind	Water	Biomass	Other	Total
Existing	0	0	178	0	0	308	2,281	5	0	2,772
Announced Withdrawal	0	0	0	0	0	0	0	0	0	0
Existing less Announced Withdrawal	0	0	178	0	0	308	2,281	5	0	2,772
Committed	0	0	0	0	0	0	0	0	0	0
Proposed	0	0	0	0	0	329	0	0	0	329
Withdrawn	0	-208	0	0	0	0	0	0	0	-208

South West Interconnected System	Coal	CCGT	Gas/gas & diesel peaking	Gas other	Solar	Wind	Water	Biomass	Other	Total
Existing	1,778	876	1,242	880	4	86	0	16	176	5,058
Announced Withdrawal	340									340
Existing less Announced Withdrawal	1,438	876	1,242	880	4	86	0	16	176	4,718
ADDITIONAL INFORMATION (not from AEMO)										
Proposed					100 ¹	500 ²				600
Coal retirement MID RE	-874	Muja is assumed to close								
Coal retirement HIGH RE	-874	Muja is assumed to close								

Notes:

1. 100 MW Cunderdin Solar.
2. 100 MW Pacific Hydro proposal for Lancelin; <<http://www.pacifichydro.com.au/english/projects/development-construction/nilgen-wind-farm>>; 300 MW Dandaragan <<http://dandaraganwindfarm.com.au>>; 100 MW Badgingarra.

APPENDIX 4

AUSTRALIAN ORGANISATIONS INVOLVED IN ENERGY STORAGE

The Australian National University's (ANU) Energy Change Institute conducts research on fuel cells, energy nanomaterials, PHES, and solar thermal energy storage. Researchers in the College of Engineering and Computer Science at ANU, together with researchers at the University of Sydney and industry partners, were recently awarded an ARENA grant to develop network aware co-ordination algorithms and capabilities for residential energy storage on Bruny Island (Consort, 2016).

The Australian Centre of Excellence for Electromaterials Science (ACES) has energy storage projects (including metal-air batteries, the electrolysis of water hydrogen, and nitrogen reduction to ammonia) based at Monash University, Deakin University and the University of Wollongong.

The Australian Nuclear Science and Technology Organisation (ANSTO) is working on the development of new materials for use in molten salt reactor systems, and is involved in research on concentrated solar thermal, hydrogen energy storage, lithium batteries, and fuel cells.

The Australian Solar Thermal Research Initiative (ASTRI) is an eight-year international collaboration between research institutions and industry, including CSIRO, ARENA,

Flinders University, University of South Australia, ANU, The University of Adelaide, Queensland University of Technology (QUT), and The University of Queensland (UQ), investigating concentrated solar thermal power technologies.

CSIRO has experience with a range of energy storage technologies including various battery chemistries, supercapacitors, fuel cells, and hydrogen energy storage.

The Future Grid Research Program by the University of Sydney. The program is conducting research that draws together engineering, economic and policy aspects of grid development and optimisation. The four major areas of focus are – improved understanding of different loads, generation sources and energy storage on system security (University of Sydney); grid planning and co-optimisation of electricity and gas networks (University of Newcastle); Economics of alternative network development paths and estimates of total cost and price impacts (University of Queensland); and Policy measures and regulatory changes to facilitate a smooth transition to a decarbonised future grid (University of New South Wales). The program is supported by an industry group comprising senior executives from the energy sector.

Curtin University's Fuels and Energy Technology Institute is investigating the properties of hydrogen storage materials suitable for transport applications such as cars, high temperature hydrogen storage materials suitable for heat storage in concentrated solar power (CSP) applications, and the properties of hydrogen storage materials suitable for CSP, static and heavy transport applications (Curtin University, 2016). Additionally, Curtin's Hydrogen Storage Research Group (HSRG) aims to produce viable new hydrogen storage materials that will meet the ground transportation and static applications associated with a transition to a solar hydrogen economy.

Deakin University's Institute for Frontier Materials investigates new battery chemistries such as metal-air and sodium-based batteries, as well as improving the performance of existing technologies. In 2016, Deakin established the Battery Technology Research and Innovation Hub (BatTRI-Hub) as a joint venture with CSIRO. BatTRI-Hub collaborates with industry groups to develop new battery technologies for manufacturing in Australia (Deakin Research, 2016).

Griffith University is developing a forecast-based energy storage scheduling and operation system for better load balancing and management of energy supply from solar photovoltaics (Bennett, Stewart, & Lu, 2015).

Monash University's Energy Materials and Systems Institute (MEMSI) has world-leading graphene supercapacitor experience, including spinoff company SupraG. Monash also has active research programs in magnesium- and aluminium-based batteries, and hosts the Energy Program of the ARC Centre of Excellence for Electromaterials Science (ACES), which is developing chemical energy storage technologies including nitrogen reduction to ammonia.

PMB Defence develops and manufactures batteries for submarines, including the Collins Class battery system (PMB Defence, 2017).

Redflow developed the world's smallest zinc bromine flow battery, which can be scaled for a number of applications (Redflow, 2016).

The Queensland University of Technology have a microgrid facility for trialling energy storage technologies (Queensland University of Technology, 2016), and have active research in graphene supercapacitors, and optimisation of metal-air and lithium metal phosphate batteries.

The University of Adelaide's Australian Energy Storage Knowledge Bank is an ARENA-funded energy storage research hub that trials energy storage technologies, with a focus on system design and integration.

The University of Melbourne's Melbourne Energy Institute conducts research into pumped hydro, hydrogen storage, and liquid air energy storage.

The University of New South Wales' (UNSW) Material Energy Research Laboratory in Nanoscale (MERLin) is researching metal-air batteries, sodium-based batteries, and hydrogen storage, including the EnergyH Project. This is a crowd-funded project to support research and commercialisation of hydrogen-based energy technologies. The vanadium redox flow battery was invented at the University of New South Wales by Emeritus Professor Maria Skyllas-Kazacos, FTSE.

