Bottling sunlight[1]: using energy storage technology as a lens to view the factors affecting technological change in the electricity supply industry

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November 2014

Working paper

This working paper contributes to Securing Australia's Future (SAF) Project 05.

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[1] *The first man I saw was of a meagre aspect, with sooty hands and face, his hair and beard long, ragged, and singed in several places. His clothes, shirt, and skin, were all of the same colour. He has been eight years upon a project for extracting sunbeams out of cucumbers, which were to be put in phials hermetically sealed, and let out to warm the air in raw inclement summers. He told me, he did not doubt, that, in eight years more, he should be able to supply the governor's gardens with sunshine, at a reasonable rate: but he complained that his stock was low, and entreated me 'to give him something as an encouragement to ingenuity, especially since this had been a very dear season for cucumbers.'*

Jonathan Swift, Gulliver's Travels, Chapter 5.

Contents

The purpose of this paper is to use energy storage as a lens to view a broad range of factors affecting technological change in a large and complex system - the electricity network. This paper does not attempt to analyse energy storage options for Australia. There exist a number of excellent reports that already do that, some of which the working paper summarises in Section 2.1 Does the Australian electricity market have the capacity to adopt new energy storage technologies?

Overview

- Access to reliable and affordable electricity has transformed households, industries and the broader economy. Today's electricity system faces many challenges – ageing infrastructure, declining average demand, and integration of variable and distributed[2] energy from renewable energy sources.
- Energy storage technologies have the potential to deal with uncertainty in the electricity system and allow for greater flexibility to deal with change. Energy storage can improve system stability and efficiencies across the electricity grid. It allows household and commercial customers greater choice in meeting their energy needs. Storage also offers small and remote communities a viable alternative for electricity supply.
- Examples of energy storage technologies include pumped hydro, compressed air, flywheels, thermal energy storage, flywheels, fuel cells and batteries.
- Energy storage technologies vary in their ability to respond to demand, transmission, flexible generation and energy management practices. Assessment of the costs and benefits of energy storage technologies must take into account the application and use of each technology at different stages in the electricity system.
- No one storage technology meets all the requirements of energy storage. A portfolio of storage technologies will be required to meet the needs of different applications. Suitability depends on key energy storage parameters such as energy density, power, charge rates, discharge rates and lifecycle.
- Advances in the performance of any technology will depend on a range of factors, including physical and chemical constraints. For example, battery technology has progressed more slowly than other areas of electronics in the past few decades. The amount of power available in a battery is dependent on chemical composition and battery design.
- The traditional electricity network can be transformed into a smart grid by adding technologies such as smart sensors, IT systems, smart meters and a communications network. Energy storage will play a significant role in developing a reliable and flexible smart grid system.
- The electricity network can be viewed as a techno-institutional complex. Technological systems can be deeply embedded in institutional structures that lead to lock-in. Lock-in can manifest in many ways, for example in the resistance to changes in social norms, technology inertia, companies, institutions and governments. When lock-in occurs in a system as large and complex as the electricity system then interdependencies, sunken costs and vested interests can become substantial barriers to change.

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[2] Distributed generation refers to decentralised energy that is generated or stored by multiple, small, grid-connected devices such as household solar PV panels

- To reduce the impact of vested interest and technological lock-in, policy should support the growth of new niche industries. Niche markets can play a crucial role in the development, improvement and diffusion of emerging technologies.
- There are a range of technical and non-technical solutions that can mitigate many of the problems faced by the electricity grid. These include building more poles and wires, installing underground wires, using energy storage technologies, consumer behavioural changes, ensuring accurate pricing structures, and regulating for lower emissions and grid stability. There is no single clear solution, no one-size fits all answer.
- Increasingly, consumers are making environmental, financial and social choices about the energy they use. The electricity grid needs to become more flexible and accept the changing relationship of consumers with energy. A reliable and efficient modern electricity grid requires greater interaction between consumers, industries and regulators.
- Changes in technology are difficult to predict. Government can allow for change in the system and for unforseen innovation by choosing to regulate via a market rather than seek to prescribe a specific technology as the best option. Governments that legislate for an ultimate end goal (e.g. carbon emissions reduction) and allow business to determine for themselves how to achieve that goal, remove the need to predict future technology advances.

1. Change and uncertainty in the energy system

Electricity infrastructure is essential for most functions in the home, business and the broader economy. The transformative effect of electricity makes it important to Australia’s economy on a national and global scale. Economic growth and improved living standards can be directly attributed to so-called ‘general-purpose technologies’ such as electricity. Such technologies are significant in their ability to spread across most sectors, improve over time and support new innovations (Jovanovic et al., 2005).

There is increasing demand for reliable electric power in all economies. More recently in Australia, electricity consumption and peak demand have been decreasing (see Figure 9), but total primary energy consumption is still projected to grow by approximately 21% (0.5 % per year) over the period 2012—13 to 2049–50 (Syed, 2012). This moderate growth reflects a long-term decline in the energy intensity of the Australian economy which is due to a number of energy-saving interventions: increased energy efficiency practices in residential and non-residential sectors; a reduction in industrial load; and consumer responses to higher retail electricity prices (BREE, 2014, Saddler, 2013).

Electricity systems have always faced change and uncertainty as a result of variable supply and demand. Two factors currently identified as driving change in the electricity system are variable peak demand and variable supply as a result of renewable energy sources. Energy storage technologies can help address the variable demand on existing electricity grids, and benefits can be identified along the entire chain of the electricity system. The potential impacts of energy storage technologies include improving energy system efficiency, increasing use of renewables, increasing self-production of energy including off-grid generation, increasing end-use sector electrification and creating a more stable and reliable electricity system (IEA, 2014). Ways in which to do this can be listed under different stages of production and consumption, as follows:

- **Generation.** Storage can provide additional energy when generators are operating at capacity by storing energy when excess is available.

- **Integration of renewables.** The intermittent nature of wind and solar generation poses planning and operational difficulties at distribution and transmission level. Energy storage can provide grid stability.
- **Transmission.** Reduction of transmission congestion and deferral of investment
- **Distribution.** Voltage support, loss in distribution reduction, increased capacity, deferral of distribution investment
- **End use.** Increased power quality, reliability and access to electricity for consumers in remote areas. Reduction of time of use and demand charges. Ability of consumers to store their own supply.

1.1. Variable peak demand

Demand for electricity is highly variable at different times of the day and from one day to the next (often depending on the weather, i.e. extremely hot or cold days). The variability of peak demand means that the network needs to be able to accurately predict, and reliably deliver, electricity during peak periods. The challenge for electricity providers is to have the resources and infrastructure to meet demand when it occurs. Currently, to ensure a reliable supply, networks are built exceed the capacity necessary to meet peak demand i.e. they produce the maximum required network capacity at all times, to accommodate the peaks when they occur (Figure 1).

Peak demand usually occurs in the afternoon when many households are using electric appliances at the same time. Other peaks are experienced during very hot summer days when households and businesses are running air conditioners to cool buildings.

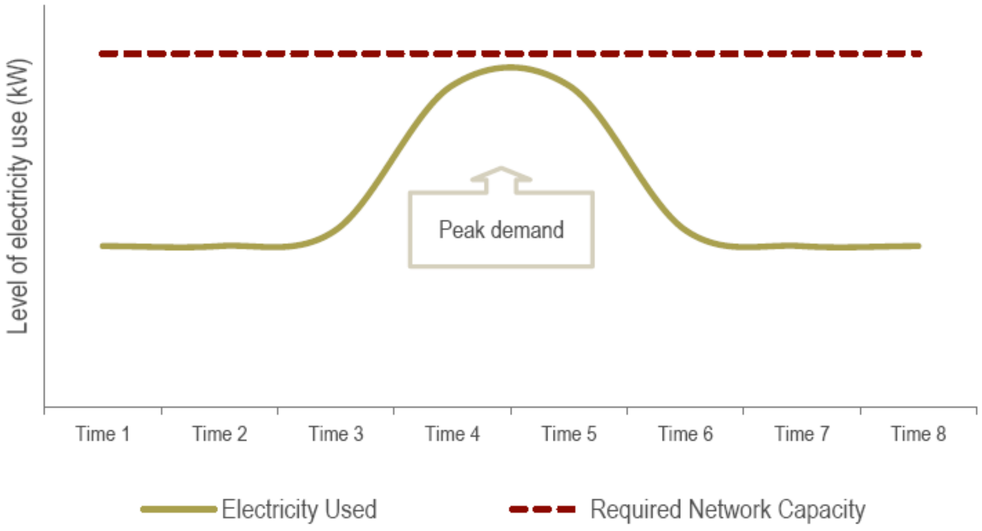

Figure 1: Peak demand and its effect on required network capacity. Source (Marchment Hill Consulting, 2012)

Electricity is usually produced at the time of use because it is difficult to store large quantities of electricity and be able to access it in real time. Energy storage can help alleviate the peaks, decreasing the maximum network capacity required to deliver electricity to consumers (Figure 2).

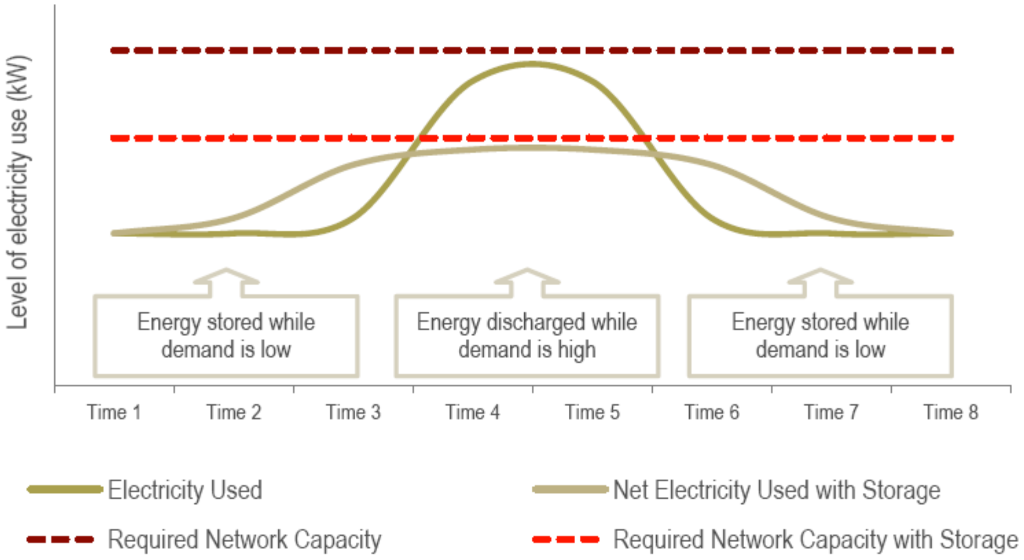

Figure 2: Peak shifting using energy storage.
Source (Marchment Hill Consulting, 2012)

Demand depends on how much electricity consumers are using across the distribution network at any one time. Electricity generators must supply enough to meet this demand and allow some reserve in case of any unexpected events. The grid requires the capacity to handle peaks in demand and to provide a reliable supply of electricity over extended periods of time (Geth et al., 2013). Energy storage technology has the potential to help deal with this inherent uncertainty and to provide greater flexibility in the electricity grid.

1.2. Uptake of new energy technologies by consumers

In Australia, public electricity supply was initially developed by local government bodies in the 1880s. As demand for electricity grew, groups of isolated systems were interconnected and electricity was supplied from central power stations (Australian Academy of Technological Sciences and Engineering (ATSE), 1988). Electricity systems in most countries are designed to generate electricity from fossil fuels and provide power to the consumer via a centralised grid. Most systems were set up with alternating current supply which allowed power to be carried long distances and worked well to power induction motors and incandescent light, the greatest consumers of electricity at the time (Singh et al., 2014).

Until recently the electricity system has remained largely unchanged. But today the electricity industry finds itself in need of changing the way it operates. Two key drivers of this change are the greater use of more efficient, affordable renewable technologies and the impact of higher energy prices (Syed, 2012). These changes leave electricity providers with some challenging problems to manage:

- Customers who use energy more efficiently and/or generate their own electricity require less electricity from the grid. This will lower consumer demand and reduce profit to the electricity provider.
- Increasing amounts of renewable energy feeding into the grid.
- To provide electricity all day and night and generate enough capacity to meet peak demand, excess electricity is generated during non-peak times.
- Continued investment is required to maintain equipment, power plants and transmission lines.

In Australia, residential electricity consumption has been falling since 2009. Some of the drivers of change identified include increased use of energy efficiency measures in the house, increased use of solar power generation and increasing electricity prices which have resulted in behavioural change by consumers (Energy Supply Association of Australia, 2012, Saddler, 2013). The Australian Bureau of Statistics found that in 2011–2012, 89% of Australians took steps to limit their personal electricity use by practices which included purchasing efficient appliances, switching off appliances not in use, and installing their own energy-saving products such as solar hot water heaters and insulation (Clean Energy Council, 2012).

