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Energy Storage

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Executive Summary

Energy storage can take many forms but this chapter addresses energy storage mechanisms that are capable of absorbing and storing energy via a reversible process, prior to then converting the majority of that stored energy into electrical energy.

The role and importance of energy storage is changing with the introduction of renewable energy generation such as wind and solar photovoltaics, whose output is inherently variable. This increasing generation variability has created a need for energy storage to provide energy balancing, something that will become increasingly vital as the percentage of renewable generation in power systems globally increases over the decades ahead.

This chapter discusses the different requirements for energy balancing within renewable-based power systems over various timescales, including long- (weeks to seasonal), medium- (hours to days) and short-term (seconds to minutes) ones. The requirements for balancing services across these differing timescales will be met by different forms of energy storage, highlighting the need for a portfolio of energy storage mechanisms and technologies.

Energy storage also provides other benefits for operating modern power systems. For example, energy storage can provide network services for maintaining networks within voltage and thermal limits, underpin resilience to contingency events occurring within power systems (for example when a generator or transmission line unexpectedly fails) and provide black start capabilities when generation needs to be restarted from rest.

This chapter discusses a multitude of energy storage mechanisms that include pumped storage hydro (PSH) systems and various forms of battery storage, as well as other forms of energy storage with varying levels of technical and commercial maturity.

An important issue explored within this chapter is the integration of energy storage into electricity grids. It is noted that there is significant experience to support the integration of PSH systems, although work remains to be done to determine the best ways to integrate battery storage, which can offer a range of benefits.

This chapter also reviews social research related to energy storage uptake, noting that equity and sustainability issues are important in the transition to new energy systems.

Finally, the chapter presents an outlook for energy storage where it is noted that the uptake of energy storage globally is on track to meet the International Energy Agency's

Sustainable Development Scenario. The outlook also emphasises the importance of better understanding how to robustly calculate the levelised cost of storage in order to allow comparisons with levelised cost of energy generation metrics.

7.1 Introduction

Energy storage is widely regarded as one of the key elements, or perhaps *the* key element, required to enable successful operation of secure, reliable and resilient electrical power systems in a future with increasingly high and very high levels of variable renewable and distributed energy generation. Highly controllable energy storage technologies are capable of providing various power system balancing and management functions. Such storage technologies can provide balancing between available and required power on timescales ranging from milliseconds to days. These have hitherto been largely provided by high-capacity-factor synchronous generators with their inherent operating characteristics. Without these balancing and management functions, electrical power systems are generally unable to maintain a reliable supply of energy when and where it is needed, while also maintaining dynamic stability or system security. A suite of energy storage technologies can be deployed to meet these functional power system needs.

In the context of electrical power systems, we define an energy storage system as one that is capable of absorbing and storing energy over some period of time via a reversible process, prior to then converting the majority of that stored energy into electrical energy that can, in a controllable manner, be injected into an electrical power system. We consider energy storage systems those that convert either electrical energy or some other form of input energy into an energy storage medium. However, we exclude energy storage systems that are incapable of converting stored energy back into electrical energy. We make this definition based on the utility of the storage technology in providing services necessary for the operation of electrical power systems. Thus, we do, for example, consider thermal storage supplied directly by a heat source that is used primarily to generate electrical energy, but we exclude from our consideration any thermal storage supplied directly via consumption of electrical energy but which is subsequently only used to service non-electrical loads. We recognise the potential benefits of these latter technologies (for example, hot water systems and building space heating/cooling) in helping to balance and manage electricity networks and the power system. Nonetheless, we argue that these are best considered alongside other flexible and controllable loads which also provide demand response capabilities. For similar reasons, we also exclude from our consideration various other forms of energy storage that may be encountered in everyday life (storage of energy-rich liquid fuels or gas for example) but which are not, generally speaking, readily available via a bidirectional energy storage system.

In this chapter, we first outline the current state of energy storage deployed in power systems today, highlighting key global energy storage projects. We go on to describe the various balancing and management functions that are required by the power system, before describing individual energy storage technologies and capabilities in greater detail. Subsequently, we provide perspectives on the integration of energy storage into the grid,

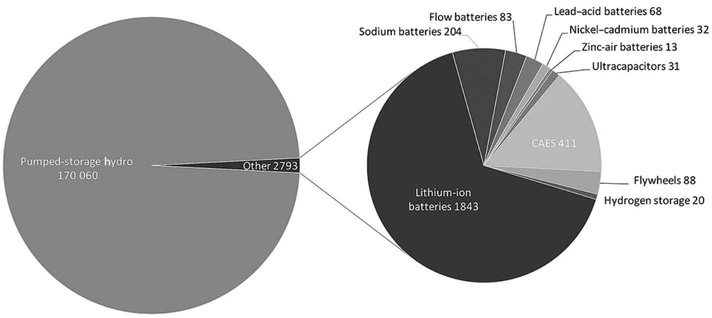

Figure 7.1 Overwhelmingly, energy storage installed in global electricity grids is provided by PSH. Total global installed grid-scale energy storage capacity (power capacity, megawatts (MW)) by technology type.[1]

Source: US DOE (n.d.). For a colour version of this figure, please see the colour plate section.

including the social implications of integrating energy storage. We conclude this chapter with a brief summary of the future outlook for energy storage.

In our assessment, and based on the status and availability of storage technologies today, we expect a mix of distributed and central battery storage, pumped hydro and possibly some other currently less-developed storage technologies, to contribute significantly to the balancing and management of electrical power systems in the long term as we make the transition to systems based largely on variable renewable generation. In particular:

- Pumped hydro technology will be used for the provision of inertia, primary frequency response and secondary spinning reserve, medium-term energy balancing, voltage stability and black start capabilities.
- Battery storage will provide very fast dynamic primary frequency response, secondary response (or spinning reserve) services, short-term and medium-term energy balancing, as well as local demand and generator smoothing, network voltage management, as well as facilitating grid forming for islanded or microgrid operations.

Overwhelmingly the most significant form of energy storage installed in global power systems today is pumped storage hydro (PSH). After the first decade of the twenty-first century, PSH represented over 99% of all installed energy storage globally (IEA 2014), a dominance which continues today. The prominence of PSH in electricity systems to date has arisen due to its long history of development (Barbour et al. 2016), and because of its ability to manage diurnal load variations in power systems comprising generators with limited flexibility (Rogner and Troja 2018). In the decade to 2020, installed energy storage capacity has continued to grow; PSH has still dominated new capacity additions, but is accompanied by a growing share of alternative and emerging energy storage technologies (see Figure 7.1).

At the start of 2020, the global power capacity of grid-scale reversible electricity storage is estimated to be 173 GW (gigawatts). A definitive source of data on global energy storage

[1] Flywheel storage capacity does not include grid-connected installations that store energy via flywheels for the dedicated purpose of generating high-energy pulses in fusion research facilities.

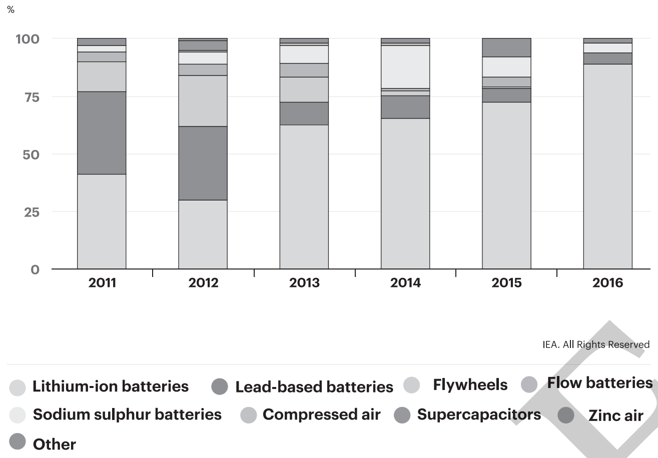

Figure 7.2 For non-PSH storage, battery storage will dominate the growth of energy storage capacity over the years ahead.
Source: IEA (2019b). For a colour version of this figure, please see the colour plate section.

capacity does not readily exist, particularly given the proliferation of small-scale systems. Our figures are based on the US Department of Energy Global Energy Storage Database (US DOE n.d.), which is widely accepted as a reliable source of up-to-date information on grid-scale operational storage projects, but which does not reflect behind-the-meter storage and likely also underrepresents small battery storage systems. This total storage capacity is equivalent to approximately 2.5% of the world's total electricity generation capacity (IRENA 2019). The share of grid-scale reversible storage capacity held by PSH has declined to around 98%, or to less than approximately 95% of global energy storage capacity if behind-the-meter storage and solar thermal storage are also included.

The decline in PSH's dominance is set to continue, with the rise of non-PSH storage technologies, most notably lithium-ion batteries. The reported 2018 annual deployment of non-PSH storage, for example, nearly doubled from 2017, with over half of this newly installed capacity being located behind the meter (IEA 2019b). The vast majority of behind-the-meter storage installed to date, which is generally accompanied by on-site solar photovoltaics, has also been based on lithium-ion batteries (Zinaman et al. 2020). This trend towards lithium-ion technology being the dominant or almost sole non-PSH storage technology being deployed, illustrated in Figure 7.2, is being driven primarily by the declining costs of lithium battery technology, owing to the continuing scale-up in manufacturing of batteries for electric vehicles (EVs) (IEA 2019b).

While the global install base for battery storage is growing, it is important to realise that battery storage, particularly lithium battery storage, is starting from a relatively small install base. By way of example, in 2017 the Hornsdale Power Reserve (HPR) was installed in Australia (Neoen 2017) and at the time of commissioning was the world's largest lithium battery, with a capacity of 100 MW (megawatts)/129 MWh (megawatt-hours). This single installation represented approximately 10% of all lithium battery storage installed globally by 2017 (Robson and Bonomi 2018; US DOE n.d.).

Battery storage in the grid will also increase through global uptake of EVs. In 2018, another 1.98 million EVs were sold, increasing the global EV footprint to 5.12 million (IEA 2019a). While much of this energy storage is not accessible for power system participation or support, this is likely to change from 2019 as vehicle-to-grid (V2G) capable EVs start being manufactured globally.

7.2 Key Global Energy Storage Projects

Given the increasing importance of energy storage in supporting energy security, reliability and resilience, it is instructive to understand some of the key energy storage projects already operating and under development globally. In recent years, the addition of new storage capacity has included major innovative projects using both PSH and battery storage technologies.