The University of Queensland researchers investigate energy storage through the application of a RedFlow zinc bromine flow battery to their UQ solar array, including systems integration and monitoring (The University of Queensland, 2016).

The University of Sydney houses the Australian Institute for Nanoscale Science and Technology. A flagship program of this institute is nano-engineered reversible energy storage. Gelion, a spin out from the ihas successfully partnered with London-headquartered company, Armstrong Energy.

The University of Technology Sydney Centre for Clean Energy Technology includes research efforts on advanced battery technologies, supercapacitors, hydrogen production and storage, fuel cells, and graphene applications for energy storage.

The University of Wollongong Institute for Superconducting and Electronic Materials is building a pilot-scale sodium battery production facility to develop battery packs for testing in residential and industrial settings (University of Wollongong, 2016). They also undertake research in lithium-ion air batteries, potassium-ion batteries, hydrogen storage, and anode materials.

Vast Solar is an Australian company undertaking R&D on concentrated solar thermal power (CSP) technologies. It has an operational 6 MW pilot scale CSP in NSW with intentions to expand this to a 30 MW commercial-scale plant, which would be Australia's first (Vast Solar, 2016).

APPENDIX 5

EXISTING AND EMERGING RAW RESOURCES

Existing Mineral Resource Opportunities

The following raw resources are used in the energy storage market.

Lithium

Currently, the most significant raw material opportunity for Australia is in lithium.

Lithium-ion batteries are one of the most popular energy storage technologies, especially for distributed and behind-the-meter energy storage markets (Navigant Research, 2016a). Tesla's intention to significantly increase production to 35 GWh/yr of lithium-ion battery cells by 2018 (Tesla, 2017) is but one example demonstrating the increasing demand for lithium. Kingsnorth (2015) estimated 10–15 per cent average annual growth in lithium demand for batteries between 2015 and 2025, contributing to a total lithium demand of 350–400 ktpa in 2025 (up from 150–170 ktpa in 2015).

Australia is the world's largest single supplier of lithium, with lithium deposits accounting for just over 11 per cent of the world's Economic Demonstrated Resources (EDR), ranking fourth globally after Chile, China, and Argentina (Britt et al., 2016). The world's largest and highest grade spodumene (LiAlSi₂O₆) deposit, Greenbushes, is located

in Western Australia and hosts 82 per cent of Australia's lithium EDR (Britt et al., 2016). This mine is operated by Australian mining company Talison Lithium.

Lithium Australia has developed a new process, Sileach, which is predicted to reduce the cost of processing lithium from spodumene and recycled lithium (Griffin, 2017). The process also has the potential to reduce by-products and waste, and has low energy consumption. The Sileach process is expected to be operating at a commercial scale by 2018 (Griffin, 2017).

A new lithium plant to be installed in Kwinana, Western Australia, will process concentrate from the Greenbushes mine, commencing production in late 2018 (Tianqi Lithium, 2016). This will be exported primarily for use in lithium battery manufacturing. The Kwinanaplant is owned by Chinese company Tianqi Lithium, but is expected to create up to 615 jobs locally (Tianqi Lithium, 2016).

An additional lithium chemical plant is undergoing commercial and technical feasibility assessment by Australian companies Neometals Ltd and Mineral Resources Ltd (Neometals, 2016). The plant would be located in the Eastern Goldfields of Western Australia, and would use lithium from the Mt Marion mine to produce lithium hydroxide for use in battery cathode production (Neometals, 2016).

Lead

Lead is a component of lead-acid batteries. Australia has the largest lead EDR, accounting for 40 per cent of world resources, and is the second largest producer of lead after China (US Geological Survey, 2017). There are 18 lead mines operating throughout Australia (Britt et al., 2016). These include world-class deposits such as the Broken Hill lead-zinc-silver mine operated by Australian company Perilya, and the Cannington mine in northern Queensland, which is operated by Australian company South32 and is one of the largest producers of lead in the world.

Smelting and refining of lead takes place at Port Pirie, South Australia, operated by Swiss company Nyrstar. This plant is being upgraded to an advanced multi metals processing and recovering facility, with support from the South Australian Government (Nyrstar, 2015).

Cobalt

Cobalt is commonly used as a cathode in lithium-ion batteries. In 2015 and 2016, China was the world's largest consumer of cobalt, with almost 80 per cent of its consumption in the energy storage industry (US Geological Survey, 2017). This presents a significant opportunity for Australia, as the national cobalt resource is 15 per cent of the world's resource, second only to Congo (Britt et al., 2016; US Geological Survey, 2017).

Australian cobalt usually occurs in association with nickel and is mostly mined in Western Australia. Emerging mining company Cobalt Blue, a subsidiary of Broken Hill Prospecting, plans to capitalise on the demand for cobalt in the energy storage industry by developing one of the world's largest undeveloped cobalt resources, the Thackaringa Cobalt Project near Broken Hill in NSW (Macdonald-Smith, 2017).

Nickel

Nickel is used in nickel-based batteries, as well as some lithium battery chemistries. Australia has the largest nickel EDR, accounting for 24 per cent of the world's total resource, and is ranked second for nickel production after the Philippines (US Geological Survey, 2017).

Australia's nickel resources are contained in both primary and secondary weathered mineral resources, the majority of which occur in Western Australia (Britt et al., 2016). BHP Billiton subsidiary Nickel West operates two of these nickel mines, as well as the Kalgoorlie nickel smelter, Kwinana nickel refinery, and Kambalda nickel concentrator (BHP Billiton, 2005).

Zinc

Zinc is used in flow batteries, such as Redflow's zinc bromide battery technology, and could be used in metal-air batteries.