The share of renewable energy in Australian electricity generation is projected to increase. Fastest growing energy sources are expected to be solar and wind (Syed, 2012). Renewable energy produced more than 14.76% of to Australia's electricity in 2013, up from 13.14% in 2012 (Clean Energy Council, 2012, Clean Energy Council, 2013). The increasing use of intermittent renewable energy sources such as solar and wind means that managing the balance between supply (which is variable) and demand is challenging, but given the imperative to further decarbonise energy supply, this is a problem that needs to be solved.

Residential consumers are also becoming generators of electricity, which means that consumers are no longer simply at the end of the supply chain. As energy generation and storage technology becomes more affordable, consumers are using the technology to become producers and exporters of electricity (Sommerfeld et al., 2014).

Governments worldwide have encouraged rapid uptake of renewable energy technology such as solar photovoltaic (PV) panels, using subsidies as incentives. Falling costs for solar PV units have also influenced the uptake of distributed energy generation technologies such as solar PV units which allow consumers to generate their own electricity. Although solar PV installations around the globe only generate 0.1% of the world's electricity, installations grew at an average annual rate of 40% in the period 2005 to 2010 (Figure 3).

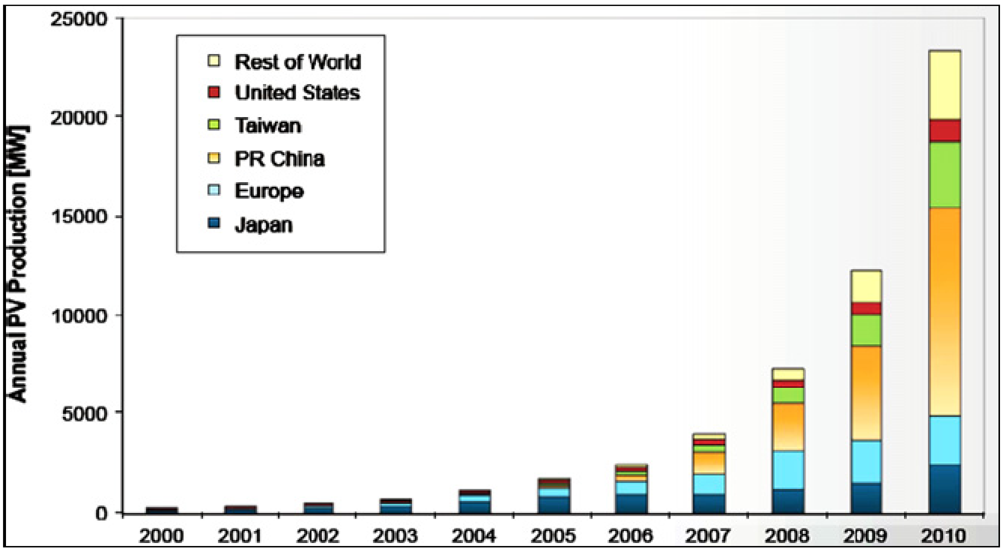

Figure 3: Production of PV cells (given in total MW capacity), 2000 to 2010.
Source: (Frankl et al., 2010)

The unit costs of PV technology has fallen by about a third over the past five years, making it an affordable option for households when paired with subsidies and feed-in tariffs (Frankl et al., 2010). The next major shift in renewable energy uptake is likely to be driven by the cost of energy storage technologies such as batteries. A report commissioned by the Clean Energy Council in 2012 predicts that the market for energy storage technologies will continue to grow and that by 2020, the cost of fully installed storage will halve (from $800 per kW to approximately $400 per kW).

The rate of return depends on the cost of electricity as well as the cost of battery storage. Studies in Germany indicate that at current prices when a solar PV module is installed, the addition of a battery notably diminishes the return on investment to the household, and return on investment will not match that of solar PV (without batteries) until battery prices have halved (Parkinson, 2013b) (Parkinson, 2013a). In 2013, the Energy Supply Association of Australia commissioned a report on the implication of distributed generation for Australian electricity markets. The report concludes it is plausible that future development will see distributed generation technologies offer grid-standard reliability at costs that are competitive (ACIL Tasman, 2013).

1.2.1. The relationship between green consumer attitudes and action

Consumers are making environmental, financial and social choices about the energy they use. Studies have found that the main drivers for adoption of renewable energy alternatives are environmental concerns and saving money. The main barriers to adoption of these alternatives are capital costs and lack of trustworthy information and brands. Much existing consumer research is based on regulatory, financial and information impact on consumer choices, but research shows that social context is also crucial in understanding consumer behaviour. To better understand uptake of energy technology, we also need to research personal values and attitudes, and cultural issues (Sommerfeld et al., 2014)[3].

In 2013, a study by the Dublin Institute of Technology investigated the mismatch between the expressed desire of consumers to support renewable energy products and whether they purchase these products. The report concluded that certain actions would increase the adoption of renewable energy products:

- improving efficiency of solar panels and raising the financial attractiveness of installation (e.g. through feed-in tariffs, which offer long-term contracts to renewable energy producers)
- reducing high initial costs of installation as well as uncertainty around compatibility with existing systems
- continuing to reinforce the need for sustainable and renewable energy (O'Driscoll et al., 2013).

2. Energy storage technology

Electricity is usually produced synchronously with its use because of the difficulty of storing large quantities of electricity for later access. ‘Energy storage technologies’ are collective sets of technologies that store energy. Electricity is converted into a form of stored energy (chemical, mechanical, thermal) which is then converted back into electrical energy for later use. Energy storage has a broad range of applications from powering mobile devices or electric vehicles to providing storage for the electricity grid.

Technologies in this broad category range from electrochemical batteries to mechanical flywheels to thermal storage methods. Although the term ‘storage technologies’ is useful in grouping them, these technologies are in fact vastly different in their makeup and application from each other. Depending on their individual characteristics, existing energy storage technologies are capable of providing different functions at different points in the energy system. They are valuable in all energy systems, regardless of the energy source.

Energy storage technologies will help to manage variability from renewable energy sources and manage peak demand from fossil fuel plants. Traditional baseload plants using coal or nuclear materials can meet the base level of electricity demand throughout the day but coal fired plants for example can be slow to fire up. Energy storage technologies would allow all baseload plants,

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[3] Refer to REF Faiers et al. 2007 and REF Caird et al. 2008, cited in (Sommerfeld et al., 2014)

regardless of the energy source, to generate and store electricity at low peak times and deliver electricity during peak times (Jenkins, 2012).

To determine the potential benefit of storage at any point in the electricity grid, it is necessary to assess the technical and economic impacts of a variety of potentially competing technologies. Different technologies will offer different solutions to demand response, transmission, flexible generation and energy management practices.

Some of the important parameters in assessing the quality and application of an energy storage device are:

- power rating (kW or MW) – the amount of power that can be supplied from the technology
- discharge time (secs, mins, hours, days) – the period of time over which the technology can release its stored energy
- energy density (Watt hours/kg) – the amount of energy that can be supplied from the technology per unit weight
- cycle life – the number of charge/discharge cycles the device can deliver in its life cycle.

Table 1 provides a summary of different energy storage technologies outlining key features, their primary applications and challenges.

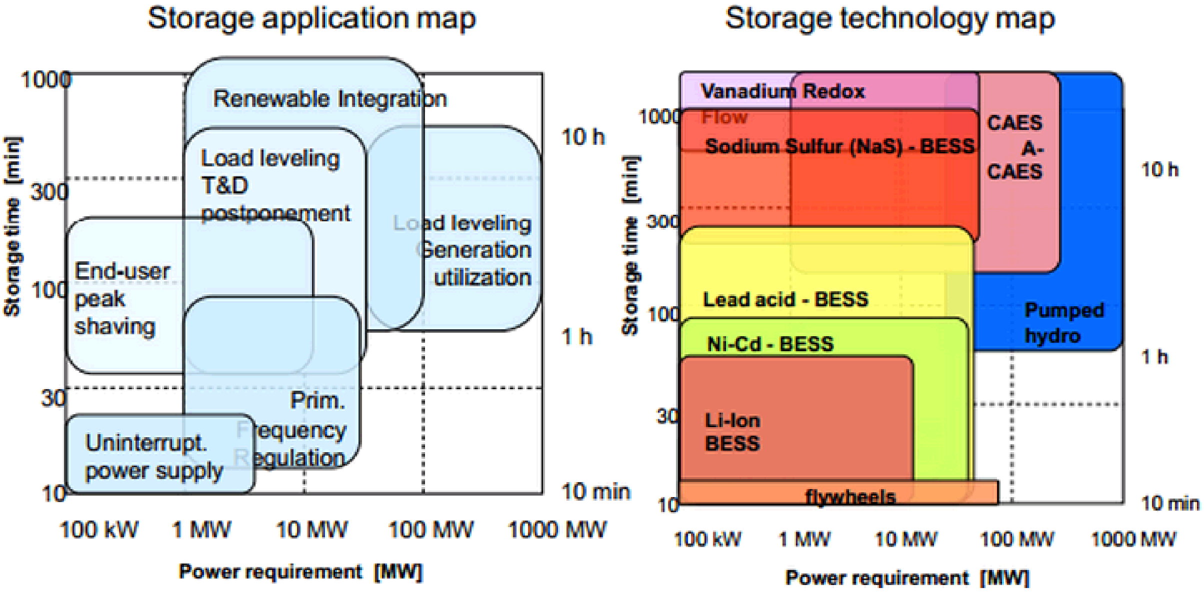
	power rating	efficiency	storage time	discharge time	self–discharge/ day	energy density	cycle life	lifetime	energy cost	maturity	environmental impact
pumped hydro	This system uses two reserves to separate water vertically. Water is pumped uphill during off peak time and released at peak times. The flow of water drives turbines. Pumped hydro is the main form of energy storage worldwide. Its primary application is for energy management and backup reserves. **Challenges**: large capital cost involved in building facilities, geographic limit (availability of suitable land), environmental impact.										
	100–5000 MW	65–85%	Hours to months	1–24 hrs	0%	0.5–1.5 Wh/kg	2–5 x 10^4	40–100 years	US$5–100/ kWh	Mature	Requires geological structure.
compressed air	Air is pumped into storage at high pressure and released at peak. During discharge air is combined with fuel (natural gas) and combusted then passes through turbines. As the air expands, energy is released. Its primary application is for energy management, backup reserves and it can be used to integrated renewables. **Challenges:** geographic limit, slow response time, low efficiency, environmental impact.										
	5–300 MW	42–54%	Hours to months	1–24 hrs	0%	10–60 Wh/kg	5 x 10^3 – 2 x 10^4	20–45 years	US$2–50/ kWh	First generation deployed, second generation demonstration	Requires geological structure. Combustion emissions. Storage of high pressure gases.
flywheel	Rotating mechanical device that is used to store energy. Its primary application is in load levelling and frequency regulation. **Challenges:** rotor tensile strength limits, limited energy storage time due to high friction loss. If operated in a vacuum the amount of friction is reduced, improving efficiency and reducing damage to device.										
	0–250 kW	85–95%	Seconds to minutes	millisec – 15mins	20–100%	5–130 Wh/kg	10^5–10^7	20+ years	US$1000–5000/kWh	Deployed	Minimal environmental impact.
batteries	Convert stored chemical energy into electrical energy. The reversible reaction allows for recharge. Different battery types: lead acid, NaS, lithium–ion. Lithium–ion batteries can be used for power quality and frequency regulation. **Challenges** (Using lithium–ion batteries as an example): scalability, high production cost, sensitivity to temperature.										
	0–40 MW	60–95%	Seconds to months	Seconds–hours	0.1–20%	25–250 Wh/kg	100–10^4	3–20 years	US$200–2500/kWh	Research stage to mature	Lithium and metal air battery materials can be recycled, but if not, the toxic materials can be a fire hazard
fuel cells	A fuel cell converts chemical energy to electricity through a chemical reaction with oxygen or an oxidising agent. It requires a constant source of fuel. Primary applications for power quality and energy management.										

	power rating	efficiency	storage time	discharge time	self–discharge/ day	energy density	cycle life	lifetime	energy cost	maturity	environmental impact
	Challenges: cost.										
	0–50 MW	40–60%	Hours to months	Seconds–days	0%	800–10,000Wh/kg	1000+	5–15 years	–		Use of fossil fuels.
thermal	Allows excess thermal energy to be stored for later use. A range of technologies can collect thermal energy each with their own performance and application characteristics e.g. solar, heat or cold produced from heat pumps, geothermal, heat and power plants. **Challenges:** storage performance stability, cost.										
	0–60 MW		Minutes to months	1–24 hrs	1%	80–200 Wh/kg	–	10–20 years	–		Reduce energy consumption, CO_2 and emissions.
superconducting magnetic	Stores electric energy in a magnetic field within a cooled superconducting coil. High efficiency and fast discharge time. Primary application in power quality and regulation. **Challenges:** low energy density, cost.										
	0.1–10 MW	95%	Minutes to hours	millisecs – 5 mins	10–15%	0.5–5 Wh/kg	10^4	20+ years	US$1000–10000/kWh	Research and development stage	Large magnetic fields on human physiology.
supercapacitor	This is a hybrid between batteries and capacitors. Supercapacitors store energy in the electric field between a pair of charged plates. The primary application is for load levelling and stabilisation. They are capable of fast charge and discharge and have a long lifecycle. **Challenges:** cost.										
	0–300 kW	95–98%	Seconds to hours	millisecs– 1 hr	20–40%	0.1–15 Wh/ kg	10^4	20+ years	US$300–2000/kWh	Development to demonstration stage	Enhance energy performance of cars, but require materials for construction and ultimate disposal.