7.2.1 Australia

Perhaps the most prominent example of a utility-scale battery system was the 2017 installation of the Hornsdale Power Reserve (HPR) – or, colloquially, the 'Tesla Big Battery' – in South Australia. At the time of installation, this was the world's largest lithium battery installation (Neoen 2017).

The HPR provides a total of 129 MWh of energy storage, and is rated for 100 MW discharge and 80 MW charge (Australian Energy Market Operator 2018a). The HPR development has been notable for several reasons, but perhaps most importantly it has demonstrated the opportunities for battery storage to participate in markets for energy and ancillary services, contributing directly to supporting energy reliability and energy security in the Australian National Electricity Market (NEM) in:

- energy arbitrage;
- reserve energy capacity;
- network loading control ancillary services; and
- frequency control ancillary services.

Crucially, the participation of the HPR in the NEM has been profitable for its operators (Parkinson 2019), demonstrating the commercial opportunities for deploying battery storage and supporting the case for the wider deployment of these battery storage capabilities around Australia, and in similar jurisdictions globally.

Alongside the HPR, Australia is notable for its uptake and demonstration of virtual power plant capabilities through several projects and initiatives. Virtual power plants are widely considered to be an important capability for harnessing the uptake of residential battery storage systems for participation in markets for energy, ancillary services and network services (Australian Energy Market Operator 2018b).

In addition to battery storage projects, several major PSH developments are also well under way in Australia. Most notably, the pumped hydro Snowy Scheme expansion

('Snowy 2.0') will see 2 GW of new generation and pumping capacity added to the existing generation capacity, designed primarily to store energy generated from the solar- and wind-resource-rich regions in south-eastern Australia and then supply this energy to major load centres on the east coast as required (Snowy Hydro 2019). A closely related project is under development by Hydro Tasmania, this time designed to exploit the wind-resource-rich coastal regions of Tasmania and to utilise the existing and potential high-voltage DC interconnects to the major south-eastern Australian load centres. This project, or group of projects, is commonly being referred to as the 'Battery of the Nation Project', and includes proposals for projects amounting to multi-gigawatts of new capacity (Hydro Tasmania 2018).

7.2.2 USA

While the HPR is colloquially referred to as the 'Tesla Big Battery', it will shortly no longer be the biggest Tesla or Lithium battery in the world, after the announcement of several projects with the Pacific Gas and Electric utility in California (California Public Utilities Commission 2018). These projects, which will replace existing gas generation power plants, will add over 2 GWh of energy storage across four individual installations. Installations under way in California continue to demonstrate the leading role that this US state has taken in supporting the uptake of renewable generation and energy storage.

In California, the California Public Utilities Commission (CPUC) is also a global leader in driving the development and uptake of standards for the connection and integration of distributed and residential energy and battery storage capabilities through their Rule 21 activities (California Public Utilities Commission n.d.). Through driving the adoption of international standards and guiding implementation (Sunspec Alliance 2016), it is hoped that manufacturers of energy storage, as well as their customers, will be better placed to take advantage of the benefits of the interconnection and integration of energy and battery storage systems in global electricity systems.

7.2.3 Asia

Korea continues to be a leading light in the deployment of grid-scale and behind-the-meter installations, contributing to one-third of installed global storage capacity in 2018 (IEA 2019b). This leading role is largely attributed to favourable policy measures and is no doubt assisted by the leading global role of Korean industry in driving the development and manufacturing of battery storage capabilities.

China is also contributing to the uptake of energy storage in Asia, providing an important global demonstration of alternatives to lithium-based batteries, with a significant deployment of vanadium flow batteries in Dalian, China (Weaver 2017). Deployment of vanadium storage technology is an important demonstration of this technology's maturation since it was first developed at the University of New South Wales, Australia, in 1985. China is also home to the recently commissioned Liyang Pumped Storage Power Station

(US DOE n.d.). The power station has a generation capacity of 1500 MW, provided by six 250-MW reversible Francis pump-turbines.

In recent years, China has added significant new PSH capacity into their power system, in an effort to add the required flexibility to the country's power system. China is currently responsible for more than half of all PSH capacity additions globally, with this trend expected to continue for some years to come (IEA 2019d). Recent PSH projects include the Shenzhen Pumped Storage Power Station, a 1200-MW facility perhaps most notable for being constructed only 20 km from the centre of a major metropolitan city (Guangdong Hydropower Planning and Design Institute 2013).

7.2.4 Europe

From the European perspective, Germany is one of the global leaders in the uptake and integration of residential battery systems into power systems. Uptake is being driven by incentives, tariffs and technology availability (Colthorpe 2018). However, Europe is also interesting due to the diversity of energy storage capabilities that have been, and are being, deployed. In addition to having one of only two compressed air energy storage systems (CAESs) (Crotogino et al. 2001) globally, Europe is also home to the Andasol solar power station – a concentrated solar power station with capacity of 150 MW (NREL n.d.).

Europe has arguably also led the way in the deployment of advanced technology pumped hydro plants with the recently completed Linth–Limmern hydro storage plant, consisting of variable-speed pump/turbine sets with a total capacity of 1450 MW (Keller 2016), along with a number of other new facilities being developed elsewhere in Europe.

The variability in uptake of storage technologies in different countries provides insights into the importance of taking a socio-techno-economic perspective when analysing storage uptake and deployment globally.

7.3 The Role of Energy Storage Systems in Renewables-Based Power Systems

Electricity systems and markets have been designed to solve the fundamental problem of ensuring that the supply and demand of energy is in equilibrium. To achieve this outcome, the electricity system must ensure that supply meets demand at all times throughout the geographic area that is covered by the electricity system.

To satisfy this requirement, power systems generally operate on a generating unit dispatch basis. A power system operator will forecast electricity demand over a forward horizon of dispatch intervals for each major region of the system and, based on the available generating units, determine the optimal dispatch required to meet that demand at least cost (which in many cases is determined by the related operation of an energy market). Such a system works well provided that there are, at each dispatch interval, a sufficient number of dispatchable generating units available. Conventional generators, such as thermal, gas and hydro, may inherently be operated to provide at least some degree of schedulability, and are thus well suited to dispatch in this manner. In power systems dominated by conventional generators there is generally no need, at power systems level at least, for the participation of energy storage assets.

Owing to an improved understanding of the impacts of climate change and the required response to reduce fossil fuel use, communities and governments globally are increasingly looking to reduce the carbon intensity of electricity production. This desire, coupled with the improving economics of renewable generation (Graham et al. 2018), sees the long-term trend for energy generation as being towards large amounts of renewable generation. These renewable energy generation sources are covered in detail in other chapters in this book.

The characteristics of renewable generation units are quite different to the fossil-fuel-fired generating units described above. Chief among these differences is the fact that they are not dispatchable or schedulable, instead providing an output which is highly dependent upon the raw power resource (the sun or the wind), which is itself variable. While solar and wind resource forecasting is improving considerably (Blaga et al. 2018; Sobri et al. 2018; Liu et al. 2019), there will always be some inherent variability of output across the timescales of power system operation.

Hence, with increasing levels of variable renewable generation in power systems, there will be an increasing need to manage increased generation variability. Energy storage that is capable of being operated across the timescales of power system operation will therefore ensure both energy reliability and security.

In order to frame the various energy storage technologies in terms of their roles in providing energy system balancing, it is important to consider the energy versus power characteristics of particular storage capabilities, as well as considering the various timescales on which energy storage is needed in the power system.

7.3.1 Storage Capacity: Energy Versus Power

When considering energy storage capabilities, it is always necessary to carefully consider two key dimensions: energy and power. Energy capacity is a measure of the total amount of energy (MWh) that can be stored or can be delivered in one complete cycle by an energy storage system. Power capacity is the maximum rate of energy delivery (MW) to/from an energy storage system. Energy storage is often also referred to in terms of number of 'hours' of storage. This is simply the energy capacity divided by the power capacity, and hence 'hours' refers to the period of time that the system is able to operate at nominal or maximum power. Power capacity and energy capacity requirements are usually determined by the particular application for which a system is needed, but may also be limited by design constraints.

7.3.2 Long-Term (Weeks to Seasonal) Energy Balancing

Long-term storage may be required in a power system, or a region of a power system, when either electricity demand or generation (supply) has significant dependence upon seasonal climate patterns or strong weather variations within the year, and where the other modes of generation are unable to compensate for such variations.

Power systems have generally been designed to handle this long-term and seasonal variability in demand by ensuring an over-capacity in generation that is able to respond on long timescales and is backed by appropriate energy storage. This type of long-term energy storage is typically achieved by maintaining large water storage reservoirs in conventional hydropower facilities (as is the case in countries such as Norway and regions such as Tasmania, Australia) and/or by stockpiling fuel (or otherwise guaranteeing fuel supply) used by thermal power generation facilities.

However, as power systems become increasingly dominated by solar and wind generation, and hence contain relatively less conventional generation, variations in supply will occur seasonally or on a timescale of weeks, owing primarily to seasonal variations in solar and wind resources. In such cases, new long-term storage capacity will be required. The quantity of long-term storage required in such cases will depend upon factors such as technology and geographical diversity of the generation fleet, so a probabilistic approach will generally be needed. Storage designed to cover long-term energy balancing needs will require a very large energy capacity to power capacity ratio.

7.3.3 Medium-Term (Hours to Days) Energy Balancing

Perhaps the most immediate and obvious need for energy storage in the power system is to balance energy supply and demand on a medium-term timescale of hours to days. Electricity demand exhibits a quite strong diurnal pattern, with typically low demand overnight, higher demand during daytime hours and, for many regions, a particularly high demand in the morning and evening shoulder periods (see Figure 7.3). Furthermore, generation from solar is inherently diurnal in nature, while wind generation exhibits similar diurnal variation in many locations (Mulder 2014).

The net result of such diurnal variability in solar and wind generation can be that rapid and considerable variations in power generation are required from remaining generators in the system. In a system with a high proportion of solar and wind generation capacity, the net demand variations and associated ramping requirements can exceed the technical capabilities of other generating plants. In such cases, it becomes critical to incorporate storage that is capable of reducing net demand variations and ramping requirements over these medium-term timescales.

The level of medium-term storage capacity required in a system is largely dictated by the scarcity or surplus of supply of energy from the generation portfolio across the day. A large proportion of new energy storage being deployed presently is essentially targeting this need, and is being installed in power systems with high levels of variable renewable generation. Market drivers are generally supporting these deployments: diurnal wholesale energy price variations incentivising utility-scale energy storage projects, and retail tariff arrangements (e.g. time-of-use pricing and import/export tariff differentials) incentivising behind-the-meter small-scale storage deployment.