Australia is the second largest producer of zinc, and has the largest zinc EDR in the world at 31 per cent (Britt et al., 2016). Queensland hosts 56 per cent of the nation's zinc EDR, primarily in the Mount Isa Basin (Britt et al., 2016). Australian companies mining zinc include Perilya and South32.

Zinc smelters are located in Hobart in Tasmania, Port Pirie in South Australia, and Townsville in Queensland. These are operated by Swiss company Nyrstar and Korean company Sun Metals. Nyrstar's Hobart plant is being upgraded to treat more complex concentrates, with financial support from the Tasmanian Government (Nyrstar, 2015).

Potential Mineral Resource Opportunities

The raw resources listed below have been identified as essential for emerging energy storage technologies, and could present economic opportunities for Australia, depending on which storage technologies are commercialised.

Vanadium

Vanadium can be used in redox flow batteries. Australia's vanadium EDR ranks fourth in the world but there is currently no production (Britt et al., 2016). Australian company Australian Vanadium Ltd is evaluating their tenements, including the Gabanintha deposit in Western Australia, with plans to leverage opportunities within the emerging battery storage market. Australian Vanadium has established a pilot vanadium electrolyte production plant and has aspirations for vertically integrated operations (Australian Vanadium, 2016).

Manganese

Manganese can be used in lithium manganese oxide, and lithium nickel manganese cobalt oxide batteries. Australia's manganese EDR is the world's third largest, behind South Africa and Ukraine (US Geological Survey, 2017).

These resources are located in the Northern Territory and Western Australia (Britt et al., 2016), including the South32-owned Groote Eylandt manganese mine. A fall in the manganese price led to the suspension of operations at manganese mines in Bootu Creek in the Northern Territory and Woodie Woodie in Western Australia in late 2015, and early 2016, respectively. Groote Eylandt manganese ore is shipped to South32's Tasmanian Electro Metallurgical Company manganese alloy plant for beneficiation.

Australian mining equipment, technology, and services (METS) company Mesa Minerals Limited has developed and is attempting to commercialise improved manganese processing technologies suitable for producing "*consistently high purity, low cost electrolytic manganese dioxide suitable for use in the manufacture of both alkaline and lithium-ion batteries*" (Mesa Minerals Limited, 2017).

Aluminium

Aluminium is required for aluminium-air batteries and as high purity foil for current collectors in lithium-ion batteries. Australia has the second largest bauxite (aluminium ore) EDR in the world after the Republic of Guinea (US Geological Survey, 2017). In 2015, Australia was the leading producer of bauxite, the second largest producer of alumina, and the sixth largest producer of aluminium (Britt et al., 2016). Most of Australia's bauxite resources are located in Cape York in Queensland, Gove in the Northern Territory, and the Darling Range in Western Australia (Britt et al., 2016).

Historically, Australia has been involved in many aspects of the aluminium industry, including refining, smelting, and semi-fabrication. However, some of these processing operations have become economically unviable in recent years due to operation costs. This led to the closure of the Kurri Kurri (New South Wales) and Point Henry (Victoria) aluminium smelters, and the Gove alumina refinery (Northern Territory) between 2012 and 2014. As a result, several new operations are shipping bauxite overseas.

Iron

Iron is required for iron-air and nickel-iron batteries. Australia has the largest iron ore EDR in the world, with 28 per cent of the global total (US Geological Survey, 2017).

Most of this (89 per cent) is located in the Pilbara region of Western Australia (Britt et al., 2016). In addition, Australia has several large magnetite deposits that are mined for contained iron (Britt et al., 2016). The largest companies producing iron ore in Australia are BHP Billiton, Fortescue Metals and Rio Tinto.

Magnesium

Certain chemistries of advanced lithium-ion and metal-air batteries require magnesium. Australia has the fifth largest EDR of magnesite (magnesium ore) in the world, but is only a minor magnesium producer (US Geological Survey, 2017). Magnesium is produced at Belgian company Sibelco's Queensland mining and processing operations, and at the Causmag International (owned by Indian company Excel Colour and Frits Ltd.) Thuddungra mine in New South Wales. Queensland hosts the majority (56 per cent) of Australia's inferred magnesite resource, followed by South Australia (35 per cent), and Tasmania (5 per cent).

Phosphorous

Phosphorus can be used in anodes for advanced lithium-ion batteries. Australia has less than 2 per cent of the world's EDR of phosphate rock (phosphate and guano; Britt et al., 2016). The Georgina Basin in Queensland and the Northern Territory contain the majority of Australia's phosphate rock and 90 per cent of contained P_2O_5 (Britt et al., 2016). Production is also taking place on Christmas Island and in South Australia.

The Phosphate Hill mine in western Queensland is the largest source of phosphate rock in Australia. This mine is operated by Incitec Pivot Limited, which uses the phosphate to make fertiliser.

Potassium

Potassium can be used in metal-air batteries or as potassium nitrate for concentrated solar thermal energy storage. Canada has the largest potassium resource (US Geological Survey, 2017). Australia has only minor potassium in mineral form (Britt et al., 2016), which is being explored mainly in Western Australia by Australian companies such as Reward Minerals, Rum Jungle Resources, Salt Lake Potash Ltd, and Parkway Minerals. However, there are large reserves of potassium associated with Australia's solar salt production from sea water and brines (e.g. Rio Tinto, 2017). This potassium is treated as a waste by-product because the cost of recovery is not currently economic. A change in the potassium value chain could allow Australia to use the solar salt resource and become a large potassium producer using flow sheets that are used in solar salt fields in the United States and China.

Graphite

Graphite has the potential to be used for thermal energy storage, and in graphene-based batteries. The leading producers of graphite are China, India, and Brazil (US Geological Survey, 2017). Turkey has the largest graphite resource, followed by the United States (US Geological Survey, 2017).