Table 1: Key features of different energy storage technologies.

Sources: (Ibrahim et al., 2013), (Whittingham, 2012), (Verma et al., 2013),(Biswas et al., 2013), (Marchment Hill Consulting, 2012), (U.S. Department of Energy, 2013), (Directorate General for Energy), (Naish et al., 2008), (Carnegie et al., 2013, IEA-ETSAP and IRENA, 2013) Wikipedia

Electricity network energy storage technologies include devices suitable for power quality applications, energy management applications or for both purposes. Each technology has different storage capacities and discharge timescales (Naish et al., 2008). Figure 4 demonstrates the suitability of each technology to specific energy storage applications in the electricity system.


Storage application map

Storage technology map

Figure 4: Storage applications and technologies maps.
Source (Carnegie et al., 2013)

As the figure shows, different storage technologies are best suited to different applications; there is no single best energy storage technology. For example, flywheels are a good option for delivering uninterruptable power supplies. Compressed air energy storage (CAES) can be mapped to renewable integration and load levelling applications (Carnegie et al., 2013). Pumped hydro-electric storage can be used for managing load, but the need for a suitable location and its capital cost mean that it might not always be the best form of energy storage. By contrast, batteries provide some flexibility, and the capacity of an energy storage facility can be increased by simply adding more batteries. For example, a wind farm in southern California is connected to a massive 32MWh system made up of 608,832 individual lithium-ion batteries[4].

Because no one technology is likely to meet all the requirements for grid scale storage, it is important that a range of storage technologies continue to be supported and developed. Professor Nigel Brandon, former director of the UK's Energy Futures Lab, reported that 3–6 hours of storage time appears to be optimum for both bulk and distributed storage. Round trip efficiency does not have a significant impact on the value of storage and on its own is not a useful selection criterion. It is also important to consider the overall costs, scalability and lifetime of storage. Low efficiency can be tolerated because it will be the lowest cost of delivering the storage function that matters rather than the efficiency (Brandon, 2013).

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[4] http://cleantechnica.com/2014/09/28/tehachapi-energy-storage-project-socal-edison-opens-largest-energy-storage-project-north-america/

2.1. Does the Australian electricity market have the capacity to adopt new energy storage technologies?

The following section summarises several recent reports investigating Australia's capacity to adopt a range of energy storage technologies.

Energy storage in Australia. This report commissioned by the Clean Energy Council in 2012 examining energy storage in Australia suggests that the adoption of new energy storage technologies is inevitable. The report suggests energy storage will have a significant impact on the electricity industry which was originally designed to generate electricity in real-time rather than storing energy for later consumption. The report predicts the market for energy storage technologies will continue to grow and that by 2020, the cost (per kW) of fully installed storage will drop by 50% (from $800 to approximately $400). The report suggests Australia should adopt a range of technical and policy measures such as technical standards and regulatory rules that enable manageable connections of storage to the existing grid (Marchment Hill Consulting, 2012). Efforts to induce the uptake of energy storage in Australia should be focused on the software interfaces, technical standards, and regulatory rules that enable straightforward, consistent, and manageable connections of storage to the grid. The report concludes Australia is too small to be competitive in developing energy storage technologies.

Distributed energy storage in the Australian national electricity market. This paper was published in the Proceedings of the 50th Annual Conference of the Australian Solar Energy Society in 2012. It investigates the potential applications for distributed energy storage in the national electricity market. The authors suggest that until recently there have been virtually no cost-effective energy storage options that can be distributed across the network and that the growing deployment of solar and wind energy generation adds to this challenge. There is now a growing range of potential distributed energy storage options that can assist in managing the supply–demand balance. The study determined the most benefit obtained from energy storage is the increase in end user reliability and reduction in localised peak demand, although these results displayed a large degree of variation through the network, suggesting that the analysis is highly contextual. The study found that a broad set of applications for energy storage exists across the electricity supply chain, and goes on to propose a framework for the integration of the technology into the Australian market (Keith et al., 2012).

Australian Energy Market Operator 100% renewable energy study. In July 2012, CSIRO was contracted by the Australian Energy Market Operator to provide information on renewable energy supply, electricity generation opportunities, and storage for the national electricity market region of Australia. The report findings include:

- Solar thermal molten salt storage has significant opportunities in Australia. The cost of the storage part is offset by the cost of the non-storage part of the plant, which produces more energy, and thus the cost as a function of energy is lower.
- Biomass generation plant has a high capital cost, and as the plant is used at a low capacity factor, the cost of energy storage is dominated by the plant cost and is high compared to the other technologies.
- While the capital cost of converting biomass (woody plants and crops) to biogas is relatively high, it has the advantage over biomass generation technology in that it can be used continuously, i.e. with a high capacity factor.
- Batteries have the advantage of being locatable in any location in a variety of configurations, and can be used for both balancing applications associated with variable output from wind and photovoltaic plants and load shifting (power) applications. Considering the large number of charge–discharge cycles that these technologies are now capable of, the cost of energy

stored in and delivered from batteries is competitive with other technologies (James et al., 2012).

Opportunities for pumped hydro energy storage in Australia. The Melbourne Energy Institute studied the opportunities for pumped hydro energy storage in Australia. Pumped storage has been used in Australia since the 1890s and is the most widespread energy storage system used in electricity grids globally. Australia is reported as having approximately 1.5GW of pumped hydro energy storage capacity but no new large-scale facilities have been built in more than 30 years. Due to the perceived lack of economic need and suitable development sites, Australia has not seriously investigated opportunities for pumped hydro energy storage. The study found that Australia could build artificial dams known as 'turkey-nest' dams in locations where suitable valleys are not available. Another option is to use coastal seawater pumped hydro energy storage, which uses the ocean as the lower reservoir (Hearps et al., 2014).

Some of the messages taken from these reports include:

1. Energy storage will be an important technology for managing uncertainty and change in the national electricity grid (see Appendix 3: Examples of energy storage facilities in Australia).
2. There is no one best energy storage technology option. The choice of technology will be contingent on the specific problem to be solved and on the infrastructure and energy resources available in any given location. The optimal energy storage technology option will depend on the context within which it is used.
3. Investment in the research, development and deployment of energy storage technologies is crucial.

2.2. Interdependence of energy storage technologies with other technologies

Because energy storage technologies cover such a wide variety of devices, progress will rely heavily on technology advances in a broad range of sciences and industries. For example, the electric vehicle industry is pushing to improve the efficiency and performance of batteries for their purposes. Established car makers usually use larger battery cells because they contain more energy, but this also increases the fire risk. Car manufacturer Tesla uses a novel approach with 7000 Li ion (laptop) batteries in its electric vehicle battery pack. By choosing a set of small batteries Tesla saves on manufacturing costs and reduces fire risk (Hull, 2013).

- Innovative designs of energy storage technologies will be required to manufacture efficient that can be manufactured to scale at an affordable cost (OECD, 2012). Significant advances materials and devices are needed to reach the full potential of most energy storage Advances aim to performance improvements in key energy storage parameters such as power, charge rates, discharge rates and lifecycles. In 2010, a number of US organisations contributed to a workshop that sought to accelerate the commercialisation of stationary storage for the energy grid. A summary of their prioritised activities is captured in

Appendix 1: What problems are we trying to solve?

It is commonly argued that

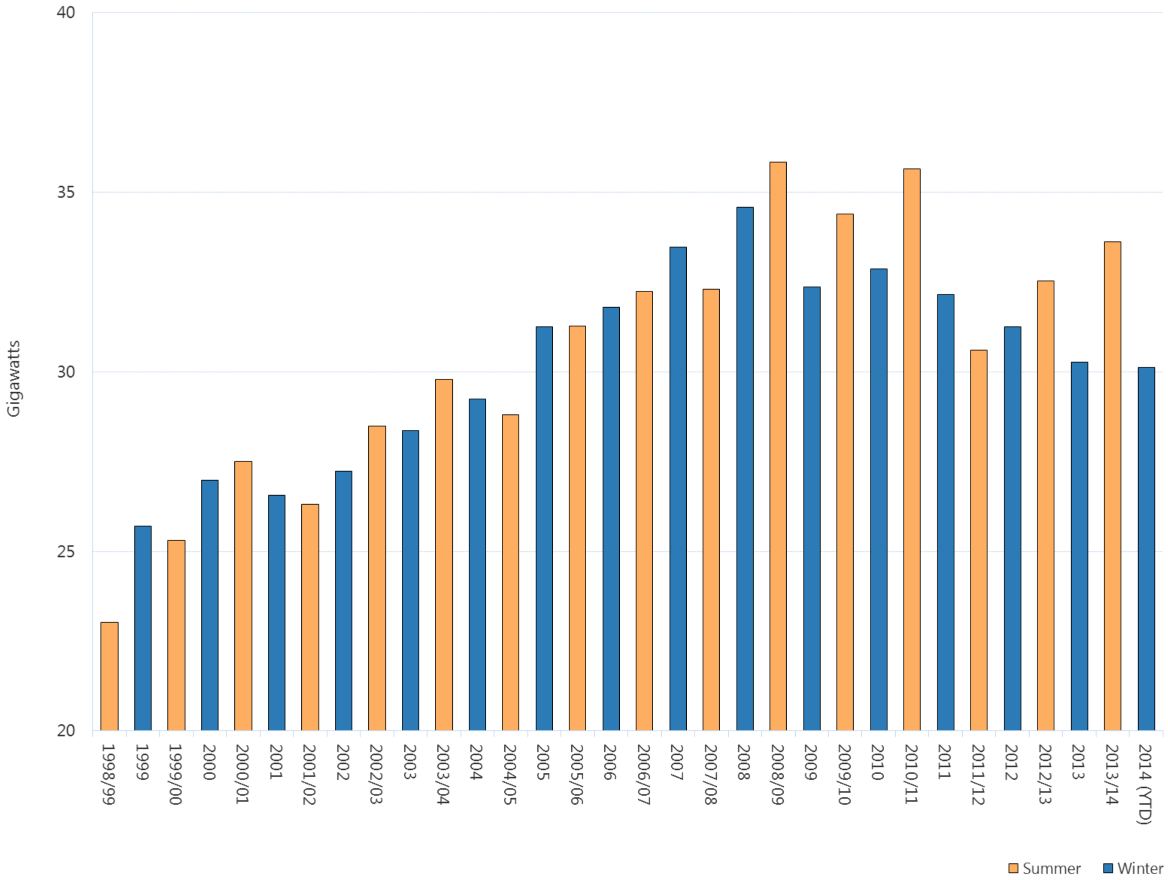
- peak demand is rising and there is an urgent need to build more infrastructure in the existing system to meet that demand
- the increased penetration of (variable) renewable energy sources threatens grid stability.

This section summarises two studies that challenge those claims.

2.2.1. Consumption and peak demand

The level of peak demand determines the required capacity of generation, transmission and distribution systems. Several years ago the year-on-year growth of peak demand was higher than the year-on-year growth in total energy consumption. As a result the electricity industry expected to see continued growth in peak demand and made plans to increase capacity and invest more in the electricity infrastructure. Because 45% of an electricity bill is attributed to network costs, the high level of investment in poles and wires led to a large increase in electricity bills.

In Australia, residential electricity consumption has actually been falling over the past four years. Perhaps what is less well known is that summer and peak demand have also fallen since 2008/2009, Figure 9.



Source: AER; AEMO, Last updated: 7 August 2014 - 2:44pm

Figure 9: Electricity consumption in Australia from 1998 to 2014, showing a decline since 2009. Source: https://www.aer.gov.au/node/9766

This drop in electricity consumption has been attributed to milder summer weather, growth in rooftop solar PV, increased uptake of solar water heating and reduced output from the manufacturing industry. In his *Power Down* report, Hugh Saddler examines the evidence to support these arguments and a number of other possible explanatory factors. The report finds three main factors contributing to the recent dramatic changes in demand for electricity and suggests which of those factors will most likely affect future levels of consumption:

1. **the impact of regulatory energy efficiency programs**. Since the late 1990s, Australia has implemented energy performance standards on a range of residential and commercial appliances and energy efficiency requirements for new buildings. It is likely that if existing programs continue, their contribution to reducing electricity demand will continue to grow.
2. **the partial and complete shutdown of some energy-intensive industries**. Between October 2011 and September 2012, three major industrial electricity users – the Port Kembla steelworks, the Kurri Kurri aluminium smelter and the Clyde oil refinery – were partially or completely shut down. The lack of growth in the electricity-intensive sector will contribute to decreased demand for electricity.
3. **the response of electricity consumers to increasing electricity prices.** This has manifested itself in several ways, including the growth of household solar PV and behavioural changes in electricity consumption through using energy efficient appliances, switching off appliances, and increased use of solar hot water. Consumers will be unlikely to move back to inefficient appliances even if electricity prices drop. If prices remain high, changes in electricity consuming behaviour will probably be sustained but this is not guaranteed (Saddler, 2013).