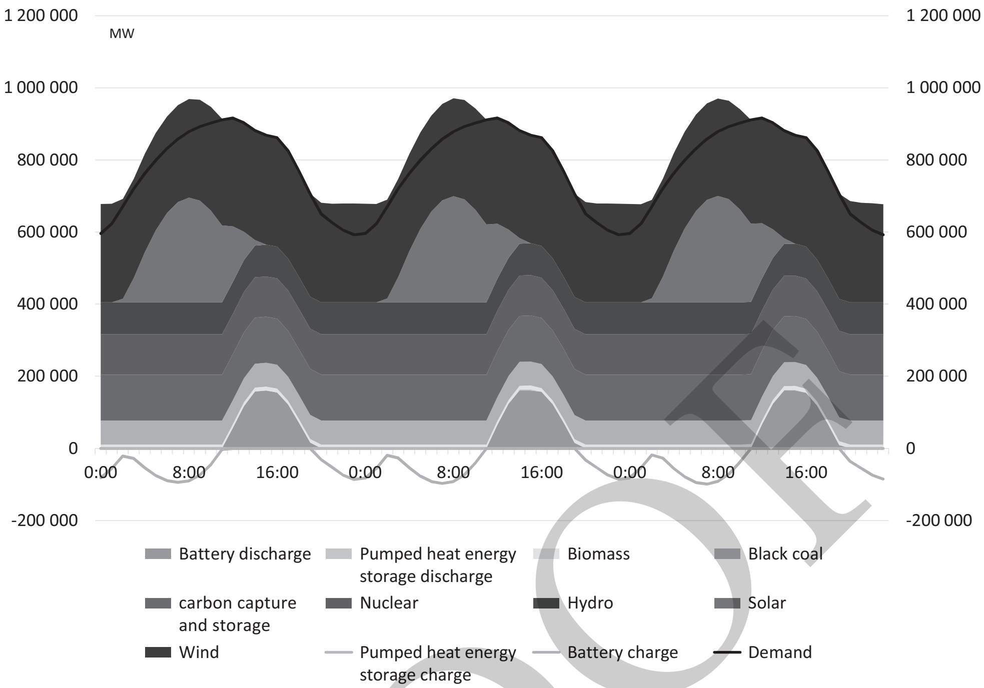

Figure 7.3 An example energy demand profile and generation mix from the North American region during spring, showing the diurnal energy storage cycle that provides medium-term energy balancing.

Source: Graham et al. (2018). For a colour version of this figure, please see the colour plate section.

7.3.4 Short-Term (Seconds to Minutes) Energy Balancing

The balance between supply and demand in a power system must be carefully maintained on all timescales, but it is arguably the short (seconds to minutes) timescale that can be the most challenging to manage, particularly as conventional generating units exit the system and are replaced by variable renewable generators. As with other timescales, demand fluctuation constantly occurs on short timescales. However, the most significant imbalance between supply and demand is when a so-called contingency event occurs, when either a large load or large generating unit is unexpectedly disconnected from the power system. After such an event, the supply and demand balance must be restored within a matter of seconds, to avoid partial or full system blackout. With insufficient time to bring new generating units online, existing generators (at least some of them) must immediately increase or decrease their power output until balance is restored.

In power systems with decreasing levels of generation sourced from synchronous generators and increasing levels of renewable generation, there is both less system inertia and also fewer generators capable of providing conventional primary frequency response. New energy storage technologies will play a critical role in providing the necessary system security functionality in future power systems by operating on this short timescale. Battery storage in particular has already demonstrated the ability of energy storage to provide near-to-instantaneous response to contingency events in the Australian grid (Australian Energy Market Operator 2018a).

7.3.5 Network Services Provision

From the previous discussion, it is clear that energy storage is able to provide energy balancing needs at the whole-of-power-system level. However, with distributed energy and battery storage becoming increasingly prevalent in distribution networks, energy storage will also be available for use by network operators to manage constraints (power flow and voltage limits) in distribution networks. Through technical regulation or economic incentives, network operators will be able to use energy storage to reduce peak reverse power flow and voltage rise on networks during periods of high coincident solar generation, and limit peak demand and voltage drop on networks when there is high demand.

7.4 Pumped Storage Hydro

As detailed previously, PSH is currently the dominant form of worldwide energy storage. Pumped storage hydro relies upon established technology and is able to provide a broad range of support services for the electricity grid. Conceptually, it is very simple to understand: water is pumped up a height difference to an upper reservoir when there is excess energy-generating capacity available (i.e. when energy costs are low) and is subsequently released to a lower reservoir, via turbine and generator to produce power, when demand (and hence cost) is high. Typically, in the order of 80% of the electrical energy required to provide pumping is returned to the electrical power system during generation, although the power loss is highly dependent upon the specific generator/pump configuration and the hydraulic design. Either the upper or lower reservoir may form part of a conventional hydropower scheme, or alternatively, they may both be purpose-built for a dedicated pumped hydro system. The basic physics of hydro storage dictates that energy storage capacity increases linearly with height difference (head) between the top surface of the upper reservoir and the turbine/pump, and thus sites with a large height difference are generally favoured and are cheaper on a stored energy capacity basis. A schematic of a PSH system is shown in Figure 7.4, and Figure 7.5 shows the 1.77-GW La Muela plant in Spain'

7.4.1 A Changing Role for PSH

Pumped storage hydro systems were first built in the early twentieth century, with the majority of schemes built in the 1960s and 1970s (Rogner and Troja 2018). The main driver for establishing these plants was to accommodate diurnal demand variations when the supply side was dominated by large, inflexible thermal generating units designed for operation at a relatively constant output. In particular, the units are unable to operate below a lower limit and hence there emerged a need to create a 'baseload'. A large number of such

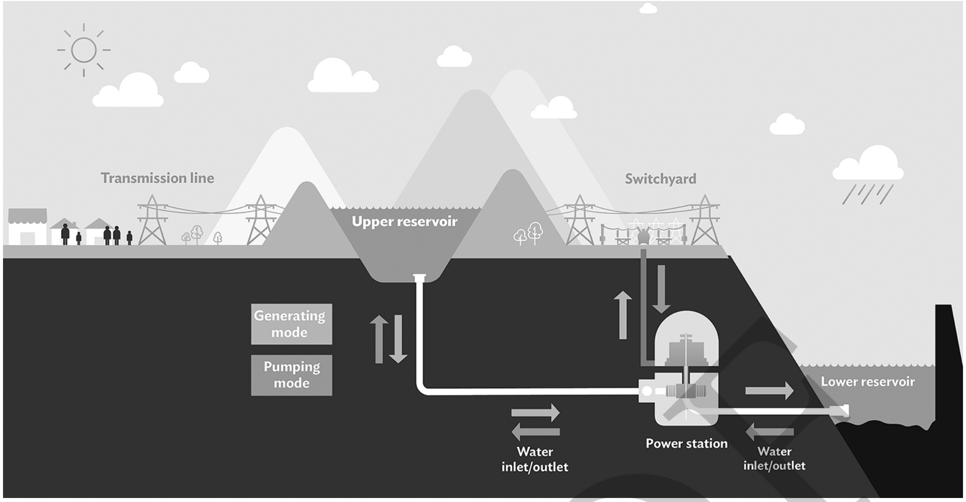

Figure 7.4 Pumped storage hydro schematic.
Source: Hydro Tasmania. For a colour version of this figure, please see the colour plate section.

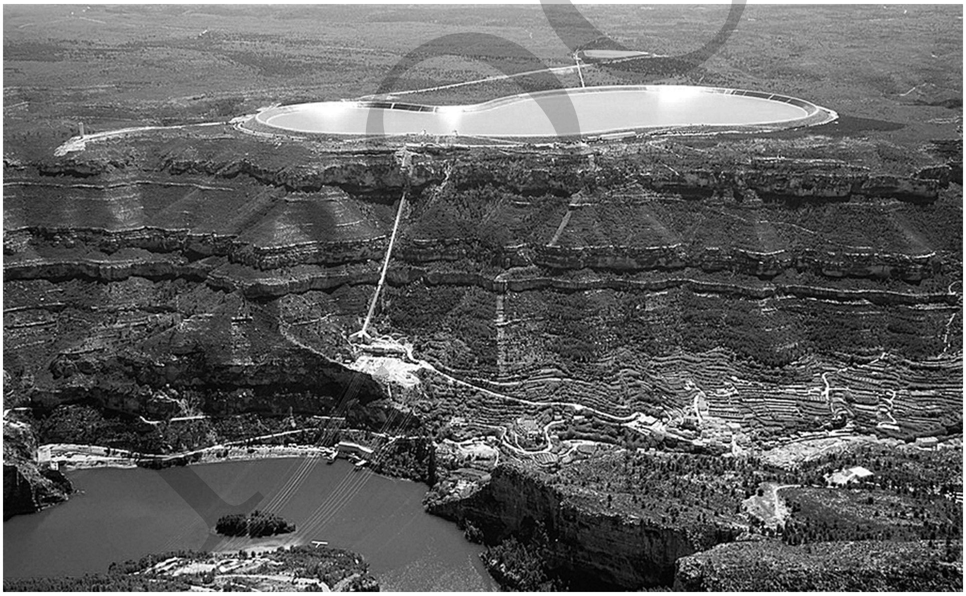

Figure 7.5 The 1.77-GW La Muela plant constructed in Spain in 2013.
Source: Patel (2013); reproduced with permission of Iberdrola.

plants were built to coincide with the development of large nuclear power stations. Pumping generally occurred overnight when demand was low, with generation occurring during peak demand periods during the day.

The recent growth in variable renewable generation has led to a resurgence of interest in PSH. However, the key drivers for deployment have changed significantly since the majority of PSH was deployed over the previous several decades. Newly deployed PSH plants are built to store energy at various times of the day when supply from variable renewable generators is plentiful, and discharge at periods where demand is high and/or renewable generation output is low. The use case for PSH is changing significantly, with the need for more frequent cycling, highly variable power consumption or production during pumping and generating modes, and energy balancing on a wider range of timescales. Importantly, despite PSH being well established and demonstrated over many decades, the specific technologies deployed and the way they need to be operated is changing markedly to suit these evolving needs.

7.4.2 PSH System Components

Pumped hydro plants can be constructed to be configured in a number of different ways, the details of which significantly alter the flexibility they offer the power system and variety of other system services they can provide. Pumped storage systems consist of four basic components:

- upper reservoir;
- lower reservoir;
- water conveyance system; and
- powerhouse, including turbine/pump and electric machine set.