Australia's EDR of graphite is relatively minor compared with other nations, and is located in Western Australia and South Australia (Geoscience Australia, 2014). There are no graphite mining operations in Australia.

APPENDIX 6

IMPACT ASSESSMENT FRAMEWORK

Impact category	Definition	Importance
Environmental impacts		
Lifetime energy efficiency	Energy efficiency including round-trip efficiency and expected lifetime.	High energy efficiency maintained over a long-expected lifetime equates to a low-order impact.
Lifecycle GHG emissions	GHG emissions from the full lifecycle of a technology (i.e., differentiating between cradle-to-gate and cradle-to-grave).	A low-order impact for lifecycle emissions correlates with a competitive round-trip efficiency because, with the current high emission-intensity of the energy mix, the use-phase emissions typically contribute the largest amount to the overall lifecycle GHG emissions; the relative dominance of emissions associated with manufacturing and decommissioning increases with the transition to a low-carbon energy system.
Supply chain criticality	'Criticality' considers a range of factors contributing to the vulnerability to supply restriction (importance, substitutability, susceptibility) and supply risk (geological, technological and economic, geopolitical, social and regulatory) for material resources.	High-order supply chain criticality recognises the potential for supply vulnerabilities with implications for future technology trends; whilst criticality is not static and is nation-specific, understanding criticality provides important insights that open up new opportunities for industry and research.
Material intensity	The use of non-renewable resources associated with material production, processing and use.	High-order material intensity impacts, and the associated environmental and social issues, undermine the potential benefits of the transition to a low-carbon renewable energy system.
Recyclability	Recyclability includes destructive recycling as well as other material efficiency strategies, including product life-extension, reuse and remanufacturing. These pathways are influenced by material recovery value and maturity of recycling technology/infrastructure.	High recyclability equates to a low-order impact, offering the potential to offset material intensity; a high-order recyclability impact rating highlights a need to either plan for recycling infrastructure and technology development or alternative technology or system design.
Environmental health	The potential damage to ecosystems and human health across the whole supply chain focusing on local impacts, e.g. air, land, water pollution and biodiversity.	High-order environmental health impacts can undermine potential benefits of the transition to a low-carbon renewable energy system.

Impact category	Definition	Importance
Social impacts		
Human rights	For the local community and broader society this includes secure and healthy living conditions, access to resources and indigenous rights; for workers this includes fair salary, no forced labour, no child labour and safe working conditions.	A high-order human rights impact due to poor respect for human rights poses a significant risk to the viability of the emerging industry (with implications for technology development and uptake trends); it highlights a need for harmonised global efforts and initiatives and brand leadership and recognition to champion better conditions.
Health and safety	Exposure to risks and hazards including fire, explosion and toxicity, considering which stakeholders are exposed and the frequency of exposure.	High-order health and safety issues equate to significant risk factors impacting many stakeholders and without established mitigation strategies; it presents a risk to the viability of the emerging industry with implications for technology development and uptake trends, and highlights a need to engage all relevant stakeholders to adhere to best safe practice.

GLOSSARY

Ancillary services	Those services which are necessary to support the transmission of capacity and energy from resources to loads while maintaining reliable operation of the transmission system. Ancillary services include frequency control, load following, voltage support and black start services.
Balance of System	All components of a photovoltaic (PV) system other than the PV panels. Components include: wiring, switches, mounting system, solar inverters, battery bank and battery charger.
Behind-the-meter energy storage	Behind-the-meter refers to storage systems that are located on the end-user's property and connected to their localised energy system, as opposed to the electricity grid.
Beneficiation	Any process that improves the economic value of a mineral ore by removing the gangue (commercially worthless) minerals, which results in a higher-grade product and a waste stream.
Black start	The process of restoring an electric power station or a part of an electric grid to operation without relying on the external transmission network.
Capacity (of energy storage)	Either the maximum sustained power output (or input) of a generator or energy storage device (measured in kW, MW, GW) or the amount of energy that may be stored (measured in kWh, MWh, GWh)
Charging	The process of injecting energy to be stored into an electricity storage system.
Contingency event	An event affecting the power system, such as the failure or unplanned removal from operational service of a generating unit or transmission network element.
COP21 Paris Agreement	A multinational agreement reached at a conference in 2015, which aimed to achieve a legally binding, universal agreement on climate, with the aim of keeping global warming below 2 °C.
Cost reflective pricing/tariff	The true cost of supplying electricity, where network prices reflect the cost of providing electricity to consumers with different patterns of electricity consumption.
Curtailement	A reduction in the output of a generator from what it could otherwise produce given available resources (e.g., wind or sunlight), typically on an involuntary basis.
Decentralised energy	Decentralised energy is energy produced close to where it will be used rather than at a large power plant elsewhere and then sent through the grid.
Demand profile	The daily variation in electricity demand aggregated across a network.
Depth of discharge	The degree to which a battery can discharge or empty relative to its capacity.

Discharging	The process of retrieving energy that has been stored in an electricity storage system.
Distributed energy resources (DER)	Smaller power sources and controllable demand that help to manage supply and demand on local networks, and that can be aggregated to provide services to the wider interconnected electricity grid. As the electricity grid continues to modernise, DER such as storage and advanced renewable technologies can help facilitate the transition to a smarter grid.
Distributed energy storage	Smaller power storage systems that store energy later use to help manage supply and demand on local networks.
Embedded networks	A small electricity network that distributes and sells electricity exclusively to homes or businesses within a specific property or areas (e.g. an apartment building, shopping complex, caravan park).
Emissions abatement	A strategy for mitigating greenhouse gas emissions
Energy efficiency	Using less energy to provide the same or improved output.
Energy reliability	The ability to meet electrical energy demand (GWh) at all times and in future.
Energy security	The ability to deliver near-instantaneous power (GW) as fast frequency response (FFR) to withstand sudden changes or contingency events in electricity generation (e.g. failure of a large generator), transmission (loss of a transmission line) or demand.
Energy Trilemma	Comprises: Energy security, which encompasses factors such as the reliability of infrastructure; Energy equity, which relates to how accessible and affordable the energy supply is across a population; and Environmental sustainability, which considers the development of renewable and low carbon sources.
Environmental health	The potential damage to ecosystems and human health across the whole supply chain focusing on local impacts, e.g. air, land, water pollution and biodiversity.
Fast Frequency Response (FFR)	The rapid injection of power or relief of loading that helps stop a decline of system frequency during power disturbances.
Feed-in tariffs (FiT)	A payment for electricity fed into the supply grid from a renewable energy source, such as wind or solar panels.
Frequency regulation	A centrally managed control process to maintain frequency on a continuous basis.