The report found no evidence to support the argument that declining consumption has been caused by consistently milder seasonal weather in either summer or winter. While changes in weather clearly contribute to changes in demand from year to year, changing weather does not explain the steady decrease in electricity demand. The *Power Down* report concludes

> *Although growth in consumption may resume in the next few years, it will then continue at much lower annual rates than those that prevailed for more than a century up to about 2004 (Saddler, 2013).*

2.2.2. Grid stability

Grid stability is measured by the number of minutes without power caused by unplanned outages in a given year. IEEE magazine reported a study released by Germany's grid regulator that revealed no sign of growing instability of the grid despite Germany's high usage of renewable energy sources Figure 10.

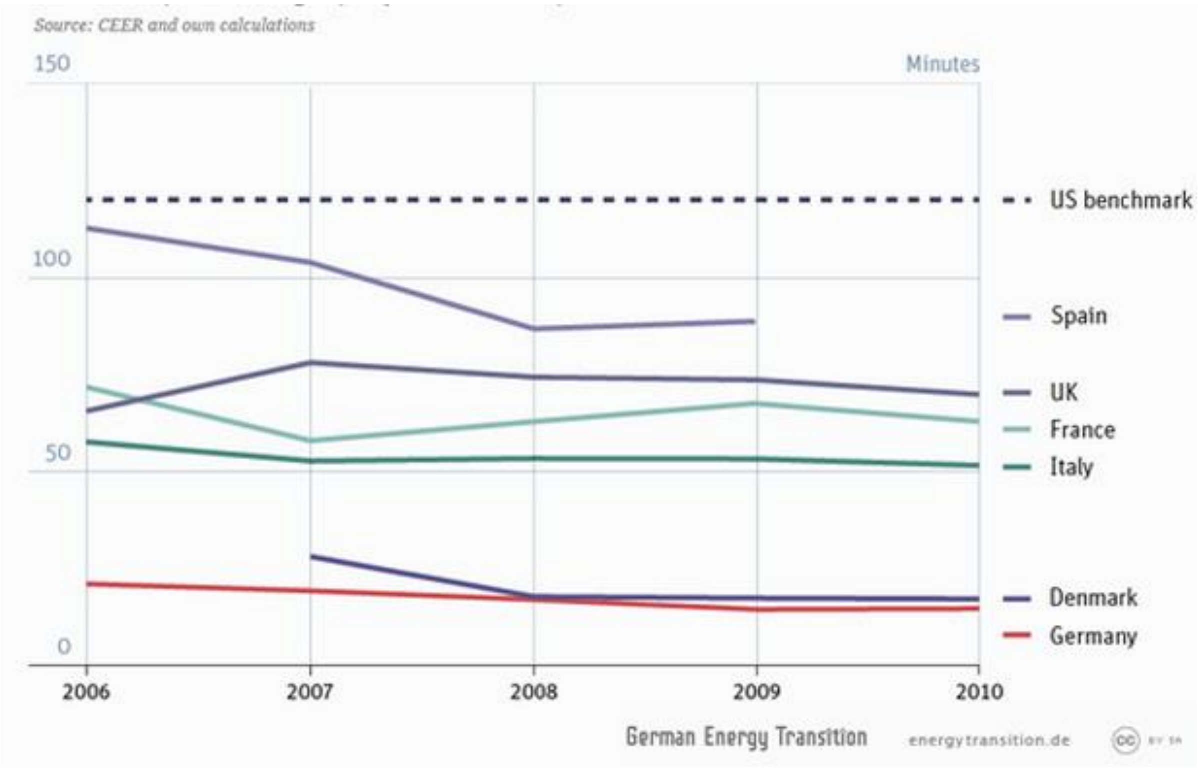


Figure 10: Grid reliability from 2006-2010 in Spain, UK, France, Italy, Denmark and Germany. Reliability is measured by the number of minutes without power caused by unplanned outages in a given year.
Source: (Fairley, 2014)

One of the key reasons suggested for grid reliability in Germany and other nations with well performing renewable energy systems is that most of the lines in the distribution network are located underground (Fairley, 2014). Underground lines are protected from external elements and are found to suffer a third the amount of outages experienced by overhead lines (Silverstein, 2012). This implies that the reliability of the grid does not solely rely on the energy source and that there are other solutions available to ensure a reliable and stable grid.

It is important for policymakers, regulators and industry to better understand the fundamental problems within the electricity system (within any system). These may not always be the most prevalent – what appears to be a problem with increasing demand and unreliable supply may actually be a problem of managing variability. For example, summer peak demand is at its highest when solar energy is likely to be at its highest too. This suggests that the summer peak can be met using a renewable energy source such as solar. The way a problem is understood will affect what is measured, how the measurement is interpreted and the approach taken to solve the problem. These two studies show a range of technical and non-technical solutions for managing supply and demand. Understanding the real problem and regulating accordingly will allow the best solutions to emerge.

Appendix 2: Prioritised activities to advance energy storage technologies. Activities include research and development of advanced materials and devices which would result in more cost-effective, efficient and reliable technologies.

Professor Nigel Brandon, former director of UK Energy Futures Lab, reports in the short term it will be important to learn about performance, failure mechanisms, and lifetime of storage technologies. To do this, demonstrations will be required to explore the relationship between duty cycle, location in the network, control strategies, grid interfaces and technology characteristics. In the medium to longer term he suggests innovation that will continue to bring down the cost of 'fit for purpose' storage technologies that are focused on electricity grid scale applications (Brandon, 2013).

Batteries and information communications are two technologies that will help the existing energy system adapt to changing conditions. The traditional electricity network can be transformed into a smart grid by adding technologies such as smart sensors, IT systems, smart meters and a communications network. Information and communications technology will play a significant role in monitoring and controlling the reliable operation of the entire system (Ipakchi et al., 2009). Also, batteries with substantially higher energy and power densities and faster recharge times are needed if electric vehicles have a chance at matching petrol powered vehicles (US Department of Energy, 2007).

2.2.3. The energy storage capacity of batteries

Improvements in materials, chemistry and design have seen batteries improve over many decades. Improvements have been made in efficiency, energy density and lifecycles. The following section uses the battery to examine how physical and chemical constraints limit performance improvement.

The ability to store energy in a portable way has changed the way people work and live. Batteries are currently being developed to power an increasingly diverse range of devices from microchips to cars to renewable energy systems. The use of batteries in an electricity system allows flexibility and portability. They are used in some distributed and centralised energy applications, but have not yet reached widespread deployment because there are performance, charging capabilities, safety and cost issues (Naish et al., 2008).

Battery technology has progressed more slowly than other areas of electronics over the years. The rate of progress of battery technology is often compared to the rate of technological improvement of computer chips. In the 1960s, co-founder of the Intel corporation, Gordon Moore, estimated that the number of transistors on an integrated circuit would double every 18 to 24 months. The hypothesis, referred to as Moore's Law, has proven accurate for predicting the technological improvement of computer chips although some would argue it has become somewhat of a self-fulfilling prophecy in the chip industry. Whether it was motivated by self-interest on the part of the chip industry or accurate prediction, this technology did improve as expected (Jogalekar, 2013).

Not all performance or specifications of a technology will neatly match a law or model (as has been shown to be the case with Moore's law). Electrons are small and don't take up much space on a chip so as long as features have been made smaller on processors then Moore's law has applied, although even processors may reach a physical limit.[5] Electrons do not take up space in a processor,

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[5] Although to date Moore's law has worked, each generation of ultra-dense chips requires new complex manufacturing processes. 'The sheer density and power levels on a state-of-the-art chip have forced designers to compensate by adding error-correction circuitry, redundancy, read- and write-boosting circuitry for failing static RAM cells, circuits to track and adapt to performance variations, and complicated memory hierarchies to handle multicore architectures.' These extra circuits add area, and copper wires used on the chip need a thick protective sheath which limits how closely the wires can be pushed together. The capacity to double the number of transistors on an integrated circuit does not necessarily mean you are getting double the

so their size does not limit processing capacity; lithographic requirements limit capacity. Ions in a battery do take up space and potentials are determined by the thermodynamics of chemical reactions (Schlachter, 2012). It is more difficult to apply Moore's law to the improvement of batteries when their capacity to store energy is limited by chemical laws (Jogalekar, 2013, Schlachter, 2013).

The amount of electrical energy per mass or electrical energy per volume is a function of a cell's voltage and capacity, and the amount of power available in a battery is dependent on the chemical composition and the battery design. Stored energy content in batteries can be maximised in three ways (Armand et al., 2008):

- by increasing the chemical potential difference between the two electrodes
- by reducing mass or volume of the reactants per exchanged electrode
- by ensuring that the electrolyte is not consumed in the chemistry of the battery.

The slowness of improvements in battery performance is due to the lack of suitable electrode materials and electrolytes, and the fact that battery technology is limited by physical and chemical laws. Technology is pushing the boundaries of chemistry by trying to overcome inefficient conversions, overheating, and spontaneous combustion (Plumer, 2013).

Table 2 illustrates that theoretically, several energy storage technologies have the capacity to make substantial increases in actual energy density, until the energy density limit is reached.

	actual energy density	theoretical energy density
lead acid battery	0.1MJ/kg	0.7MJ/kg
zinc air battery	0.47MJ/kg	1.3–5.3MJ/kg
lithium-ion battery	0.5MJ/kg	2.0–3.0 MJ/kg
petrol[6]	47.5MJ/kg	

Table 2: Comparison of actual and theoretical energy density for batteries and petrol.
Sources: (Schlachter, 2012), (House, 2009)

It is difficult to see when electric vehicles will replace petrol powered vehicles whilst purchasing decisions are made on performance and cost. As indicated in Table 2, petrol (47.5MJ/kg) contains almost 100 times the actual energy of lithium batteries (0.5MJ/kg). An internal combustion engine converts only 15% of the energy in petrol; electric motors convert energy at about 60–80% efficiency. With current efficiency rates, a battery would need to contain 10MJ/kg of energy to match the effective energy density of petrol. This is three to four times the theoretical limit of the lithium battery (House, 2009, Schlachter, 2012).

Batteries and electric vehicles

Many technologies rely on batteries. Battery performance has been a limiting factor in the deployment of some technologies, including electric cars and wireless devices. A limiting factor or weak link can be called the 'reverse salient':

> *Historian Thomas P. Hughes was the first to apply the term to the realm of technological innovation. As described in his book* Networks of Power: Electrification in Western Society, 1880–1930 *(Johns Hopkins University Press, 1983), a reverse salient often forms as a complex*

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improvement in performance. Source http://spectrum.ieee.org/semiconductors/devices/the-status-of-moores-law-its-complicated

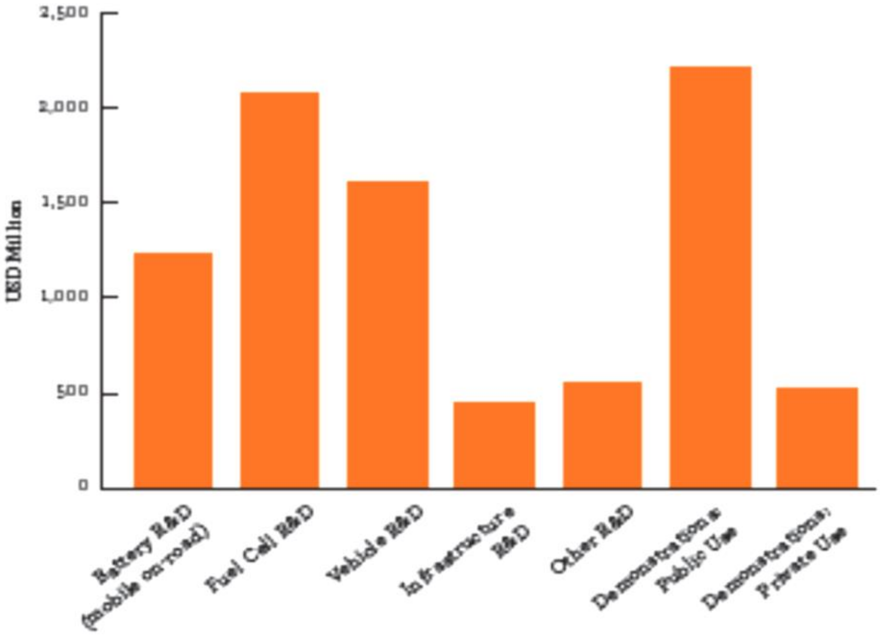
[6] The petrol in a car has the same energy content as a thousand sticks of dynamite!