The design of the upper reservoir and/or lower reservoir, and the height difference between them, dictates the energy storage capacity of pumped hydro. The size and capacity of the water conveyance system (tunnels and penstocks) and of the pump/turbine and machine dictate the power capacity.

For PSH plants built specifically for bidirectional energy flow, one or both reservoirs will typically be a relatively small 'turkey's nest'-type dam, with water depth in the order of 10–20 m. An example of such a reservoir is at Taum Sauk pumped hydro facility (Rogers et al. n.d.), shown in Figure 7.6. The second reservoir may be similarly constructed, or alternatively may be a much larger reservoir created by natural topology and conventional dam construction. Pumped storage hydro systems may be closed-loop, with no inflows at either reservoir, or open-loop, having natural inflows at one reservoir. Although new conventional hydro developments may not be possible now in many locations in the world, numerous sites for off-river PSH have been identified around the world (Blakers et al. n.d.). In many cases, existing conventional hydropower facilities can be retrofitted with pumped storage capabilities, by building either a new upper or lower reservoir (dependent upon existing topology). However, an entirely new powerhouse is usually required in either scenario, since pump/turbine sets in pumped hydro facilities are required to be situated at a sufficient depth below the intake/outlet of both reservoirs, which is not typically the case for conventional hydro plants. The powerhouse is normally situated below ground for this reason, with its specific contents (combination of pump/turbine and electric motor/generator) determining the type of operation and energy balancing functionality it can provide.

Figure 7.6 Construction during 2009 of the upper reservoir at Taum Sauk pumped storage facility, Missouri USA.
Source: KTrimble (2009).

7.4.3 Pump/Turbine Configurations and Implications

The functionality and flexibility that a PSH facility can provide depends upon the hydraulic design and the configuration of the pump/turbine and electric machines. Pumped storage hydro generating units can be categorised into four types:

- reversible pump/turbine with fixed-speed electric machine;
- reversible pump/turbine with variable-speed electric machine;
- separate pump and turbine, each with fixed- (or variable-) speed electric machine;
- combined pump and turbine (ternary set) with single fixed-speed electric machine.

Reversible Francis-type pump/turbines are able to be operated in generating mode at a fixed speed, and produce a wide range of power outputs. This is the normal mode of operation of a conventional hydropower generating unit, utilising a synchronous machine for power generation. In this mode of operation, a fixed-speed pumped hydro unit provides inertia to the power system and can (within the limitations of the hydraulic design, distance between reservoirs and penstock length) rapidly vary its output (in the order of 1% per second). Thus, it can provide short-term energy balancing functionality, including primary frequency response. In pumping mode, the plant similarly provides system inertia but is essentially restricted, owing to pump efficiency limitations, to operation at near to full power. Hence, this type of unit would not have the ability to ramp up and down for energy balancing purposes. To change operation from generating to pumping mode, this type of unit must first be desynchronised from the power system, brought to a halt, have its direction reversed and then be brought up to speed before synchronising with the power system again. A similar process is required to change the other way: from pumping to turbining mode. This changeover may take in the order of 2–6 minutes (Kruger 2018), depending upon specific system design, with start-up from standstill occupying a similar duration. This reversible, fixed-speed configuration is the cheapest option available (West et al. 2018) and is quite well suited to medium-term energy balancing, but does not provide all of the flexibility needed to manage under a highly fluctuating supply/demand balance on short timescales. Indeed, at times when there is high instantaneous penetration of wind and solar generation in a power system, when pumping operation is most likely, this configuration does not inherently provide the desired flexibility of operation unless operated concurrently with other energy balancing systems. The overwhelming majority of existing pumped storage plants are based on this reversible, fixed-speed configuration.

One way to overcome the major limitation of fixed-speed pumping systems just outlined is to replace fixed-speed synchronous machines with asynchronous machines coupled to the power system via a power electronics converter. A reversible pump/turbine with variable-speed machine is able to provide full flexibility in both generating and pumping modes. The required variable-speed functionality can be achieved by employing either a synchronous machine with full-power electronics converter interface or a doubly-fed induction machine with partial power electronics convertor. This solution is estimated to increase total project cost by 10% compared to using fixed-speed machines (West et al. 2018). Despite this additional cost, it is almost certainly preferable in situations where a high degree of short-term energy balancing is required. Despite their advantages, variable-speed pumped hydro units provide no inertia to the power system, whether in generating or pumping mode, thus exposing the system to larger and faster system frequency deviations in the absence of other mitigating technologies. Changeover time (from generator to pumping, or vice versa) is of similar order in this case to that for fixed-speed machines. Many of the recently constructed pumped storage plants, deployed in systems with high variable renewable generation content, are based on this variable-speed technology.

The limitations, in pumping mode, of using a single reversible turbine with synchronous/fixed-speed electric machine can be overcome by having more operating machines, thereby creating a system with a separate pump and turbine. Flexibility in pumping mode, the ability to quickly ramp power consumption up or down, is achieved by fixed power pumping from one set and simultaneous variable generation from another, as illustrated in Figure 7.7. With appropriate sizing of pumping and generating units, changeover from generation to consumption or vice versa can be quick and seamless since there is no reversal of machine direction required. In addition, net generation is controlled by varying the generating unit output in the same way as is done for conventional hydro generating units. This mode of operation can be quite easily achieved in a large pumped hydro facility containing multiple units. However, losses will increase significantly for this mode of operation, and the total available power capacity (generation or load) of the facility will also be reduced significantly during periods where such flexibility is being provided.

The final configuration being considered by pumped storage proponents, though not yet commonly deployed, combines the turbine and pump into one integrated set that is driven by a single electric machine. This is known as a ternary set, and is usually accompanied by a hydraulic short circuit, as shown in Figure 7.8. The pump and turbine are both coupled to

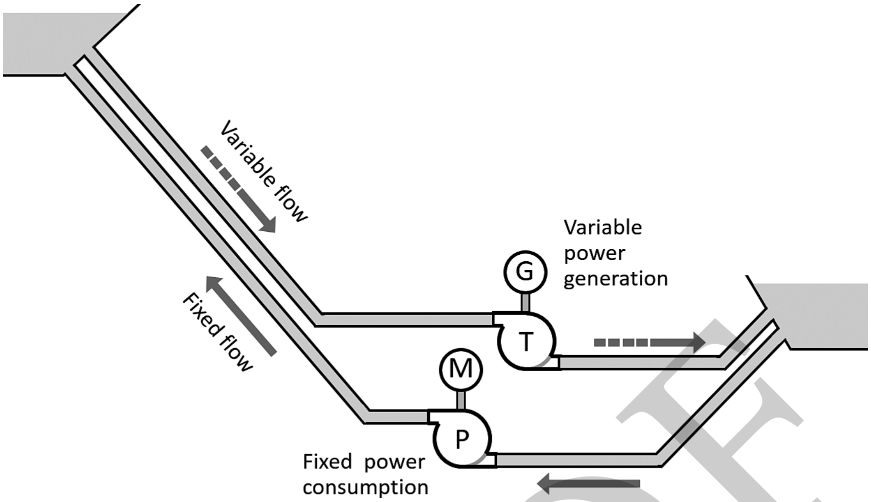

Figure 7.7 Flexibility during pumping mode can be created in PSH plants using synchronous machines, by running some units in pumping mode and others in flexible, generating mode.

Source: Courtesy of Evan Franklin.

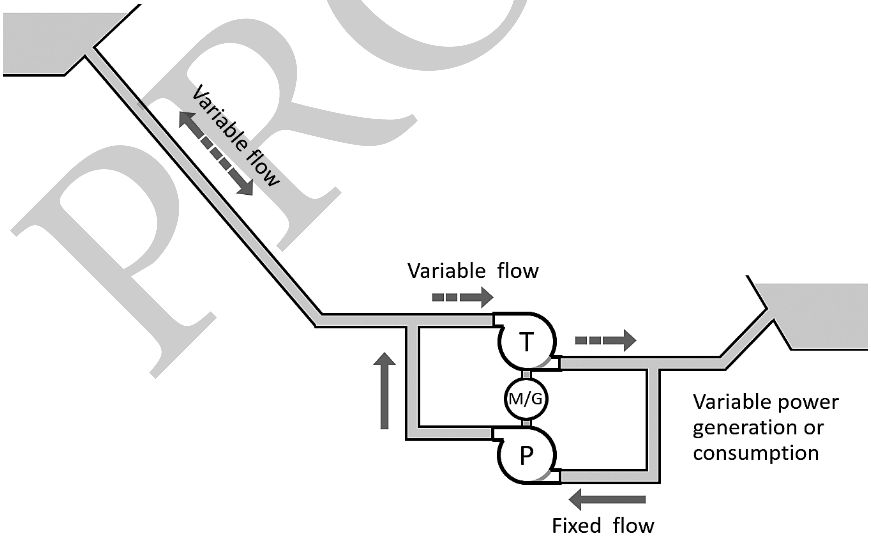

Figure 7.8 Ternary sets, utilising a single synchronous machine with integrated pump and turbine and a hydraulic short circuit, afford maximum flexibility and seamless changeover from pumping to turbining mode.

Source: Courtesy of Evan Franklin. For a colour version of this figure, please see the colour plate section.

Table 7.1. *Key features of different PSH plant pump/turbine configurations*

Pump/turbine	Electric machine	Key features
Reversible pump/turbine	Fixed-speed (synchronous)	Lowest cost Provides system inertia No flexibility in pumping mode Long changeover time Suited for medium-term balancing
Reversible pump/turbine	Variable-speed and power electronics	Increased total cost Provides no system inertia Full flexibility in pumping mode Long changeover time Suited for short-term and medium-term balancing
Separate pump and turbine	Two fixed-speed machines (synchronous)	Provides system inertia Flexibility in pumping mode Short changeover time Significantly higher losses Suited to existing facilities, but total plant capacity reduction Suited for short-term and medium-term balancing
Ternary set (combined pump/turbine)	Single fixed-speed machine (synchronous)	Moderate cost increase Provides system inertia Flexibility in pumping mode Some higher losses Short changeover time Suited for short-term and medium-term balancing

the (usually synchronous speed) machine, and either can be run individually or both can be run simultaneously. As is the case for completely separate sets, the turbine can be run as needed to provide flexibility during pumping mode. Fast changeover between modes of operation is facilitated by this arrangement. A ternary set allows for flexible operation over the almost full power range in both pumping and generating modes. Employing ternary sets is estimated to add 15% to total project costs, compared to fixed-speed reversible pump/turbine design (West et al. 2018).