Frequency variation	The change over time of the deviation from assigned frequency of a power supply system.
Fringe of grid	The parts of an interconnected electricity grid that are furthest from centralised energy sources. Energy storage and other distributed energy resources can have high value in fringe of grid applications, helping to maintain high quality and reliable electricity supply to parts of the network that are more difficult and costly to supply.
Front of meter	Front of meter refers to storage systems that are located on the grid side of an end-user's property.
Gentailer	A company that is both an electricity generator and retailer.
Gigawatt (GW)	A unit of power equal to one billion (10 ⁹) watts.
Gigawatt hours (GWh)	Unit of energy representing one billion watt hours (equivalent to one million kilowatt hours). Gigawatt hours are often used as a measure of the output of large electricity power stations.
Greenhouse gas (GHG) emissions	Emission of atmospheric gases that contribute to climate change by absorbing infrared radiation.
Hydrogen energy storage direct injection (H ₂ DI)	Direct injection into the gas grid.
HIGH RE	High renewable energy.
Inertia	The ability of large masses in steam and hydro turbines to keep spinning to maintain a steady frequency. This continued spinning allows sufficient time (seconds to a few minutes) for the system to respond to sudden changes in electricity generation, transmission or demand.
Insolation	Incoming solar radiation that reaches the earth's surface.
Levelised costs of energy storage	A summary measure of the overall competitiveness of different generating technologies. They represent the per kilowatt-hour cost (in present dollars) of building and operating a generating plant over an assumed financial life and duty cycle.
Lifecycle GHG emissions	The greenhouse gas (GHG) emissions from the full lifecycle of a technology.
Lifetime energy efficiency	Energy efficiency giving consideration to important statistics including round-trip efficiency and expected lifetime.
Load following	Adjusting a power plant's power output as demand for electricity fluctuates throughout the day.
Load shedding	When there is insufficient electricity available to meet demand, it may be necessary to interrupt supply to some areas. This is generally done to prevent the failure of the entire system when unexpectedly high demand or contingency events strain capacity.
Low FIT	Representing FITs less than 10 c/kWh, most offered by retailers and typically post-2014.

Material intensity	The use of non-renewable resources associated with material production, processing and use.
Micro-grid	A localised collection of interconnected electricity loads and sources that can connect to the wider electricity grid and also disconnect from the grid and function autonomously. Also known as a mini-grid.
MID RE	A scenario with a renewable energy uptake approximate to Australia's commitments at COP21.
National Electricity Market (NEM)	The Australian wholesale electricity market that covers the electrically connected states and territories of eastern and southern Australia, and the associated synchronous electricity transmission grid.
Network management	The operation, administration, maintenance, and provisioning of networked systems. Network management is essential to command and control practices and is generally done from a network operations centre.
Network service provider	A registered party that owns, leases, or operates an electricity network and is registered.
Off grid	Systems that do not use or depend on public utilities and network infrastructure for the supply of electricity.
Path dependency	The tendency of a past or traditional practice or preference to continue even if better alternatives are available.
Peaking plant	Power plants that generally run only on the few occasions when there is high demand, known as peak demand, for electricity.
Pre-FiT	Representing pre-2008 when the PV Rebate Program was available.
Premium FiT	Representing FiTs of more than 40 c/kWh, typically from 2009–2012.
Price inelastic	A market for an item in which the price of the product has no bearing on the supply or demand for it.
Prosumer	A producer <i>and</i> user of electricity. Various types of prosumers exist – residential prosumers produce electricity at home – mainly through solar photovoltaic panels on their rooftops; citizen-led energy cooperatives or housing associations; commercial prosumers whose main business activity is not electricity production, and public institutions such as schools or hospitals.
Pumped hydro energy storage (PHES)	A type of hydroelectric energy storage used by electric power systems for load balancing. The method stores energy in the form of gravitational potential energy of water, pumped from a lower reservoir to a higher one.
Reliability of supply	Two factors ensure reliability of supply – system reliability and system security. Ensuring reliability and security is a core function of the Australian Electricity Market Operator and the regulations that underpin that market.

Renewable energy certificates	A measurement of renewable energy that can be traded or sold.
Renewable energy integration	Incorporating renewable energy, distributed generation, energy storage, thermally activated technologies, and demand response into the electric distribution and transmission system.
Round-trip efficiency	Energy storage consumes electricity ('charging'), saves it in some manner and then delivers it back ('discharging') to the consumer or electricity grid. The ratio of energy put in to the energy delivered back from the storage plant is the round-trip efficiency, expressed as a percentage. The higher the round-trip efficiency, the less energy is lost due to storage and thus the more efficient the system.
Single wire earth return (SWER)	A single wire transmission line that supplies single-phase electric power from an electrical grid to remote areas.
Smart grid	An electricity supply network that uses digital communications technology to detect and react to local changes in usage.
Smart meter	An electronic device that records consumption of electric energy in intervals of an hour or less and communicates that information at least daily back to the utility for monitoring and billing. Smart meters enable two-way communication between the meter and the central system.
Spinning reserve	The extra generating capacity that is available by increasing the power output of generators that are already connected to the power system. For most generators, this increase in power output is achieved by increasing the torque applied to the turbine's rotor.
Subjective norms	The perceived social pressure to engage or not in a particular behaviour.
Supply chain criticality	'Criticality' considers a range of factors contributing to the vulnerability to supply restriction (importance, substitutability, susceptibility) and supply risk (geological, technological).