> *technological system advances: 'As the system evolves toward a goal, some components fall behind or out of line. As a result of the reverse salient, growth of the entire enterprise is hampered, or thwarted, and thus remedial action is required.' In technological advance as in warfare, the reverse salient is the weak link that impedes progress* (Carr, 2011).

In 1899 the US market for automobiles sold 1575 electric vehicles, 1681 steam cars and 936 petrol cars(Cowan et al., 1996b)[7]. The industrial and technological network underpinning the electric vehicle industry seemed to be strong and by 1909 the sales of electric vehicles had more than doubled. However, in the same year the sales of petrol-powered cars increased more than 120 times. The main problems for the electric vehicle were affordability and the battery's poor capacity to store energy compared to that of the internal combustion engine (Cowan et al., 1996a).

> *An important part of the explanation for the under-performance of the market relative to projections is that progress in battery technology did not live up to expectations. Current electric vehicle technology uses lead-acid batteries – the same basic technology used 90 years ago. These batteries are heavy and have low storage capacity. Currently, they can store about 40 watt-hours per kilogram (Wh/kg). Gasoline, by contrast, stores 13, 000 Wh/kg. Although these two numbers are far from telling the entire technological story, they do point to the heart of the matter – electric cars do not have the performance features (in particular range and speed) thought necessary by today's consumer (Cowan et al., 1996a).*

Today the electric vehicle continues to sell but it has not been able to compete with the lock-in phenomena and technological advances of the petrol car (Cowan et al., 1996a). Since its introduction the electric car has gone through phases of uptake, as R&D investment and sales show. The performance of batteries is important but so is the cost. The battery in an electric vehicle can be anywhere from 20–70% of the total cost of an electric car. For this reason, the electric vehicle industry and members of the Electric Vehicle Initiative (with 15 member countries) invest more than half of their R&D expenditure into battery and fuel cell technology (Figure 5).



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[7] Cited by Cowan: Flink, J. J., America Adopts the Automobile: 1895-1910, Cambridge University Press, Cambridge, MA, 1970.

Figure 5: Breakdown of R&D spending in 2008–2012.
Source *(Clean Energy Ministerial et al., 2013)*

However, as electric vehicle batteries do improve and become more affordable, they may prove useful as energy generation and storage solutions for residential and off-grid consumers. That is, the electric vehicle car battery plugged into the network can act as a battery for the grid. During low periods of electricity demand the batteries can charge on low cost electricity and then sell the power back to the grid during peak demand time. Private electric vehicles could be programmed to discharge power during certain times of the day and provide extra storage for the grid when the vehicle is not in use. But it is difficult to predict if or when adoption of electric vehicles will reach a level that can help manage peak electricity demand (Wood et al., 2013).

2.2.4. The role of ICT in energy systems

Information and communications technology can transform existing infrastructure into a system that that can monitor, measure, analyse and communicate based on the data it captures from sensors and devices. An automated energy system has the potential to improve efficiencies, manage load and monitor peak usage periods. Information and communications technologies play a key role in the creation of a smart grid. Smart grids can integrate services along the whole supply chain, help to predict change, adapt to change and optimise operations. The smart grid will play an important role in the uptake of renewable energy and energy storage technologies.

ICT plays a role in different stages of a smart grid system:

- generation – portfolio management, predictive maintenance, adaptive generation and demand management
- transmission and distribution – monitoring of power flow, integration of distributed generation, predictive maintenance, energy data management
- retail – demand and response management, bundling of services, dynamic pricing
- consumers – smart meters supporting informed decision-making.

Further ICT developments will be important for improved forecasting, including forecasting of renewable output. Sophisticated machine learning techniques are used to forecast variable demand of the current network. Similar technologies are being developed to forecast the variable supply from wind and solar, whether large-scale energy farms, or distributed.

Installation of smart meters and other monitoring equipment can keep track of distributed energy and help provide reliable power. Smart meters provide accurate digital information to users to better manage electricity supply, demand, consumption and pricing. They have the potential to balance the traditional information asymmetry between electricity producers and consumers. Smart meters can also contribute to more effective pricing and billing, enabling more dynamic pricing than traditional meters (OECD, 2012).

Electricity providers will be able to monitor flow using smart meters and install intelligent switches at key locations to redirect power in case of local outages. These intelligent control systems also allow independent management of small regions of the grid (Howell, 2009, Technical University of Denmark, 2013). Table 3 illustrates how some information and communication technologies can contribute to challenges in the electricity network.

	application	technology
integrated and networked communications	real-time control information and data exchange improved reliability and security	distribution automation supervisory and data acquisition control energy management system wireless networks

sensors	evaluating congestion and grid stability, monitoring performance	smart meters that record electricity usage in real time high speed sensors to monitor the system real-time measurement tools real-time pricing tools
power generation and flow control	matching electricity production with demand control of power flow over transmission lines	power flow control devices embedded systems and software modelling and simulation
advanced control systems	rapid diagnosis of problems with the grid prediction of demand and supply	distributed intelligent systems software algorithms for analytical tools machine learning/AI programming computational mechanism design (for variable pricing)
interfaces and decision support	allow operators and managers to efficiently operate the grid with a number of variables	visualisation techniques technologies for big data software systems user interface apps

Table 3: Electricity sector challenges and potential ICT applications.
Partly sourced from: (OECD, 2012), wikipedia

An OECD report examining ICT policy implications for the smart grid recommends that governments facilitate innovation spillover from ICT to the energy sector and related industries such as transport, construction and telecommunications (OECD, 2012). To do this, government will need to support R&D and commercialisation, reduce entry barriers into the market and support cross-sector technology development. Other ICT-specific policy recommendations include:

- having open and transparent access of information for all stakeholders
- ensuring that communication channels are available across the entire economy as reliance on the communication network increases
- making open standards available for communication protocols, data exchange etc.
- safeguarding data privacy and security
- ensuring immediate skills needs are addressed through science, technology, engineering and mathematics education and training.

2.3. Evaluating energy storage technologies

When evaluating the costs and benefits of energy storage technology, it is important to consider where the technology will be applied in the energy system – in load levelling, for example, or uninterrupted power supply (see Figure 4). The range of problems faced by the electricity system will be solved using a combination of different energy storage technologies.

However, storage has remained too expensive to be justifiable for single-service usage, in most cases. As a result, advocates of energy storage and early adopters have taken an exhaustive approach to identifying the benefits of storage, listing dozens of benefits that energy storage may be able to provide to the electric system. Lists of such benefits have been relatively consistent in spirit, but the terminology and definitions have varied, and clear distinctions have been difficult to create. As a result, to perform high-fidelity analysis, care must be taken to ensure that benefits are distinct and *do not overlap. Additionally, although certain identified services and benefits could be compatible to combine and perform with a single energy storage system, others may compete with one another or be otherwise incompatible. Clear definitions of requirements, benefit calculations, and multiple use compatibility are critical for reliable, repeatable analysis (Carnegie et al., 2013).*

The remainder of this paper examines some of the many aspects of the energy system which need to be considered when attempting to deal with change and uncertainty in such a large and complex socio-technical system.

3. Change and uncertainty in the energy system

> *And we must continue to explore the whole systems approach so that the economic and environmental value of storage can be properly understood in the context of future low carbon energy systems, such that the lowest cost and lowest carbon system can be developed, and appropriate policy and market mechanisms put in place (Brandon, 2013).*

As a large technological system, the electricity system must be understood as a complex system of technologies embedded in a strong social context which includes both private and public institutions. This complex system develops through a path-dependent, co-evolutionary process involving positive feedback between technological infrastructures and the institutions that create, diffuse and employ them (Unruh, 2000). The electricity system experiences lock-in at several different stages: technical, social, company, institutional and public.

Technological lock-in refers to the idea that technologies and technological systems follow a set path that is difficult and costly to escape. Features of technological lock-in include sunken costs from earlier investments, vested interest, learning effects which reduce cost of products, reduced uncertainty in the market and network effects. Lock-in means that existing systems continue to be used even in the presence of potentially superior substitutes (Perkins, 2003). Modern technological systems can be deeply embedded in institutional structures that lead to lock-in. In turn, these circumstances can lead to the ‘lock-out’ of new technologies, which has happened with some renewable energy technologies. This type of lock out can force alternative technology producers out of the market or work as a barrier to the creation of new businesses (Unruh, 2000).

The electricity system is undergoing significant change. Some of the drivers of change include the ageing infrastructure, variable supply, variable peak loads and the demand for sustainable and reliable energy supply. The traditional model of large remote power stations, long transmissions lines and a distribution system designed to deliver power to end users is changing. As a result, the electricity industry will need to become more flexible and accept the changing relationships consumers have with energy. This will be a difficult transition for the electricity industry considering it has been entrenched in the same system for over a century. The modern electricity grid will require greater interaction between the consumer, public, industry and regulators (Harvey et al., 2013).

The electricity industry will respond to new drivers of change in different ways. Companies will need to adapt their business models to respond to changing technology and consumer preferences. In some cases electricity providers may take a minimal role and just maintain the network (poles and wires). Others may take responsibility for the full chain in the delivery of energy services to consumers.

Large providers will still be required to generate, transport and sell energy but they may have different channels to customers. New entrants to the market may include data services and content providers. Google has already entered the energy market. Traditional energy suppliers may become energy enablers. Third party brokers could be created, as has happened in health insurance with iSelect, for example, which helps consumers choose the best option for them (Stock, 2014). Companies such as Opower in the US connect electricity utilities with consumers. Using a cloud-based platform, big data and behavioural science they help utilities reduce energy consumption and improve their relationships with customers.[8]

Energy storage systems have become an important factor, and limitation, in the evolving electrical energy system. Storage technologies can provide greater flexibility to the grid and improve management of distribution networks, reduce costs and improve efficiencies. Energy storage systems will also allow the smart grid to manage interaction between different stakeholders and take advantage of the different benefits from different systems.

The following sections will examine how change and uncertainty can be managed in certain aspects of the energy system and how government and industry might set up conditions that will help overcome techno-institutional lock-in. Issues considered are pricing models and mechanisms, alternative grid stability options, the role of vested interest, market mechanisms and niche markets.

3.1. User pays?

How electricity is traded in Australia

The Australian Energy Market Operator manages trading in the national electricity market. It maintains a gross pool market where all electricity delivered to the market is traded 24 hours a day, 7 days a week. Wholesale trading in electricity is conducted as a spot market where supply and demand are instantaneously matched in real-time through a centrally coordinated dispatch process. Generators offer to supply the market with specific amounts of electricity at particular prices. The National Electricity Market stipulates the maximum spot price of $12,500 per MWh and a minimum of minus $1000 per MWh. This lower price allows generators to pay to stay online when the cost of staying online is lower than the cost of shutting down and restarting the energy plant. These extremes in price are only rarely reached – the annual average price over 12 months is around $40–50 per megawatt hour (eex.gov.au) (ESAA, 2014).

In Australia, 45% of the household electricity bill contributes to the use and maintenance of the network (wires and poles), not to the consumption of electricity (Figure 6).

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[8] See http://www.opower.com/company.

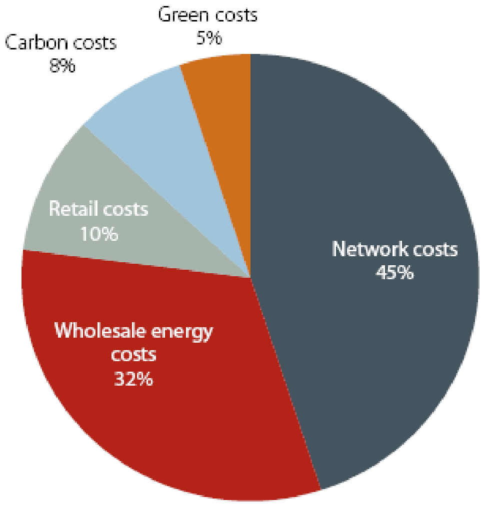

Figure 6: Breakdown of household electricity bill in Australia in 2012–2013.
Source: (AEMC, 2013)

The retail price of electricity paid by consumers in Australia is made up of two components:

1. A relatively small proportion of the bill is a fixed supply charge (cents/day).
2. A variable usage charge based on the volume of electricity consumed (cents/kWh).

The price to the consumer of an average unit of electricity is heavily weighted on the variable usage charge, that is, the amount of electricity taken from the grid. By contrast, most of the cost of supplying electricity to the customer (the cost of providing the electricity to the consumer via wires and poles) is fixed by the Australian Energy Regulator. This means that as customers begin to generate their own electricity and reduce the amount they pay to the electricity provider, they also contribute less to the maintenance of the network, even though they will continue to use the network as a back-up.