A summary of these key pumped storage pump/turbine-machine set configurations and characteristics are provided in Table 7.1.

7.5 Battery Storage

Battery storage is based upon the storage of energy in chemical bonds that can be released via a chemical reaction and directly converted to electrical energy in a reversible process.

The process is enabled by electrochemical ‘cells’, which facilitate the reversible electrochemical reactions to take place at their electrodes.

7.5.1 Battery Technologies and Chemistries

There are a variety of battery technologies that include conventional enclosed aqueous battery systems (such as lead–acid (Pb–acid) and nickel–cadmium (Ni–Cd) batteries), high-temperature batteries (sodium–sulphur (Na–S) and the so-called ZEBRA batteries), flow batteries (with vanadium and zinc–bromine (Zn–Br) chemistries as the most representative examples) and lithium-ion (Li-ion) batteries with two dominant positive electrode chemistries.

Traditionally, Pb–acid batteries have had broad industrial uses for standby applications in which secure power is critically important, such as data centres, national security and telecommunications (May et al. 2018). Grid-related energy storage is perhaps a natural extension of these uses, and lead-based batteries can be deployed due to their reliability, long cycle life (under optimised charge and discharge limits) and applicability to utility and smaller-scale domestic and commercial energy storage. An individual Pb–acid cell consists of a Pb negative plate (grid) and a PbO_2 positive plate (grid) with an aqueous sulphuric acid electrolyte, which allows for an attractive voltage of 2.05 V for such a cell. There are also now newer carbon-enhanced Pb batteries (containing a capacitor-type carbon component in their negative electrode in addition to Pb). While lead-containing materials in these batteries are toxic, efficient recycling processes are available in some countries and the recycling rate is close to 100%.

Nickel–cadmium batteries are relatively expensive with respect to Pb–acid batteries, but are attractive due to their energy density (40–60 Wh/kg versus 35–40 Wh/kg for Pb–acid batteries) (Breeze 2018). Another clear advantage is their relative robustness under electrical and mechanical abuse conditions. A major drawback of Ni–Cd batteries is the toxicity of their components, with cadmium being a particularly toxic heavy metal. Another concern is the memory effect, requiring periodic full discharge of these batteries. The transition from cadmium in this type of batteries is possible. In terms of energy density, a superior performance (up to 40% higher) is achieved in a related type of nickel–metal hydride (Ni–MH) batteries but their cost is at a substantial premium compared to that of Ni–Cd batteries.

High-temperature batteries are alternatives for grid applications (Gür 2018). Sodium–sulphur batteries incorporate molten sodium (in the negative electrode), sulphur (in the positive electrode) and a solid ceramic electrolyte, and operate at typical temperatures of 300–360 °C, which requires independent heaters to complement these battery systems. Most of the installed high-temperature Na–S batteries are located in Japan and the USA. These batteries have attractive energy density (>200 Wh/kg) and long lifetime of 15–20 years. A Na–$NiCl_2$ (ZEBRA) battery is another variation of a high-temperature battery operating at 270–350 °C. Molten sodium acts as the negative electrode in this cell, and $NiCl_2$ (Ni in the discharged state) as the positive electrode, with molten sodium tetrachloroaluminate ($NaAlCl_4$) used as an electrolyte (Dustmann 2004).

Another class of technologies suitable for grid integration applications is flow batteries (Weber et al. 2011; Ke et al. 2018). Flow batteries are able to possess very large capacities due to active materials stored in external tanks, utilised by pumping these liquids via independent anode and cathode loops through a chamber containing two terminals and a separator. In vanadium redox batteries, utilising arguably the most prominent flow battery chemistry on the market today, aqueous vanadium salts are pumped through, and the oxidation state of vanadium species changes from V^{5+} to V^{4+} on the positive carbon electrode, and from V^{2+} to V^{3+} on the negative carbon electrode in discharge. The capacity of this system is regulated by the size of the external tanks, and infinite capacities can be, theoretically, achievable. Other notable flow battery chemistries include the zinc–bromine ($Zn–Br_2$) system, which offers higher energy density but which also comes with practical challenges and is currently being pursued by only a small number of proponents. Environmental release of vanadium and bromine in both of the above types of batteries presents potential risks.

7.5.2 Lithium-ion Batteries: Current Industry Status, Resource Requirements, Battery Systems in Deployment

Among the various types of batteries, Li-ion batteries are becoming dominant in grid and grid-related applications. These batteries utilise organic (non-aqueous) electrolytes, which allows an individual cell to possess a high nominal voltage of 3.2–3.85 V (depending on the electrode configuration) and a high energy density (100–265 Wh/kg). A Li-ion battery cell operates via the so-called ‘rocking chair’ mechanism in which lithium ions sequentially insert and de-insert into/from the positive and negative electrodes; each of these processes is accompanied by a redox reaction in a corresponding electrode. In particular, during the battery discharge, lithium leaves the negative electrode and inserts from the electrolyte into the positive electrode, causing electrons to flow in the external circuit.

Most of the current grid and home installations are dominated by two Li-ion battery configurations, and commercial batteries are available from Tesla, Enphase Energy and numerous other market participants. While graphite is typically used as the negative electrode material, two dominant chemistries of positive electrodes are employed in energy storage for grid applications. The first type of Li-ion batteries uses lithium iron phosphate ($LiFePO_4$) as the positive electrode material. While this type of battery has a lower energy density, and a larger number of cells in the module are needed to reach the required capacity and voltage, the high reliability and safety makes this type of Li-ion battery an attractive candidate for home and office energy storage. A common alternative Li-ion battery format involves lithium nickel manganese cobalt oxide (NMC) as the positive electrode material. These batteries have a higher voltage and capacity, leading to their inherent higher energy density.

As discussed, Li-ion batteries are emerging as a dominant battery type for energy storage in grids with high penetration of renewables. However, the potential limitations of this battery technology are the availability of the required raw materials. The geographic distribution of lithium in particular is uneven (predominantly located in Chile, Bolivia, Australia and China), and its total content in Earth's crust is low. Lithium-ion batteries with NMC cathodes also have additional drawbacks due to the scarcity of cobalt and nickel. Potentially, resource limitations may pose long-term challenges for the use of Li-ion batteries at a large scale. In this context, there is a growing need for recycling of spent Li-ion batteries (Li et al. 2018; Lv et al. 2018). The techniques for recovering materials from used batteries are not well developed, requiring substantial improvements before matching older battery technologies such as Pb–acid batteries, where most of the materials can be successfully recovered.

Driven by the raw material limitations of Li-ion batteries, there has been considerable attention in recent years devoted to the development of room-temperature Na-ion batteries. Instead of using lithium ions in their operation, sodium ions act as ionic shuttles in the same 'rocking chair' mechanism. Due to the similar chemical properties of sodium and its natural abundance (global reserves exceeding those of lithium by about 1000 times), Na-ion batteries may represent a sustainable alternative to Li-ion batteries (Hwang et al. 2017). Commercial prototypes are currently being tested in trial applications (such as e-bicycles) but the expectation for this emerging technology (should it be proven operational) is for it to be deployed in large stationary energy storage such as grid-related applications.

7.5.3 Interface with the Power System

Battery storage systems, regardless of size and technology, are inherently DC power sources. These sources are connected to the AC power system via a power electronics interface that converts the DC power source into an AC power source. The power electronics and associated control software determines the direction and amount of power flow at each instant in time, ensuring operation within the limits of the battery hardware itself.

These power electronics capabilities also underpin the provision of both real and reactive AC power and are capable of ramping power up and down or reversing power flow, with a typical response time of milliseconds.

7.5.4 Electric Vehicles as Energy Storage

Battery electric vehicles (BEVs), also known as all-electric vehicles or EVs, use battery technology that is very similar to stationary battery storage. Some vehicle manufacturers, such as Tesla, even use the same battery cells in both vehicles and stationary storage (Brown 2017). Similarly to stationary battery storage, BEVs can connect to the grid via AC coupling, where the vehicle contains an AC to DC inverter, or DC coupling where the inverter is located outside of the vehicle in the charging infrastructure. Therefore, BEVs can provide all the same benefits to the energy system as stationary storage, with the crucial differentiation that BEVs are a large net load, with energy eventually expended on mechanical propulsion.

The coincidence in technological specifications, particularly around Li-ion battery chemistries, has provided efficiencies of scale to both stationary and mobile storage. While BEVs have historically been the main driving force behind increasing production volumes and decreasing costs, this is beginning to change as both markets mature, with utility-scale stationary storage projects in particular doubling their capacity in 2018 to 33 GW (Hering 2019). The divergence in battery technologies is occurring due to both desire for higher power density in BEVs and greater cycling capacity in stationary storage, as well as the high prices of raw materials such as cobalt (Maloney 2018).

Battery electric vehicles and typical residential battery storage have different energy storage capacities. While distributed energy resource (DER) storage systems typically have energy capacities of up to 5–15 kWh (kilowatt-hours), BEV energy capacities begin at 40–62 kWh for a Nissan LEAF (Kane 2019) and are 60–100 kWh in Tesla models S and X (Lambert 2019a). There is also likely to be considerable deployment of battery electric freight vehicles, whose battery capacities range from 40–300 kWh for urban distribution trucks such as those manufactured by StreetScooter (StreetScooter n.d.) and Volvo (Lambert 2019b), to an advertised 800 kWh for the Tesla Semi (Lambert 2018).

The large net load of BEVs may become a significant challenge for distribution networks, which will host all but the largest BEV chargers, while motivating an increase in distributed generation and storage. These stresses will be exacerbated by the deployment of DC fast-chargers with power ratings of between 45 kW to 350 kW (Dow 2018; EV SafeCharge 2019).

At the same time, the advent of newly available BEVs, such as the Nissan LEAF, that support V2G functionalities (Kane 2018) creates opportunities for BEVs to enhance grid resilience and energy reliability and security. Managing the integration of BEVs into the power system, and unlocking the benefits of V2G BEVs, will depend critically on innovations in planning, control and coordination. While these innovations may build on learnings from stationary storage, there are unique elements to BEVs, such as their non-deterministic availability: for example, when they are being used as a means of transport and thus not connected to the grid. Such non-deterministic availability is an important consideration for the delivery of network and grid services where the provision or absorption of power is highly time sensitive.