Synchronous generation	Generation whose operation is tightly synchronised to the operating frequency of the power system. The rotating parts of synchronous generating units spin at a rate that divides exactly into the system frequency (in Australia) of 50 Hz or 3,000 revolutions per minute.
System reliability	The ability of the electricity system to provide an adequate supply of electrical energy (GWh) at all times of the day, the year and in future years.
System security	The ability to deliver near-instantaneous power (GW) as fast frequency response (FFR) to withstand sudden changes or contingency events in electricity generation (e.g. failure of a large generator), transmission (loss of a transmission line) or demand.
Tariff	The pricing structure a retailer applies to customers for their energy consumption comprises two parts: a fixed charge for daily supply to a premise and a variable charge for the amount of energy used.
UltraBattery	A hybrid, long-life lead-acid energy storage device. It combines the fast charging rates of an ultracapacitor technology with the energy storage potential of a lead-acid battery technology in a hybrid device with a single common electrolyte
Ultracapacitor	A high-capacity capacitor with values much higher than other capacitors (but lower voltage limits) that bridge the gap between electrolytic capacitors and rechargeable batteries.
Variable generation	A generating unit whose output is non-dispatchable due to its fluctuating nature, including, for example, solar generators, wave turbine generators, wind turbine generators and hydro generators without any material storage capability.
Voltage support	The ability to produce or absorb reactive power and the ability to maintain a specific voltage level under both steady-state and post-contingency operating conditions subject to the limitations of the resource's stated reactive capability.

ABBREVIATIONS

AAH	Australian Academy of Humanities
AAS	Australian Academy of Science
ACCC	Australian Competition and Consumer Commission
ACES	ARC Centre of Excellence for Electromaterials Science
ACOLA	Australian Council of Learned Academies
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AGL	Australian Gas Light Company
AINST	Australian Institute of Nanoscale Science and Technology
ANSTO	Australian Nuclear Science and Technology Organisation
ANU	Australian National University
ARC	Australian Research Council
ARENA	Australian Renewable Energy Agency
ARPA-E	Advanced Research Projects Agency-Energy
ASSA	Academy of Social Sciences in Australia
ASTRI	Australian Solar Thermal Research Initiative
ATSE	Australian Academy of Technology and Engineering
BatTRI-Hub	Battery Technology Research and Innovation Hub
CAES	Compressed air energy storage
CEFC	Clean Energy Finance Corporation

CCA	Climate Change Authority
c/kWh	Cents per kilo-watt hour
CO ₂	Carbon dioxide
CSIRO	Commonwealth Science and Industrial Research Organisation
CSO	Community Service Organisation
CSP	Concentrated solar power
CSTP	Concentrated solar thermal power
CSP TES	Concentrated solar power with thermal energy storage
CST	Concentrated Solar Thermal
CWEEP	Centre for Water Economics, Environment and Policy
DER	Distributed energy resources
DRC	Democratic Republic of Congo
EDR	Economic demonstrated resources
E-LCA	Environmental life cycle assessment
ENA	Energy Networks Australia
ERA	Excellence in Research for Australia
EWG	Expert Working Group
FCAS	Frequency control ancillary services
FE2W	Food, Energy, Environment and Water
FFR	Fast frequency response
FiT	Feed in tariff
Gas OCGT	Open Cycle Gas Turbine
GHG	Greenhouse gas emissions
GW	Gigawatt

GWh	Gigawatt hour
HIGH RE	High renewable energy scenario
IP	Intellectual property
IRENA	International Renewable Energy Agency
ISF	Institute for Sustainable Futures
ktpa	Kilo-tons per annum
KWh	Kilowatt hour
Li-ion	Lithium-ion
LAES	Liquid air energy storage
LCA	Lifecycle assessment
LCOE	Levelised cost of energy
LCOS	Levelised cost of storage
LFP	Lithium-iron phosphate
LMP	Lithium-metal polymer
LNG	Liquefied natural gas
LRET	Large-scale Renewable Energy Target
MW	Megawatt
MWh	Megawatt hour
NEM	National Electricity Market
NGO	Non-governmental organisation
NISA	National Innovation and Science Agenda
NMC	Nickel manganese cobalt oxide
O&M	Operations and maintenance
OCE	Office of Chief Economist
PEM	Polymer exchange membrane
PHES	Pumped hydro energy storage
PMB Defence	Pacific Marine Batteries Defence
PV	Photovoltaics

R&D	Research and development
RE	Renewable energy
REC	Renewable energy certificate
RET	Renewable energy target
RoCoF	Rate of Change of Frequency
S-LCA	Social lifecycle assessment
SMES	Superconducting magnetic energy storage
SRES	Small-scale Renewable Energy Scheme
SWOT	Strengths, weaknesses, opportunities and threats
SWER	Single wire earth return
TAF	Technology acceptance framework
TES	Thermal energy storage
tCO _{2e} /kWh	Tonnes of carbon dioxide equivalent per kilowatt hour
ToU	Time of use
TRL	Technology readiness level
UAV	Unmanned aerial vehicle
UK	United Kingdom
ULAB	Used lead-acid batteries
UNSW	University of New South Wales
UQ	University of Queensland
USA	United States of America
USD	United States dollars
UTS	University of Technology Sydney
VRB	Vanadium redox battery
VRE	Variable renewable energy
Zn-Br	Zinc bromine
ZBF	Zinc bromide flow battery

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EXPERT WORKING GROUP

Dr Bruce Godfrey FTSE

Bruce's career has been built in business, innovation investment, government and technology development fields. His current role is as CEO of Australian Scientific Instruments Pty Ltd, an Australian National University-owned scientific instruments manufacturing and exporting company.