Affordability is critical to the adoption of renewable energy technology by consumers. The cost of solar PV units has been made more affordable by government subsidies and tariffs. This has ensured that early adopters are at an advantage, receiving financial support for the initial outlay required to purchase units. Figure 7 shows the electricity bill for two customers whose electricity consumption is the same. One of these, ‘Customer 1 (no DG)’, does not have a solar PV system; ‘Customer 1 (with DG)’ has a solar PV system generating some of their own electricity. Because most of the electricity bill is weighted to the amount of electricity taken from the energy provider, ‘Customer 1 (with DG)’ using solar PV pays less overall for their electricity bill. More importantly this customer pays less toward the network costs, even though the level of maintenance required is the same as that of ‘Customer (no DG)’ (ACIL Tasman, 2013).

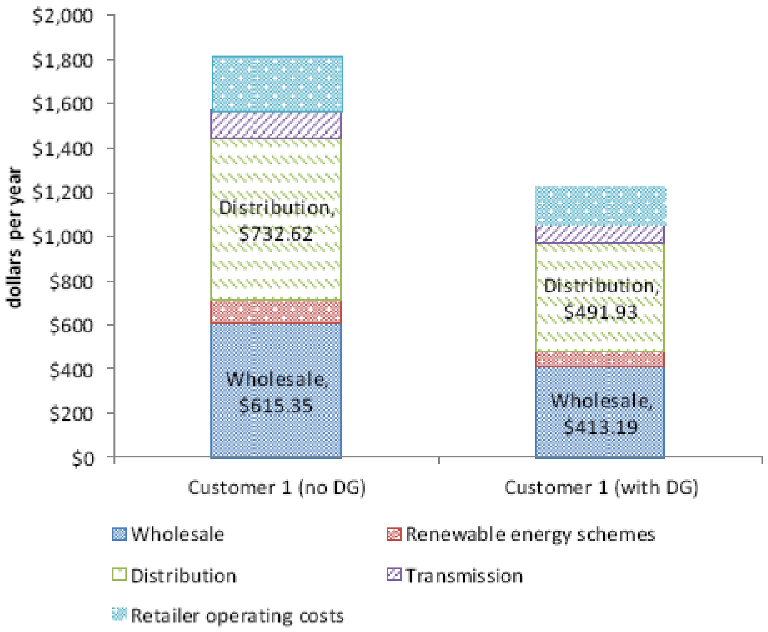

Figure 7: Retail electricity bill comparison with and without a solar PV system. Retail electricity bill comparison with and without a solar PV system. 'DG' (distributed generation) refers to household generation of electricity.
Source: (ACIL Tasman, 2013)

This results in shifting the burden of network cost to those who do not generate their own electricity. Under current policy settings in Australia there is little or no incentive to install distributed generation (self-generation of electricity) where it has the most network value. Instead, distributed generation continues to be scattered randomly, driven by individual household choice rather than where it benefits the network most (ACIL Tasman, 2013).

The largest electric utility in Arizona has been awarded the right to charge customers with rooftop solar panels a monthly fee of 70c/month/kW for maintenance costs. The utility has also requested permission to pay rates below market value, saying that the current structure creates an unfair cost shift to non-solar customers. The solar industry is concerned that a drop in rates and the additional maintenance charge will affect the economic viability of solar panels for their consumers (Assis, 2013).

The cost of connecting to the grid could be used as a mechanism to encourage or discourage connection. To more fairly share network costs, regulators may require residential consumers to pay a substantial connection fee for any access to the grid, but grid connection cost is a significant barrier for the renewable energy industry. If the goal is to develop the renewable energy industry, grid connection costs could be reduced. The current scheme in Australia sees a compromise between optimal resource location, grid quality and proximity, which means projects develop in suboptimal locations because regulation operates as a disincentive to connect to the grid (Byrnes et al., 2013).

Current pricing and tariff structures do not send accurate price signals to customers about the cost of using electricity. The *Power of Choice* report released by the Australian Energy Market Commission in 2012 looked at ways to facilitate 'demand side participation', which allows energy consumers to make decisions on the quantity and timing of their energy consumption that reflect their value of the supply and delivery of electricity. The report recommended

> *Arrangements for the market to provide prices that better reflect the costs of supply and delivery of electricity services; potential for cost reflective prices to promote consumer uptake of demand side participation; and arrangements for vulnerable consumers, where required (AEMC, 2012).*

In 2013, the Queensland government released a 30 year electricity strategy to address changes in the electricity supply system. One of its main thrusts is a move to reform existing business models and regulation by taking into consideration customer preferences, competition, innovation, accurate pricing of electricity to provide clear price signals for consumption and product innovation, and building in flexibility to deal with changes in the energy network (Department of Energy and Water Supply, 2013).

Do users ever pay the true cost of using infrastructure?[9]

There is great benefit in comparing costing issues with a larger class of problems. The transmission and distribution system of the electricity system can be seen to be analogous to the role of the roads themselves in the road transport system. Do users of roads pay their 'fair share' of the cost of the roads?

Evaluating road wear caused by vehicles is challenging. Many factors that need to be considered including the composition of the road, type of suspension, number and type of axles. Engineers use the concept of an 'equivalent single-axle load' to assess the effects of heavy vehicles on the road. It is said that heavy vehicles cause most road wear and damage. The traditional method to calculate road damage is the 'fourth power law'. That is, the effect on the road of a 12 tonne single-axle truck compared with a 1.5 tonne car would be $(12/1.5)^4$. In effect, this means that a 12 tonne truck will cause 4,096 times more damage to the road than a 1.5 tonne car (Leduc, 2009). In NSW it costs approx. $422/annum to register a car. If the registration fee was used solely to cover road wear then a 12 tonne single-axle truck should in theory cost $1,728,512 a year. Heavy vehicle registration fees in NSW range from $500 to $10,000 depending on truck type, weight and number of axles.[10] http://www.rms.nsw.gov.au/roads/registration/fees/index.html

3.2. Feed-in tariffs and schemes

Feed-in tariffs have encouraged uptake of renewable energy technologies such as rooftop solar PV panels. A substantial part of the benefit to using a solar PV system comes from avoiding the contribution to the network services cost (ACIL Tasman, 2013). This leaves those who cannot afford to become early adopters at a disadvantage, including those who rent properties and are unable to add solar PV systems to their buildings.

Feed-in-tariffs that have been used to encourage uptake of renewables are funded by higher electricity charges passed to all customers, including those in lower socio-economic demographics and those who cannot afford to generate their own electricity (Sommerfeld et al., 2014). The value of feed-in tariffs is still up for debate. One analysis of Australia's solar feed-in tariffs found that lower income households do not adopt solar PV. Wealthier households benefit from the tariffs and the effective taxation rate for low-income households is three times higher. The study concluded the Australian government should investigate alternative options to feed-in tariffs (Nelson et al., 2011).

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[9] Setting the price to use an infrastructure that is too costly to duplicate is an old and well–known theoretical problem in economics. It was at first addressed one hundred and fifty years ago by a French economist, Jules Dupuit (1849), for calculating bridge tolls. In economic jargon, the conundrum designates the problem of tariff–setting applied to a natural monopoly. It raised a long controversy in the first half of the twentieth century between theorists. Some were advocating pricing at marginal cost in association with a public subsidy whereas others were supporting average cost pricing to make the users pay for the full costs of the infrastructure. Railways rather than bridges were then at the core of the economists' thinking. After 1950, the optimal pricing analysis of natural monopolies was extended to other infrastructures, such as urban roads, airports or local telecommunication networks. The case of the electricity grid is one of the last to have been studied. In fact, it is only at the end of the 1980s that the optimal transmission tariff was theoretically solved by Schweppe *et al.* (1988). Francois Levaque, *Transport pricing of electricity networks*, Introduction (page xvii) (Leveque, 2003).

[10] http://www.rms.nsw.gov.au/roads/registration/fees/index.html

A subsequent study found the highest solar penetration rates are typically in rural and regional communities or the outer metropolitan mortgage belt. Solar is particularly popular among retirees and in low- to middle-income suburbs (Clean Energy Council, 2014).

3.3. Vested interest

Vested interest is often blamed for the lock-out of new products and businesses and is perceived to be a mechanism deliberately used by incumbents, but it can influence all players in the system. Supporters of the incumbent energy industry seek to defend their position through messages of stability, reliability and low cost. For example, the homepage of *Australians for Coal* states:

> *Australian coal employs almost 200,000 people and is worth $60 billion to the national economy. Take action to support Australian coal.*
>
> *Coal underpins Australia's reliable and historically cheap electricity supply. Low cost, reliable energy has been the cornerstone of Australia's economic growth and high living standards for several decades.*
>
> *Your electricity bill is being driven up by powerful groups trying to shut the coal industry down. If you are concerned about your electricity bill, please support the Australian coal industry.*

Supporters of the renewable energy industry trying to break through the market appeal to politicians and the public using messages based on mistrust of large companies, job creation and cost. For example, from the homepage of GetUp!:

> *The Big 3 power companies are using their might to wreck renewables. Only a large public outcry, especially from their customers and shareholders, will stop them.*
>
> *The impact of the Big Three's plans would be devastating for consumers, job creation and the cost of your energy bills, while they reap windfall profits as power prices soar. It's selfish and short-sighted business with no care for their customers or the economy. With the Renewable Energy Target under review right now, we need to shift the game — and quickly.*
>
> *The dirty energy companies know that every single name on this petition is a potential customer lost. Please share it widely and let us know if you're a customer or shareholder.*

And concerned citizens will draw attention to unknowns that exist with any technology change and diffusion. For example, from the home page of Stop Smart Meters Australia:

> *Smart meters can be hacked!*
> *A smart meter cost blowout threatens to add up to $520 more to many power bills.*
> *Electrosensitivity – has society lost its moral compass?*

Interest groups play an important role in the entire vested interest structure, but other factors in addition to the existence of interest groups and lobbying of politicians also make it difficult to effect change in well established systems of users, makers, producers, distributors and governments. In a study comparing the structural change and vested interest at play in the uptake of wind power by Norway and Denmark, author Espen Moe found five key indicators of a nation that will favour vested interest and be less likely to overcome techno-institutional lock-in:

- Human capital (know-how) required to exploit change will not exist i.e. there exists more human capital in the incumbent sector.
- Entrepreneurship is not supported at an institutional level.
- There exists a preference for cost effectiveness which automatically benefits more mature technologies and industries.

- There is a lack of a social mandate from the public: politicians are risk-averse and will not make change without wider public support.
- Existence of active vested interest groups.

Old industries and the structures around them can unwittingly obstruct new entrants into the market, through the social, structural, legal and political forces in existence. The longer an industry is in existence and the more the country depends on one or a few industrial clusters, the greater their dominance and impact. Moe's paper concludes:

> *Governments who insist on neutrality with respect to new industries are bound to keep favoring the existing actors. For structural change, policy must be implemented to counter neutrality and to provide new industries with proper growth conditions. Norway has ended up with a structure favoring neutrality, Denmark has not. (Moe, 2012)*

3.4. Picking a technology winner

By choosing to regulate via a market rather than seek to prescribe which technology is the best, regulators allow for unforseen innovation. Economist Paul David argues that public policy should work to counteract any premature commitment to one particular product or technical standard before there is enough learnt about potential effects and applications of that particular technology (David, 2007).

Governments that wish to reduce the chance of prematurely locking in to a technology that may prove suboptimal should implement policies that support a wide range of solutions and recognise that innovation is inherently risky and that failures outnumber successes. Experimentation is critical. Creating an environment that supports experimentation is critical.

Reports by the Grattan Institute on energy policy suggest that the best strategy in the face of uncertainty is to support a variety of options. Over time this will be the cheapest way to use the most appropriate technologies and get the best results. As illustrated in the previous section, industry tends to find innovative and affordable ways to solve problems. Governments that legislate for an ultimate end goal (e.g. putting a price on pollution) allow businesses to determine for themselves how to achieve that goal. This approach minimises the need for government to predict the future and it provides businesses with certainty and flexibility (Daley et al., 2011).

> *There is no reason to believe that government has any special ability to foresee these developments and yet all government decisions about which technologies are eligible for support, and to support particular projects implicitly makes choices about technologies. (Wood et al., 2012)*

Similarly, in its 30 year plan to deal with the changing electricity network, the Queensland government has proposed the following strategies:

> Not picking 'technology winners', instead allowing the market to determine the best options i.e. not creating incentives for specific technologies and removing regulatory barriers for the emergence of new generation technologies. Ensuring there is diversity in energy source options by removing regulatory prohibitions that impede the development of some technologies.
>
> Not investing in new energy generation whilst the market continues to deliver sufficient capacity, this will allow the market to operate commercially. The government will set the test for market failure at a high level. Government intervention would not necessarily be through direct investment but will be determined by the market (Department of Energy and Water Supply, 2013).

Any new technological infrastructure or policy regime should not be seen as *the* solution but just another step in the development path. Any interventions, legislative and regulatory structures, models and market mechanisms must support flexibility in order to deal with the ever present change and uncertainty that exist in any system. Modelling, simulation and scenarios can be useful tools to help governments manage uncertainty of technological change. These tools can permit governments to assess which system or options perform best under changing conditions, thus choosing the more flexible policies (Wilson et al., 2011a).