7.6 Other Energy Storage Technologies

7.6.1 Thermal Storage

Thermal storage media represents one of the largest energy storage capacities globally. In the built environment, energy is stored primarily in hot water systems designed for direct use or space heating, but is also stored in the fabric of buildings for and via space heating systems. With a typical household hot water storage system, for example, containing in the order of 20 kWh of energy, one billion homes represents around 20 000 GWh of energy storage capacity. This is greater than twice the total estimated energy storage capacity from all PSH and battery systems globally. Much of this stored energy is sourced via the electrical power system, meaning that thermal energy storage could play an important role in managing electricity systems with large amounts of variable renewable generation. However, we do not consider this in any detail in this chapter since it cannot be considered as a reversible or bidirectional storage technology. Instead, thermal storage of this type is best considered elsewhere as part of the narrative on flexible loads, demand response and energy efficiency.

In this section we limit our discussion to those thermal storage technologies which provide generation flexibility or injection of power into the energy system.

7.6.1.1 Concentrating Solar Power with Thermal Storage

Concentrating solar thermal power (CSP or CST) plants with thermal storage involve the use of a large array of mirrors to concentrate sunlight onto a 'receiver' where the energy is collected by heating a fluid. The fluid can be stored and then used later, when needed, to generate steam and run a turbine/generator to produce electricity. Concentrating solar power's particular benefit is that its configuration allows energy storage as an easily and cost-effectively integrated part of the system. Systems with as much as 15 hours of storage capacity have been installed (e.g. Gemasolar, Spain and Crescent Dunes, USA), achieving a commercial supply of 24-hour solar energy (Fitzpatrick 2013). Storage is achieved, in most practical implementations, via molten salts.

Energy storage in CSP plants is not currently bidirectional in nature, being designed to store energy from the solar energy source and subsequently inject that energy into the electricity system as needed. However, there is no clear technological impediment to augmenting plants to convert electrical energy into heat for storage in the same medium, thus becoming bidirectional storage systems.

Concentrating solar thermal power plants primarily use synchronous generators to interface directly with the electrical power system. They operate a thermal cycle in much the same way that a modern, conventional thermal power plant does. Consequently, a CSP plant's output operating characteristics (minimum output, start time and ramp rates) are also quite similar and so are able to provide energy balancing across short-term and medium-term timescales. The use of a synchronous generator means that CSP plants automatically provide power system inertia, and the primary frequency response can be an integral part of operation; furthermore, the integrated thermal storage facilitates secondary 'spinning reserve' functionality in the same manner as conventional thermal power plants.

A more complete treatment of CSP technology is provided in Chapter 4.

7.6.1.2 Direct, Reversible Thermal-Electric Storage Technologies

There is an emerging family of thermal-electric storage technologies which have been proposed, but have not been implemented at any significant scale. These technologies allow direct bidirectional storage of energy in high-temperature thermal storage mediums. One proposed technology at development stage uses molten salts, similar to the technology now prevalent in CSP projects, but converts electrical energy to the molten salt storage and subsequently generates electrical energy via a closed-cycle Brayton engine (Laughlin 2017). Other emerging direct thermal storage technologies in the early stages of development include technologies based on molten silicon as the energy storage medium (1414 Degrees n.d.; Chu 2019).

7.6.2 Compressed Air Energy Storage

Compressed air energy storage (CAES) involves storing energy as pressurised air, either through compression of air into a fixed volume (isochoric CAES) or by inflating a volume by injecting air at a (relatively) constant pressure (isobaric CAES). This stored potential energy (more precisely the exergy) is converted into electricity by expansion of the pressurised air through a turbine to drive a generator.

Compressed air energy storage systems have similar energy and power properties to PSH systems, which typically makes them best suited to load shifting energy across hours or days and discharging over a few hours (Garvey 2018). Similarly to hydro turbines, they provide the power system with black start backup (Cavanagh et al. 2015) and inertia (which, depending on the turbine, may exceed the inertia constant of hydro turbines) (Banks et al. 2017). Like pumped hydro, CAES systems have a longer life but lower cycle efficiencies than batteries (CAES having lower efficiencies than pumped hydro) (Energy Storage Association n.d.a), and have to date required bespoke engineering for each installation.

There are three thermodynamic approaches that can be employed in driving CAES: following diabatic, adiabatic and isothermal pressure–volume (P–V) curves in compression and expansion. The closer the P–V curve is to an isotherm, the more efficient the process, the larger the energy storage density and the shorter the start-up time (Budt et al. 2016).

Diabatic CAES (DCAES) is the least efficient process because the heat generated through compression is ejected as waste. The system therefore requires an external heat source (typically fossil-fuel-powered) to inject heat prior to expansion at the time of power generation.

Adiabatic CAES (ACAES) systems capture this heat, store it and reintroduce it at the expansion step. The heat can be extracted in one – high-temperature (>500 °C) – step, or in multiple – lower-temperature, 200–400 °C –steps. Each additional step adds complexity but improves start-up time from cold conditions, due to reduced thermal stress, from around 15 minutes to 5 minutes, and enables more off-the-shelf components to be used.

Isothermal CAES (ICAES) systems are yet to be commercially demonstrated. In this concept, compression and expansion occur at a slower rate to minimise temperature increases that deviate the P–V curve away from the isotherm and produce efficiency losses. These concepts have focused primarily on piston machinery.

To date, most CAES developments have been isochoric DCAES and ACAES systems. Two large isochoric DCAES plants have been operating for over 20 years in Huntorf, Germany, and McIntosh, USA. These both use solution-mined salt caverns as large impermeable storage spaces and have power ratings of 290 MW (Crotogino et al. 2001) and 110 MW (Seltzer 2017) respectively. Recently there has been renewed interest in CAES, with companies such as Hydrostor innovating with isobaric ACAES designs underwater and in water-filled mines (ARENA 2019).

7.6.3 Flywheel Storage

Flywheels convert electrical energy into the kinetic energy of a rotating mass, typically made of steel or fibre composite (Chen et al. 2009). Other key components are vacuum housing and bearings, either mechanical or magnetic, to suspend the rotor mass and reduce friction; a motor-generator that both provides the power to accelerate the mass and decelerates it to convert energy back into electricity; and power electronics connected with the motor-generator. The inherently non-hazardous nature of these components is one of the advantages of flywheel storage.

The energy and power capacities of flywheels can be tuned independently. The size and speed of the rotor determines the energy capacity, and the power rating of the motor-generator determines the power capacity (Hebner et al. 2002). As a mechanical system, the frictional losses in flywheels scale inversely with the flywheel size, so flywheels typically have power and energy capacities exceeding a kilowatt. The main applications of flywheel storage have been frequency regulation, voltage support and smoothing of power profiles from wind farms, all of which have suited high power ratios (Ding and Zhi 2016). Large systems include a 20-MW facility in the USA (Beacon Power n.d.) and a 2-MW facility in Canada (Spears 2014).

Advantages of flywheels as a storage technology include the negligible degradation of cycling, leading to long lives estimated at over 100 000 cycles (Energy Storage Association n.d.b), fast response times of under a second (Amiryar and Pullen 2017), and cycling efficiencies of over 90% (Pena-Alzola et al. 2011). In contrast to batteries, the power output of flywheels degrades less across their discharge cycle. The major disadvantage of flywheels is their high self-discharge rate, which limits the duration for which they can store energy to less than 15 minutes. Recent developments claim to address this shortcoming and extend storage times to more than 4 hours (Amber Kinetics n.d.).

7.7 Integrating Energy Storage into the Grid

While ensuring that we have sufficient uptake of energy storage is of critical importance, there is also considerable work to be done to understand how best to integrate all of these storage technologies into global electricity systems. Due to its strong global uptake and ability to provide inertia, global market and system operators already understand how to integrate and operate PSH (Rogner and Troja 2018). However, further work is needed to enable emerging energy storage capabilities, particularly those with a power-electronics-based interface to the power system, to be integrated and operated effectively.

From a technical perspective, there are important questions about how power electronics should behave. While energy storage systems with a power electronics interface provide no natural inertia, they can be designed to behave like synchronous machines, delivering virtual inertia (Fang et al. 2018) to the grid. In microgrids, energy storage systems with a power electronics interface can already provide grid-forming capabilities (Singh et al. 2015).

In this context, there are important questions about whether power-electronics-interfaced storage should provide virtual inertia, provide grid-forming capabilities or operate in new ways to provide a new class of synchronisation services. Better understanding these challenges and opportunities for providing stability services is the subject of a significant European project, MIGRATE (European Commission 2016).

In addition to technical interface questions, it is also important to better understand the implications for operating the grid with a significant amount of distributed and distribution-connected energy storage. Within the transmission network, it is possible to decouple the management of voltage and frequency due to the low resistance compared to reactance of the conducting equipment in the transmission network. Consequently, in the transmission network, real power is typically used to maintain frequency and reactive power is used to manage voltage.

In the distribution network, resistance and reactance can be of similar order, so both real and reactive power have an impact on system frequency and voltage. It will therefore be particularly important to understand the implications of this on the value, performance and operation of service delivery from DER assets into markets for energy, ancillary and network services.

In Australia (Energy Networks Australia 2018) and the UK (Energy Networks Association n.d.) issues of coordination are primarily focused on the need for a distributed/distribution system operator (DSO) or a distributed/distribution market operator (DMO), with considerable activity around the development and trialling of appropriate orchestration technology for consumer-owned storage devices (Scott et al. 2019). In addition to questions of coordination there are also important considerations about the behind-the-meter optimisation and control strategies being utilised to operate energy storage assets and their impact on energy networks (Ratnam et al. 2016) and the broader electricity system and markets. These considerations become particularly important given the high level of decentralisation that many global grids will have over the coming decades, as seen in Figure 7.9.

7.8 Social Implications for the Deployment of Energy Storage

There is a dearth of research on the social dimensions of the transition to a grid with significantly higher rates of storage. Implications for institutional and regulatory conditions, social equity and energy consumption behaviours and patterns, not to mention public acceptance, have yet to be fully explored (Devine-Wright et al. 2017). New actors such as aggregators and ‘prosumers’ are entering the system, with key questions about their associated roles and responsibilities and interactions with incumbents and regulatory bodies yet to be worked through. As with many technological transitions, research on the implications of these changes is playing catch-up.