He has focused on the advancement and commercialisation of technologies (particularly new energy technologies ranging from solar cells to fuel cells to low emission coal utilisation), investment readiness of products and companies, and innovation policy and programs.

He has served on a number of AusIndustry and other government agency innovation funding and advisory committees, including most recently as Chair of ARENA's Advisory Panel until mid-2014. He currently is a Member of AusIndustry's R&D Tax Incentive Committee.

A Fellow of the Australian Academy of Technology and Engineering (ATSE), he is Chair of ATSE's Energy Forum.

Professor Robyn Dowling

Robyn Dowling is Professor of Urbanism and Associate Dean Research in the University of Sydney School of Architecture, Design and Planning, a position she took up in 2016. Prior to that she was at Macquarie University, where she initiated the institution's Bachelor

of Planning program and was the inaugural head of the Department of Geography and Planning. She holds a B.Ec (Hons) from the University of Sydney, and MA and PhD degrees from the University of British Columbia, Canada. She is currently an editor of *Transactions, Institute of British Geographers*.

Robyn's research focuses on contemporary transformations in patterns of life for urban households, and urban policy responses to environmental challenges and technological disruptions. Currently this involves a focus on energy in commercial office spaces, technological alternatives to the private car like car sharing and autonomous vehicles, and the implementation of smart city strategies. This research has been supported by a number of ARC-funded projects and has appeared in over 80 published papers.

Professor Maria Forsyth FAA

Maria Forsyth graduated with a PhD in Chemistry from Monash University, Australia in 1990 and received a Fulbright Postdoctoral Fellowship to work on lithium and sodium battery electrolytes at Northwestern University in Evanston, USA. She returned to Australia in 1993 and shortly thereafter joined the Department of Materials Engineering at Monash University as a lecturer, being promoted to Professor in 2002. She moved to Deakin University in 2010 to start a new group as Chair in Electromaterials and Corrosion Sciences which has now grown

to more than fifty researchers including young academics, research fellows and PhD students.

Maria currently holds positions as the Associate Director of the ARC Australian Centre for Electromaterials Science and Deputy Director of the Institute for Frontier Materials at Deakin University. She has served on several editorial boards and is currently senior editor for *Journal of Physical Chemistry Letters*. She was elected to the Australian Academy of Sciences in 2015 and has received the Galileo Galilei award for her contributions to the Polymer Electrolyte and energy storage field, The Australasian Corrosion Medal for her work in the corrosion mitigation as well as an Australian Laureate Fellowship to undertake research in the area of novel energy materials.

Her research informs the broad field of materials science, particularly as it applies to energy storage and corrosion. She is a leader in the area of transport properties of materials and has had significant impact in both theoretical and applied areas. Specifically, she has focused on developing novel electromaterials for safe batteries and environmentally friendly corrosion inhibitors and on understanding the phenomenon of charge transport at metal/electrolyte interfaces and within electrolyte materials. She is passionate about clean energy, educating the next generation of scientific and technological leaders in this area and facilitating the creation of innovative technologies in Australia.

Professor R. Quentin Grafton FASSA GAICD

Quentin Grafton is Professor of Economics, Chairholder UNESCO Chair in Water Economics and Transboundary Water Governance and Director of the Centre for Water Economics, Environment and Policy (CWEPEP) at the Crawford School of Public Policy at the Australian National University. He is a Fellow of the Academy of Social Sciences in Australia, an Adjunct Professor at the National University of Singapore, Honorary Professor at Lincoln University and President (2017–18) of the Australasian Agricultural and Resource Economics Society.

Quentin previously served as Chief Economist and Foundation Executive Director of the Australian Bureau of Resources and Energy Economics (2011–2013). Quentin currently serves as the Director of the Food, Energy, Environment and Water (FE2W) Network which he helped found in 2014, as Editor in Chief of Policy Forum.net that was established in 2014 and as Executive Editor of the Global Water Forum which he founded in 2010. He has served in various advisory roles, including as Chair of the International Geothermal Expert Group (2013–14) and Chair of the Social and Economics Reference Panel of the Murray-Darling Basin Commission (2008–2009). He has previously contributed advice to Expert Working Groups of two ACOLA studies: Project 6 Engineering Energy: Unconventional Gas Production and Project 7 Australia's Agricultural Future.

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Further details of the extensive consultation can be found under Evidence Gathering. The views expressed in the report do not necessarily reflect the views of the individuals or organisations listed..



EVIDENCE GATHERING

Consultants Reports

All input reports can be accessed on the ACOLA website <www.acola.org.au>.

Phase 1 Report

Banfield, D, Rayner, J. 2016 *Energy Storage: Opportunities and Challenges of Deployment in Australia*, Australian Academy of Technology and Engineering (ATSE)

Work Package 1

Rutovitz, J, James, G, Teske, S, Mpofu, S, Usher, J, Morris, T, Alexander, D. 2017 *Storage Requirements for Reliable Electricity in Australia*, UTS: Institute for Sustainable Futures

Work Package 2

Banfield, D, Finch, E, Wenham, M. 2017 *Research and Industry Opportunities and Challenges*, Australian Academy of Technology and Engineering (ATSE)

Work Package 3

Florin, N, Dominish, E. 2017 *Sustainability Evaluation of Energy Storage Technologies*, UTS: Institute for Sustainable Futures

Work Package 4

Ashworth, P, Sehic, S, Harris, J. 2017 *Understanding the Socio-economic and Socio-technical impacts of Energy Storage*, The University of Queensland