The crucial point to be made here is that in some cases government policy can directly favour incumbents (by picking technology winners), or indirectly favour incumbents by sheer neglect of alternative technologies. Aiming for technology neutrality can result in maintaining the status quo which in effect will favour incumbents (refer to quote by Moe in Section 3.3 Vested interest).

3.5. Niche markets

In their paper *Escaping lock-in: the case of the electric vehicle*, Cowan and Hulten list six events that need to occur to overcome existing lock-in: a crisis in the incumbent technology, regulation, technological breakthrough, changes in taste, creation of a niche market, and/or scientific evidence (Cowan et al., 1996a). Empirical studies show it takes a substantial performance improvement to induce a transition to a new technology. The need for an order of magnitude improvement arises due to inertia created by technological lock-in and vested interests. New technologies often come from niche and entrepreneurial entrants, not those incumbent in the dominant design market. Niches markets are an attractive policy target. Dominant designers are not interested in defending niches thus removing some of the potential barriers (Christensen, 2010).

> *Legislation may create niche markets, and if there is variety in the niches, which is likely to be the case if legislation is aggressive enough, technical advances will be promoted. This has two effects. The first is simply that costs will fall, especially when accompanied by the benefits from scale in production. The second is more subtle. As the technology advances in a variety of directions, more and more consumers will be willing to forego what appeared to be 'necessary' features of the automobile (as defined by the gasoline car) in order to have access to the new features of the electric car. This type of effect will be crucial in creating the snowball that gives the electric car a chance to establish itself as a significant part of the automobile market(Cowan et al., 1996a).*

When a new technology is introduced into the market, performance can dominate economics as the driver of technology change. New energy technologies are attractive because they can perform a particular task or deliver a new or improved service. Costs fall substantially after an extended period of testing, learning and other improvements. Widespread adaption follows a period of experimentation where the technology is tested, refined and adapted. Niche markets play an important role here (Wilson et al., 2011a).

3.6. Market mechanisms

Widespread deployment of energy storage technologies will rely heavily on cost. There is a great deal of support to allow demand and supply in the market to determine prices and diffusion. The International Energy Agency (IEA) recommends that governments avoid policies that mandate storage technologies but instead allow the market to drive uptake. However to create a market driven push, the IEA notes more work needs to be done on the lack of price transparency, high upfront investment costs and significant price distortions in current energy markets (IEA, 2014).

A report prepared by Energy Retailers Association of Australia outlines how retailers could lead a rollout of smart metering in Australia without the need for government intervention, while operating in a competitive market and maintaining customer choice. The smart meter provides consumers and energy suppliers with up to date and accurate data on electricity usage, and can help provide reliable power. Instead of mandating them, as Victoria has attempted to do, the Electricity Authority of New Zealand ensured there was open third-party access to metering services and that there were no barriers to competition or access to information. In this instance, the role of government is to ensure that appropriate legislative and regulatory structures are in place to support the market-driven rollout of smart meters by retailers. If consumers are willing to have their meters upgraded in order to access better products, the political risk to governments is minimised (ERAA).

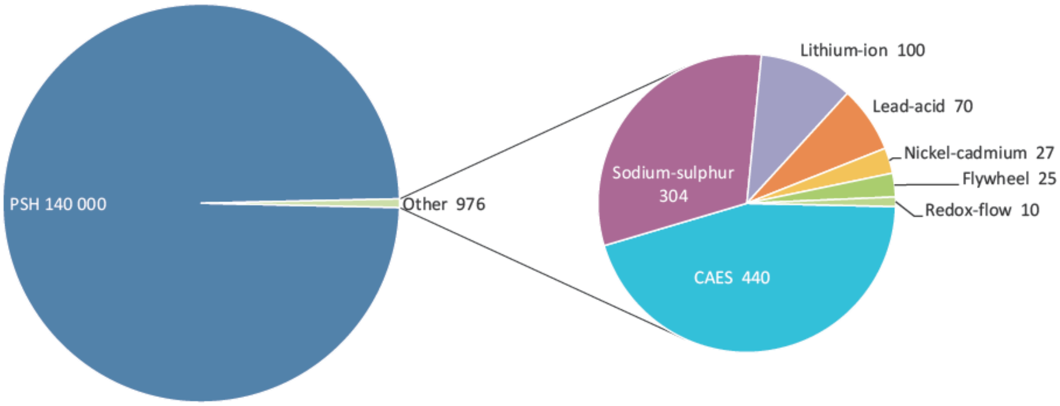
By choosing to regulate via the market instead of prescribing the best technology, governments and regulators can allow for unforseen innovations and problems can be solved more cheaply than originally expected. This is neatly illustrated in the emissions trading scheme implemented by the US Environment Protection Agency in the 1990s, when the government announced its intention to reduce sulphur dioxide emissions by ten million tons per year by 2010.

> *At root, what the emissions allowance market is doing, like any other competitive market, is generating information. It reveals how to reduce pollution in the lowest-cost way, as well as what the costs of reducing pollution actually are.*
> *The prices of the allowances surprised most observers, being far lower than expected. The surprise came because command and control had left everyone (except perhaps the polluters themselves) with a distorted impression of these costs. Before emissions trading began, the EPA estimated it would cost $750 to clean up a ton of sulphur dioxide. The electric-power firms claimed it would cost them up to $1500. The average price at which the allowances actually traded over 1994–1999 was about $150.*
> *(McMillan, 2002)*

3.7. Timescales

It is possible to escape lock-in of pervasive and complex systems. Past examples include the transition from whale oil to gas to electric lighting; from vacuum tube to transistor to integrated circuit; from canals to trains to trucking transportation of goods; and from fixed phone to the wireless phone (Unruh, 2002). These transitions require change in technology, government, legal and regulatory structures which can take decades to achieve.

Currently over 99.3% of the global installed energy storage capacity on the grid uses pumped storage hydroelectricity, Figure 8.



Source: IEA analysis and EPRI (Electric Power Research Institute) (2010), "Electrical Energy Storage Technology Options", Report, EPRI, Palo Alto, California.

Figure 8: Current global installed grid-connected electricity storage capacity MW. Source: (IEA, 2014)

> *Perhaps the most misunderstood aspect of energy transitions is their speed. Substituting one form of energy for another takes a long time. U.S. nuclear generation began to deliver 10 percent of all electricity after 23 years of operation, and it took 38 years to reach a 20 percent share, which occurred in 1995. It has stayed around that mark ever since. Electricity generation by natural gas turbines took 45 years to reach 20 percent.*
> *(Smil, 2012).*

Energy transitions at a global scale are generally quite slow. It takes 80 to 130 years for new technologies to achieve market dominance, and twice as long when considering the entire technology lifecycle from invention to market maturity. The ability for individual technologies to transform large and complex energy systems is due to combinations of interrelated technologies and spillover of applications to areas for which they were not originally intended (Smil, 2012).

It will take substantial improvements in alternative technologies and many decades to change the institutional dimensions in the system to make a change when incumbent technologies are so well established (IEA, 2014). Improved performance of energy technology capacity may take many decades (Figure 11).

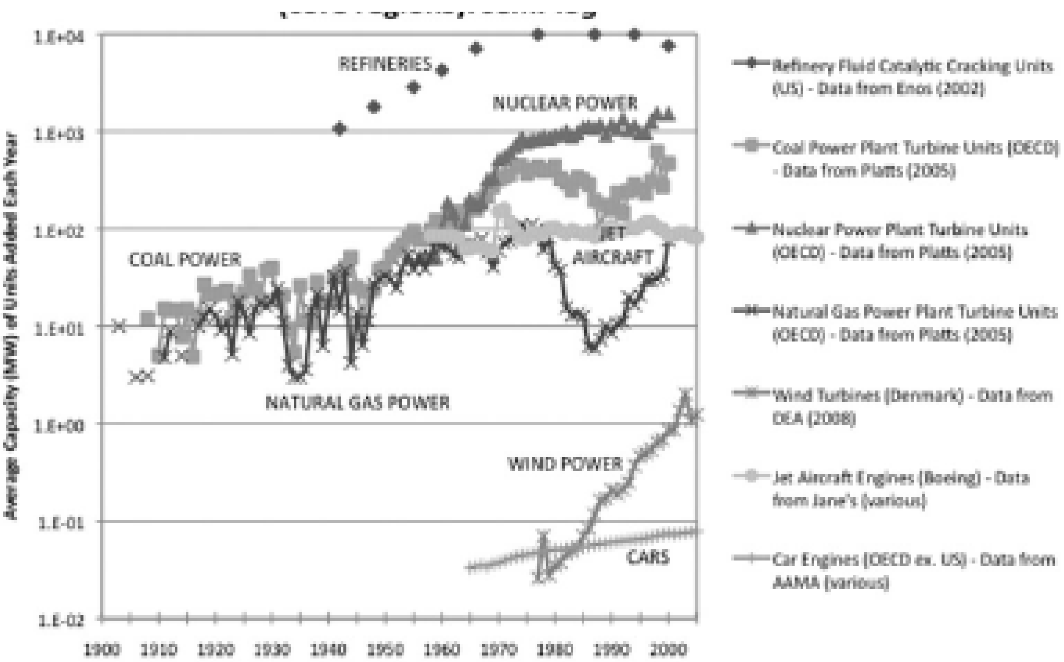


Figure 11: Growth in average unit capacities of selected energy technologies since 1900: semi-log scale. Each line describes the changes over time of the average capacity in MW of newly installed 'units': steam turbine units in coal, gas and nuclear power plants; wind turbines in wind farms; jet engines in passenger aircraft; internal combustion engines in cars; and compact fluorescent light bulbs in lighting systems. Source: (Wilson et al., 2011b).

Examining interventions that have helped to overcome the lock-out of renewable energy technologies may be useful in understanding how to facilitate the uptake of other technologies (such as energy storage) in the electricity grid. We know of barriers to the renewable energy innovation system in:

- competing with well-established infrastructure and systems. Accessibility and integration into existing infrastructure controlled by incumbents.
- providing the support required to move technologies along the innovation chain to commercialisation
- securing financial support, assuring the certainty of emerging markets, minimising high initial costs
- learning from failed innovations
- training and skills of industry workers
- managing patents for small companies and universities
- having stable and consistent policy (Foxon et al., 2005) (Rio et al., 2007).

Appendix 1: What problems are we trying to solve?

It is commonly argued that

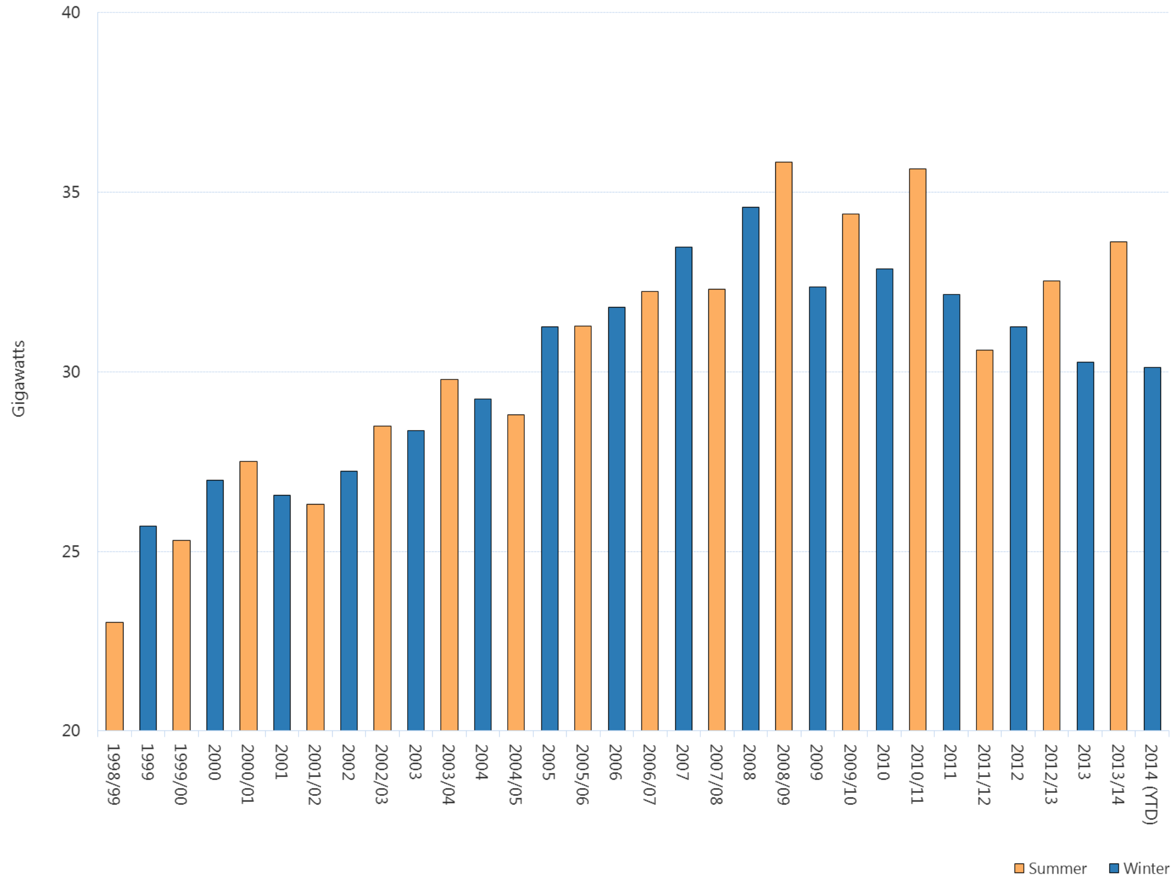
- peak demand is rising and there is an urgent need to build more infrastructure in the existing system to meet that demand
- the increased penetration of (variable) renewable energy sources threatens grid stability.