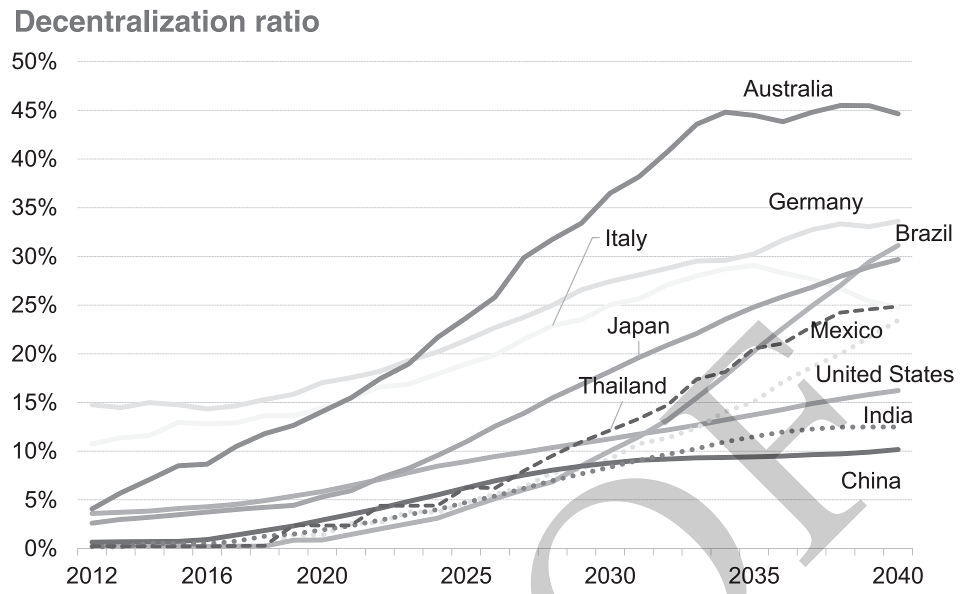

Figure 7.9 Many grids globally will demonstrate increasingly high levels of decentralisation over the decades ahead.

Source: Bloomberg NEF (2017). Note: decentralization ratio is the ratio of non-grid-scale capacity to total installed capacity. For a colour version of this figure, please see the colour plate section.

More generally, while there are cogent arguments for integrating social sciences in energy research, social science concepts and methodologies remain underutilised in battery and storage research (Sovacool 2014). Researchers and practitioners interested in how storage will be integrated into a changing grid have an opportunity to build on several decades of energy social science to ensure that the transition can not only reduce costs, but also improve well-being and sustainability goals.

There is already a well-developed literature in the energy social sciences, across several subdisciplines in the social sciences (e.g. human geography, sociology, science and technology studies, behavioural economics, policy studies, etc.), that can contribute to emerging questions about storage grid integration. Topics with active research agendas include experiences and impacts on demand management (Hui and Walker 2018), energy efficiency (Lutzenhiser 2014), solar photovoltaic installation (Bulkeley et al. 2016), community energy (Hicks and Ison 2018) and smart meters (Lovell 2017), as well as studies that have examined how technology innovation can be scaled up (Kemp 1994). There is a significant research gap on experiences and perceptions of battery storage. Devine-Wright et al. (2017) have developed a research agenda for the social science of storage, which is informed by public acceptance research and research on governance and innovation. This research agenda provides a multiscale, multi-method series of questions to explore the various dimensions of acceptance across regulation, markets and innovation, and sociocultural acceptances. This is an important call to social researchers who have neglected battery storage to date, but must also be extended to researchers in the technical fields whose research can be broadened out to consider social dimensions alongside technical requirements and considerations.

To date, there are only a handful of studies that examine perceptions of prospective storage integration into the grid (Romanach et al. 2013; Ginninderry Energy Research Team 2017; Jones et al. 2018), only one of which uses an in-depth method (focus groups) to capture detail and nuance (Ambrosio-Albalá et al. 2019). The latter study, conducted in the UK, found that perceptions of community-level battery storage were complex, influenced by specific local energy cultures including forms of energy consumption, costs, expectations of family members, previous experiences, perceptions of government and the municipal authority, and expectations about the technologies. All these factors were explored as likely to shape acceptance and adoption of battery storage at the household and community level.

There are even fewer studies that examine the experiences of households (or businesses) that own a battery, whether providing support to the network or not. We now turn to a brief summary of one of these studies – the CONSORT project on Bruny Island, Tasmania, Australia – in order to highlight the importance of considering the social dimensions of storage integration. CONSORT was a multidisciplinary research project and industry collaboration involving three universities, a network service provider and a technology start-up with a battery management system.

The technological innovation that underpinned the demonstration in CONSORT was a software platform that allowed the distribution network to trade energy with households, via control of the residential battery system, in near real time, so that energy from household batteries could be used to support the network at peak times, at overall least cost (for the network and for the households). Several dozen households were provided a subsidy to select a package of technology which included solar photovoltaics, a battery, an inverter and an energy management system. The social research activity covered focus groups, interviews, household observation and energy diaries with all of the participating households (for a summary of this research see Watson et al. 2019).

The in-depth longitudinal research carried out through this study revealed a number of important insights for the roll-out of storage at a household scale. While the majority of households felt generally comfortable with the technology in their homes, all but one experienced some degree of confusion, frustration and stress associated with the selection, installation and ongoing use of the technology. While the study was small in scale, its findings challenged a common assumption among industry and government reports on DER: that householders are likely to be willing and unproblematic participants in DER sharing with distribution networks at early stages of technological development. Research carried out on new models should integrate the social dimension of technology roll-out so that learnings about technology deployment and user needs can be integrated early on.

7.9 Outlook for Energy Storage

In their 2017 report, IRENA provide a forecast breakdown, by storage type, of the growth of energy storage capability out to 2030:

> Total electricity storage capacity in energy terms may grow from an estimated 4.67 TWh in 2017 to between 6.62 TWh and 7.82 TWh in the Remap Reference case in 2030, which is 42–68% higher than in 2017. In the Remap Doubling case, where the share of renewable energy in the global energy system is doubled from 2014 levels, electricity storage capacity could increase to between 11.89 TWh and 15.27 TWh in 2030, or 155–227% higher than in 2017. *(IRENA 2017: 103)*

Globally, the uptake of energy storage is on track to meet the International Energy Agency's Sustainable Development Scenario (IEA 2019c); however, there are clearly several factors that will underpin the forecast growth in energy storage broadly and battery storage specifically.

Importantly, it is clear that the price of energy storage will be key to its long-term uptake, particularly in the contribution of energy storage to the levelised cost of energy (LCOE) supply across regional or national electricity systems. Unlike traditional calculations for the LCOE, the levelised cost of storage is heavily dependent on its use case. Recent analyses taking this into account (Lazard 2018) do highlight significant cost declines across most use cases and energy storage technologies.

Given that storage is required in the power system on multiple timescales, and that the cost of energy storage capacity for different technologies can vary markedly (increasing design energy capacity for a PSH facility comes at relatively low marginal cost, compared with doing so for a battery system) it is apparent that more than one storage technology will be required. On current cost expectations, it appears likely that PSH technologies will secure a dominant position in providing storage at medium to long timescales, while battery technologies will gain traction for short to medium timescale applications.

For battery storage generally and lithium batteries in particular, future costs will depend heavily on global commodity prices and supply chains. The dependence of many battery storage technologies on rare earth metals has implications for price, based on international geopolitics as well as human rights and environmental concerns for global supply chains (Amnesty International 2017).

Ultimately, as we discussed in this chapter, energy storage is necessary to underpin the global adoption of renewable generation. As a consequence, future growth in the adoption and deployment of energy storage will also heavily depend on the global ambition for adopting renewable generation sources, the rate at which those renewable technologies are taken up and the subsequent demand for the firming capacity required to maintain secure and reliable power systems.

References

1414 Degrees (n.d.). How. *1414 Degrees*. Available at: https://1414degrees.com.au/how/.

Amber Kinetics (n.d.). Flywheel energy storage. Available at: www.amberkinetics.com.

Ambrosio-Albalá, P., Upham, P. and Bale, C. S. (2019). Purely ornamental? Public perceptions of distributed energy storage in the United Kingdom. *Energy Research and Social Science*, 48, 139–150.

Amiryar, M. E. and Pullen, K. R. (2017). A review of flywheel energy storage system technologies and their applications. *Applied Sciences*, 7, 286.

Amnesty International (2017). Industry giants fail to tackle child labour allegations in cobalt battery supply chains. *Amnesty International*. 15 November. Available at: www.amnesty.org/en/latest/news/2017/11/industry-giants-fail-to-tackle-child-labour-allegations-in-cobalt-battery-supply-chains/.

ARENA (Australian Renewable Energy Agency) (2019). South Australian zinc mine to be converted into Australia's first compressed air facility for renewable energy storage. *ARENA*. 8 February. Available at: https://arena.gov.au/news/south-australian-zinc-mine-to-be-converted-into-australias-first-compressed-air-facility-for-renewable-energy-storage/.

Australian Energy Market Operator (2018a). *Initial Operation of the Hornsdale Power Reserve Battery Energy Storage System*. Australian Energy Market Operator. Available at: www.aemo.com.au/-/media/Files/Media_Centre/2018/Initial-operation-of-the-Hornsdale-Power-Reserve.pdf.

Australian Energy Market Operator (2018b). *NEM Virtual Power Plant (VPP) Demonstrations Program*. Consultations paper. Australian Energy Market Operator. Available at: www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2018/NEM-VPP-Demonstrations-program.pdf.

Banks, J., Bruce, A. and MacGill, I. (2017). Fast frequency response markets for high renewable energy penetrations in the future Australian NEM. Paper presented at the Asia-Pacific Solar Research Conference 2017, Melbourne, 5–7 December. Available at: www.ceem.unsw.edu.au/sites/default/files/documents/024_J-Banks_DI_Peer-reviewed.pdf.

Barbour, E., Wilson, I. G., Radcliffe, J., Ding, Y. and Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, 61, 421–432.

Beacon Power (n.d.). Stephentown, New York. *Beacon Power*. From https://beaconpower.com/stephentown-new-york/.

Blakers, A., Stocks, M., Lu, B., Cheng, C. and Nadolny, A. (n.d.). Global Pumped Hydro Atlas. The Australian National University. Available at: http://re100.eng.anu.edu.au/global/index.php.

Blaga, R., Sabadus, A., Stefu, N., Dughir, C., Paulesu, M. and Badescu, V. (2018). A current perspective on the accuracy of incoming solar energy forecasting. *Progress in Energy and Combustion Science*, 70, 119–144.

Bloomberg NEF (New Energy Finance) (2017). *New Energy Outlook 2017*. London: Bloomberg New Energy Finance

Breeze, P. (2018). *Power System Energy Storage Technologies*. London: Academic Press.

Brown, A. (2017). Tesla's Gigafactory to build Model 3 motors in addition to batteries. *The Drive*. 18 January. Available at: www.thedrive.com/news/7008/teslas-gigafactory-to-build-model-3-motors-in-addition-to-batteries.