Stakeholder Consultations

Work Package 2

Through a combination of interviews and written responses to discussion questions, ATSE received input from over 80 representatives and experts from the energy and energy storage sectors. These included representatives from government, industry, finance, research, not-for-profit and industry associations. Input was also received from a number of ATSE's expert Fellows. Direct input was received from representatives of the following stakeholder organisations (note that some interviewees requested that their organisation was not listed):

- 1414 Degrees
- ACT Government
- AECOM
- Australian Energy Market Commission (AEMC)
- Australian Energy Market Operator (AEMO)
- AGL
- ARC Centre of Excellence for Electromaterials Science (ACES)
- Australian Renewable Energy Agency (ARENA)
- Australian Energy Storage Alliance
- Australian National University (ANU)
- Australian Nuclear Science and Technology Organisation (ANSTO)
- Clean Energy Council
- CSIRO
- Curtin University
- Deakin University
- Defence Science and Technology Group
- Department of Environment and Energy

Department of Industry, Innovation and Science
 Ecoult
 Energy Networks Australia (ENA)
 Energy Storage Council
 Enirgi Group
 Ergon Energy
 Gelion
 General Electric
 Genex Power
 Geoscience Australia
 GreenSync
 Igniteer
 Imagine Intelligent Materials
 IT Power – Testing the Performance of Batteries
 Marchmont Hill Consulting
 Monash University
 Nano Nouvelle
 NSW Government
 Redback Technologies
 Relectrify
 Renewable Hydrogen P/L
 SA Department of Premier and Cabinet
 SA Power Networks
 Siemens
 Tesla Energy Australia
 University of New South Wales (UNSW)
 University of Queensland (UQ)
 University of Technology Sydney (UTS)
 University of Wollongong
 VAST Solar
 VSun
 Yara
 Zen Energy

Work Package 3

Interviews were undertaken with a mix of stakeholders including government representatives, academics, not-for-profit organisations and industry (including energy utilities, manufacturers, retailers).

Government (4)

- Two from Commonwealth and two from State

Industry (6)

- Two recyclers, two utilities, one manufacturer and one retailer

Not-for-profit (5)

- Two energy, two recycling and one environmental organisation

Academics (5)

- Three experts on technology development (batteries, CSP and hydrogen)
- One on material criticality and one on recycling

Work Package 4

Telephone interviews – key representatives from across the energy sector.

Focus Groups – Brisbane (2) and Melbourne (4) involving participants across all ages.

A National Survey – 1015 participants.

REVIEW PANEL

This report has been reviewed by an independent panel of experts. Members of this review panel were not asked to endorse the report's conclusions and findings. The Review Panel members acted in a personal, not organisational, capacity and were asked to declare any conflicts of interest. ACOLA gratefully acknowledges their contribution.

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Professor John Loughhead is Chief Scientific Adviser at the UK's Department for Business, Energy and Industrial Strategy. He was previously Executive Director of the UK Energy Research Centre and prior to that Corporate Vice President of the ALSTOM group. John is also a Fellow of the Royal Academy of Engineering and chair of its Engineering Policy Committee.

John's professional career has been predominantly in industrial research and development for the electronics and electrical power industries, including advanced, high power industrial gas turbines, new energy conversion systems, spacecraft thermal management, electrical and materials development for electricity generation and transmission equipment.

He is Past-President of the UK's Institution of Engineering and Technology, Fellow of the Australian Academy of Technology and Engineering (ATSE), Fellow of the Royal Academy of Engineering, Professor of Engineering at Cardiff University and Fellow of Queen Mary University of London.

Dr Thomas Maschmeyer FAA FTSE

Dr. Thomas Maschmeyer, is Professor of Chemistry and serves as Founding Director of the Australian Institute of Nanoscale Science and Technology (AINST) and of the Laboratory of Advanced Catalysis for Sustainability (School of Chemistry). He is Honorary Distinguished Professor at the University of Cardiff and Honorary CSIRO Research Fellow.

In 2011 he was elected (the youngest and as only the second Australian resident) Foreign Member of the Academia Europea, as well as Fellow of the Australian Academy of Sciences (AAS), the Australian Academy of Technology and Engineering (ATSE) and the Royal Australian Chemical Institute (RACI). In 2014 he was elected Fellow of the Royal Society of NSW (Australia's oldest scientific society).

He is Founding Chairman of Gelion (2015), a new high performance battery university spin-out, and co-founder of the low carbon/renewables start-ups Ignite Energy Resources (2006) and Licella (2007) and was one of the founding Professors of Avantium (2001), a Dutch High-tech company, now with 160+ employees.

He serves on the editorial/advisory boards of nine international journals and on the external advisory boards of the top catalysis institute of both the UK (Cardiff) and China (Dalian).

He has received many awards, including the New South Wales Science and Engineering Award for Renewable Energy Innovation (2013), the RACI Weickhardt Medal for Economic Contributions through Chemistry (2012), the Royal Australian Chemical Institute (RACI) Applied Research Award (2011), the Le Févre Prize of the Australian Academy of Sciences for Outstanding Basic Research in Chemistry by a Scientists under 40 (2007).

Professor Libby Robin FAHA

Libby Robin FAHA, is Professor at the Fenner School of Environment and Society, and Convenor of the Australian Environmental Humanities Hub. She is Affiliated Professor of the KTH Royal Institute of Technology Stockholm and the National Museum of Australia. She is a member of the Scientific Advisory Board of the Rachel Carson Center for Environment and Society, Ludwig-Maximilian University (LMU). She is a prizewinning historian with 16 books and over 100 articles and chapters, including *The Future of Nature* (2013, Yale), *Natural Resources and Environmental Justice* (2017, CSIRO) and, forthcoming, *The Environment: A History* (Johns Hopkins).







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