This section summarises two studies that challenge those claims.

3.7.1. Consumption and peak demand

The level of peak demand determines the required capacity of generation, transmission and distribution systems. Several years ago the year-on-year growth of peak demand was higher than the year-on-year growth in total energy consumption. As a result the electricity industry expected to see continued growth in peak demand and made plans to increase capacity and invest more in the electricity infrastructure. Because 45% of an electricity bill is attributed to network costs, the high level of investment in poles and wires led to a large increase in electricity bills.

In Australia, residential electricity consumption has actually been falling over the past four years. Perhaps what is less well known is that summer and peak demand have also fallen since 2008/2009, Figure 9.



Source: AER; AEMO, Last updated: 7 August 2014 - 2:44pm

Figure 9: Electricity consumption in Australia from 1998 to 2014, showing a decline since 2009. Source: https://www.aer.gov.au/node/9766

This drop in electricity consumption has been attributed to milder summer weather, growth in rooftop solar PV, increased uptake of solar water heating and reduced output from the manufacturing industry. In his *Power Down* report, Hugh Saddler examines the evidence to support these arguments and a number of other possible explanatory factors. The report finds three main factors contributing to the recent dramatic changes in demand for electricity and suggests which of those factors will most likely affect future levels of consumption:

4. **the impact of regulatory energy efficiency programs**. Since the late 1990s, Australia has implemented energy performance standards on a range of residential and commercial appliances and energy efficiency requirements for new buildings. It is likely that if existing programs continue, their contribution to reducing electricity demand will continue to grow.
5. **the partial and complete shutdown of some energy-intensive industries**. Between October 2011 and September 2012, three major industrial electricity users – the Port Kembla steelworks, the Kurri Kurri aluminium smelter and the Clyde oil refinery – were partially or completely shut down. The lack of growth in the electricity-intensive sector will contribute to decreased demand for electricity.
6. **the response of electricity consumers to increasing electricity prices.** This has manifested itself in several ways, including the growth of household solar PV and behavioural changes in electricity consumption through using energy efficient appliances, switching off appliances, and increased use of solar hot water. Consumers will be unlikely to move back to inefficient appliances even if electricity prices drop. If prices remain high, changes in electricity consuming behaviour will probably be sustained but this is not guaranteed (Saddler, 2013).

The report found no evidence to support the argument that declining consumption has been caused by consistently milder seasonal weather in either summer or winter. While changes in weather clearly contribute to changes in demand from year to year, changing weather does not explain the steady decrease in electricity demand. The *Power Down* report concludes

> *Although growth in consumption may resume in the next few years, it will then continue at much lower annual rates than those that prevailed for more than a century up to about 2004 (Saddler, 2013).*

3.7.2. Grid stability

Grid stability is measured by the number of minutes without power caused by unplanned outages in a given year. IEEE magazine reported a study released by Germany's grid regulator that revealed no sign of growing instability of the grid despite Germany's high usage of renewable energy sources Figure 10.

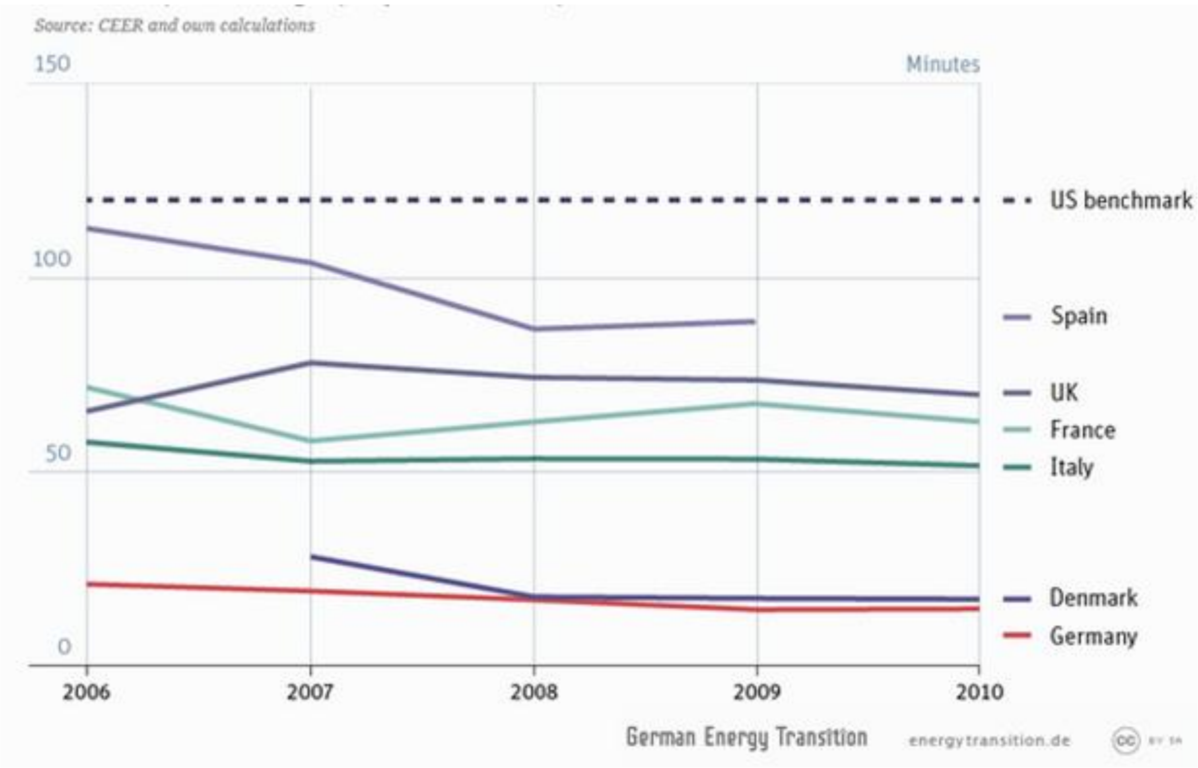


Figure 10: Grid reliability from 2006-2010 in Spain, UK, France, Italy, Denmark and Germany. Reliability is measured by the number of minutes without power caused by unplanned outages in a given year.
Source: (Fairley, 2014)

One of the key reasons suggested for grid reliability in Germany and other nations with well performing renewable energy systems is that most of the lines in the distribution network are located underground (Fairley, 2014). Underground lines are protected from external elements and are found to suffer a third the amount of outages experienced by overhead lines (Silverstein, 2012). This implies that the reliability of the grid does not solely rely on the energy source and that there are other solutions available to ensure a reliable and stable grid.

It is important for policymakers, regulators and industry to better understand the fundamental problems within the electricity system (within any system). These may not always be the most prevalent – what appears to be a problem with increasing demand and unreliable supply may actually be a problem of managing variability. For example, summer peak demand is at its highest when solar energy is likely to be at its highest too. This suggests that the summer peak can be met using a renewable energy source such as solar. The way a problem is understood will affect what is measured, how the measurement is interpreted and the approach taken to solve the problem. These two studies show a range of technical and non-technical solutions for managing supply and demand. Understanding the real problem and regulating accordingly will allow the best solutions to emerge.

Appendix 2: Prioritised activities to advance energy storage technologies

In 2010, a number of US organisations contributed to a workshop that sought to accelerate the commercialisation of stationary energy storage for the energy grid. The workshop focused on the research and development of advanced materials and devices which would result in more cost-effective, efficient and reliable technologies that could contribute to long term solutions. The participants prioritised activities required to advance certain energy storage technologies, Table 4.

	near term (<5 years)	mid term (5–10 years)	long term (10–20 years)
advanced lead acid and lead carbon batteries	Conduct DOE-funded validation tests of system lifetime, ramp rates, etc. Develop high-power/energy carbon electrode for lead-carbon battery	Understand poor materials utilisation through diagnostics and modelling	
lithium ion batteries		Develop models for ion transport through solids (inorganic solids, polymers) Conduct experiments to develop a quantitative understanding of catastrophic cell failure and degradation Design and fabricate novel electrode architectures to include electrolyte access to redox active material and short ion and electron diffusion paths (e.g. non-planar geometries) Develop a highly conductive, inorganic, solid-state conductor for solid-state Li-ion batteries	Develop new intercalation compounds with low cycling strain and fatigue; aim for 10,000 cycles at 80% depth of discharge
sodium based batteries	Develop robust planar electrolytes to reduce stack size and resistance Implement pilot-scale testing of battery systems to develop performance parameters for grid applications	Decrease operating temperature, preferably to ambient temperature	Develop a true sodium-air battery that provides the highest value in almost any category of performance. Use surface-science techniques to identify species on sodium-ion anodes and cathodes
flow batteries	Establish a centre for stack design and manufacturing methods, including joint and seal design Develop low-cost,	Improve membranes to enable minimum crossover, lower system cost, increased stability, and reduced resistance Improve mass transport via	Develop non-aqueous flow battery systems with wider cell-operating voltages to improve efficiency

	formable, chemically and thermally tolerant resins for piping, stacks, and tanks Develop an inline, real-time sensor that can detect impurities in electrolyte composition for various flow battery chemistries Create a computational fluidics centre at a national laboratory or university Identify low-cost hydrogen suppression materials (anti-catalysts) and redox catalysts for negative electrodes	a tailored catalyst layer and flow field configurations to increase operating current density and reduce system cost per kilowatt	
power technologies	Develop a 1-megawatt flywheel motor capable of vacuum operation and superconduction Develop high-power/energy carbon electrode for electrochemical capacitors	Optimise materials utilisation through diagnostics and modelling Develop hubless flywheel rotor with four times higher energy	
emerging technologies		Improve thermal management in endothermic electrolysis reactions and exothermic fuel cell reactions in regenerative fuel cells	Develop new catalysts for metal-air batteries with low overpotentials for oxygen reduction in order to make systems more efficient, cost-effective, and bifunctional Explore the untapped potential of multivalent chemistries Develop air electrodes for metal-air batteries with high electrochemical activity and lower polarisation and resistance

Table 4: Activities required to advance certain energy storage technologies Source (Lichtner et al., 2010)

Appendix 3: Examples of energy storage facilities in Australia

As reported in http://www.energystorageexchange.org/projects

project name	**technology type category**	**rated power in kw**	**duration at rated power hh:mm**	**status**
Ausgrid SGSC – 40 RedFlow Systems	electrochemical	200	2:0.00	decommissioned
Ausgrid SGSC – 20 RedFlow Systems	electrochemical	100	2:0.00	decommissioned
Redflow, University of Queensland M90	electrochemical	90	2:0.00	decommissioned
Tumut Hydroelectric Power Station 3	pumped hydro	1500000	0:0.00	operational
Wivenhoe Power Station	pumped hydro	500,000	10:0.00	operational
Kangaroo Valley Pumping and Power Station	pumped hydro	160,000	0:0.00	operational
Bendeela Pumping and Power Station	pumped hydro	80,000	0:0.00	operational
King Island Renewable Energy Integration Project (UltraBattery)	electrochemical	3000	0:32.00	operational
Hampton Wind Park	electrochemical	1000	0:30.00	operational
Cape Barren Island Hybrid System	electrochemical	163	1:0.00	operational
Global Change Institute M120	electrochemical	120	2:30.00	operational
Coral Bay PowerStore Flywheel Project	flywheel	500	0:0.60	operational
Marble Bar PowerStore Flywheel Project	flywheel	500	0:0.60	operational
Leinster Nickel Operation PowerStore Flywheel	flywheel	1000	0:0.60	decommissioned
Poatina Power Station	pumped hydro	300,000	0:0.00	operational
Tods Corner Power Station	pumped hydro	1700	0:0.00	operational
Lake Cargelligo Solar Tower	thermal storage	3,000	24:0.00	operational
UTS (University of Technology) Sydney	electrochemical	25	2:0.00	under construction
CSIRO, ZBB Experimental Zinc-Bromide Flow Battery	electrochemical	100	5:0.00	decommissioned
Magellan GPSS – SWR	electrochemical	25	4:0.00	operational
Jemalong Solar Thermal Station	thermal storage	1100	0:0.00	under construction
TransGrid iDemand	electrochemical	100	4:0.00	under construction
Ausgrid SGSC – ZEN 60kW BESS	electrochemical	60	2:0.00	decommissioned
Kind Island Renewable Energy Expansion VRB	electrochemical	200	4:0.00	offline/under repair

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