Budt, M., Wolf, D., Span, R. and Yan, J. (2016). A review on compressed air energy storage: Basic principles, past milestones and recent developments. *Applied Energy*, 170, 250–268.

Bulkeley, H., Powells, G. and Bell, S. (2016). Smart grids and the constitution of solar electricity conduct. *Environment and Planning A: Economy and Space*, 48, 7–23.

California Public Utilities Commission (n.d.). Rule 21 interconnection. *California Public Utilities Commission*. Available at: www.cpuc.ca.gov/Rule21/

California Public Utilities Commission (2018). Resolution E-4949. Available at: http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M229/K550/229550723.PDF.

Cavanagh, K., Ward, J., Behrens, S., Bhatt, A., Ratnam, E., Oliver, E. and Hayward, J. (2015). *Electrical Energy Storage: Technology Overview and Applications*.

Canberra: Commonwealth Scientific and Industrial Research Organisation. Available at: www.aemc.gov.au/sites/default/files/content/7ff2f36d-f56d-4ee4-a27b-b53e01ee322c/CSIRO-Energy-Storage-Technology-Overview.pdf.

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y. and Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19, 291–312.

Chu, J. (2019). Sun in a box. *MIT Technology* Review. 27 February. Available at: www.technologyreview.com/s/612798/sun-in-a-box/.

Colthorpe, A. (2018). Germany Reaches 100k home battery storage installations. *Energy Storage News*. 28 August. Available at: www.energy-storage.news/news/germany-reaches-100k-home-battery-storage-installations.

Crotogino, F., Mohmeyer, K.-U. and Scharf, R. (2001). Huntorf CAES: More than 20 years of successful operation. Available at: www.fze.uni-saarland.de/AKE_Archiv/AKE2003H/AKE2003H_Vortraege/AKE2003H03c_Crotogino_ea_HuntorfCAES_CompressedAirEnergyStorage.pdf.

Devine-Wright, P., Batel, S., Aas, O., Sovacool, B., Carnegie Labelle, M. and Ruud, A. (2017). A conceptual framework for understanding the social acceptance of energy infrastructure: Insights from energy storage. *Energy Policy*, 107, 27–31.

Ding, K. and Zhi, J. (2016). Wind power peak–valley regulation and frequency control technology. In N. Wang, C. Kang, and D. Ren, eds., *Large-Scale Wind Power Grid Integration*. Academic Press, pp. 211–232.

Dow, J. (2018). VW's Electrify America opens California's first 350kW ultra-fast charger, before cars can actually use it. *electrek*. 6 December. Available at: https://electrek.co/2018/12/06/electrify-america-first-350kw-charger-california/.

Dustmann, C. (2004). Advances in ZEBRA batteries. *Journal of Power Sources*, 127, 85–92.

Energy Networks Association (n.d.). Future worlds: Consultation. *Energy Networks Association*. Available at: www.energynetworks.org/electricity/futures/open-networks-project/future-worlds/future-worlds-consultation.html

Energy Networks Australia (2018). A joint Energy Networks Australia and Australian Energy Market Operator (AEMO) project. *Energy Networks Australia*. Available at: www.energynetworks.com.au/joint-energy-networks-australia-and-australian-energy-market-operator-aemo-project.

Energy Storage Association (n.d.a). Mechanical energy storage: CAES. *Energy Storage Association*. Available at: http://energystorage.org/compressed-air-energy-storage-caes.

Energy Storage Association (n.d.b). Mechanical energy storage: Flywheels. *Energy Storage Association*. Available at: http://energystorage.org/energy-storage/technologies/flywheels.

European Commission (2016). Massive InteGRATion of power Electronic devices. *Cordis*. Available at: https://cordis.europa.eu/project/rcn/199590/factsheet/en.

EV SafeCharge (2019). DC fast charging explained. *EV SafeCharge*. Available at: https://evsafecharge.com/dc-fast-charging-explained/.

Fang, J., Li, H., Tang, Y., and Blaabjerg, F. (2018). Distributed power system virtual inertia implemented by grid-connected power converters. *IEEE Transactions on Power Electronics*, 33, 8488–8499.

Fitzpatrick, E. (2013). Solar storage plant Gemasolar sets 36-day record for 24/7 output. *Renew Economy*. 8 October. Available at: https://reneweconomy.com.au/solar-storage-plant-gemasolar-sets-36-day-record-247-output-12586/.

Garvey, S. (2018). Let's store solar and wind energy: By using compressed air. *The Conversation*. 24 October. Available at: https://theconversation.com/lets-store-solar-and-wind-energy-by-using-compressed-air-103183, Ginninderry Energy Research Team (2017). *Householder Attitudes to Residential Renewable Energy Futures*. Canberra: Riverview Projects. Available at https://ginninderry.com/wp-content/uploads/2016/09/Ginninderry-2017-Householder-Attitudes-to-Residential-Renewable-Energy-Futures.pdf.

Graham, P. W., Hayward, J., Foster, J., Story, O. and Havas, L. (2018). *GenCost 2018: Updated Projections of Electricity Generation Technology Costs*. Canberra: Commonwealth Scientific and Industrial Research Organisation. Available at: www.csiro.au/~/media/News-releases/2018/renewables-cheapest-new-power/GenCost2018.pdf.

Guangdong Hydropower Planning and Design Institute (2013). Shenzhen Pumped Storage Power Station. *GPDI*. 19 December. Available at: www.gpdiwe.com/en/webview/?artid=40815.

Gür, T. (2018). Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage. *Energy & Environmental Science*, 10, 2696–2767.

Hebner, R., Beno, J. and Walls, A. (2002). Flywheel batteries come around again. *IEEE Spectrum*, 39, 46–51.

Hering, G. (2019). Amid global battery boom, 2019 marks new era for energy storage. *S&P Global Market Intelligence*. 11 January. Available from: www.spglobal.com/marketintelligence/en/news-insights/trending/9GIYsd7qF8tNpiopwH7KSg2.

Hicks, J. and Ison, N. (2018). An exploration of the boundaries of 'community' in community renewable energy projects: Navigating between motivations and context. *Energy Policy*, 113, 523–534.

Hui, A. and Walker, G. (2018). Concepts and methodologies for a new relational geography of energy demand: Social practices, doing-places and settings. *Energy Research & Social Science*, 36, 21–29.

Hwang, J., Myung, S. and Sun, Y. (2017). Sodium-ion batteries: Present and future. *Chemical Society Reviews*, 12, 3529–3614.

Hydro Tasmania (2018). *Battery of the Nation: Analysis of the Future National Energy Market*. Hobart: Hydro Tasmania. Available at: www.hydro.com.au/docs/default-source/clean-energy/battery-of-the-nation/future-state-nem-analysis-full-report.pdf.

IEA (International Energy Agency) (2014). *Technology Roadmap: Energy Storage*. Technical report. Paris: International Energy Agency. Available at: www.iea.org/reports/technology-roadmap-energy-storage.

IEA (2019a). Electric vehicles. *Tracking Transport*. Paris: International Energy Agency. Available at: www.iea.org/topics/tracking-clean-energy-progress (these data accessed 2019).

IEA (2019b). Energy storage. *Tracking Energy Integration*. Paris: International Energy Agency. Available at: www.iea.org/topics/tracking-clean-energy-progress (these data accessed 2019).

IEA (2019c). *Sustainable Development Scenario*. Paris: International Energy Agency. Available at: www.iea.org/reports/world-energy-model/sustainable-development-scenario.

IEA (2019d). Will pumped storage hydropower expand more quickly than stationary battery storage? Analysis from Renewables 2018. *IEA.org*. 4 March. Available at: www.iea.org/articles/will-pumped-storage-hydropower-expand-more-quickly-than-stationary-battery-storage.

IRENA (International Renewable Energy Agency) (2017). *Electricity Storage and Renewables: Costs and Markets to 2030*. Abu Dhabi: International Renewable Energy Agency. Available at: www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

IRENA (2019). Renewable energy now accounts for a third of global power capacity. *IRENA.org*. 2 April. Available at: www.irena.org/newsroom/pressreleases/2019/Apr/Renewable-Energy-Now-Accounts-for-a-Third-of-Global-Power-Capacity.

Jones, C. R., Gaede, J., Ganowski, S. and Rowlands, I. H. (2018). Understanding lay-public perceptions of energy storage technologies: Results of a questionnaire conducted in the UK. *Energy Procedia*, 151, 135–143.

Kane, M. (2018). Nissan LEAF is Germany's first V2G-approved electric car. *Inside EVs*. 23 October. Available at: https://insideevs.com/news/340585/350ought-leaf-is-germanys-first-v2g-approved-electric-car/.

Kane, M. (2019). Here is the Nissan LEAF e+ 62 kWh battery: Video. *Inside EVs*. 9 January. Available at: https://insideevs.com/news/342009/here-is-the-nissan-leaf-e-62-kwh-battery-video/.

Ke, X., Prahl, J., Alexander, J., Wainright, J., Zawodzinski, T. and Savinell, R. (2018). Rechargeable redox flow batteries: Flow fields, stacks and design considerations. *Chemical Society Reviews*, 23, 8721–8743.

Keller, T. (2016). Could this be the most extreme power plant in the world? *GE Reports: Hydropower*. 7 June. Available at: www.ge.com/reports/how-the-swiss-turned-an-alpine-peak-into-a-battery-the-size-of-a-nuclear-plant/.

Kemp, R. (1994). Technology and the transition to environmental sustainability: The problem of technological regime shifts. *Futures*, 26, 1023–1046.

Kruger, K. (2018). Li-Ion Battery versus pumped storage for bulk energy storage: A comparison of raw material, investment costs and CO_2 footprints. Paper presented at HydroVision Conference, Charlotte, USA, 27 June. Available at: www.voith.com/corp-de/VH_Paper_Battery-versus-Pumped-Storage-_2018_HydroVision_en.pdf.

KTrimble (2009). Aerial photo of Taum Sauk reservoir under construction [image]. *Wikimedia Commons*. 22 November. Available at: https://commons.wikimedia.org/wiki/File:TaumSaukReservoir_underconstruction.jpg.

Lambert, F. (2018). Tesla Semi production version will have closer to 600 miles of range, says Elon Musk. *electrek*. 2 May. Available at: https://electrek.co/2018/05/02/tesla-semi-production-version-range-increase-elon-musk/.

Lambert, F. (2019a). Tesla releases new Model S battery pack, makes massive price drop, kills base Model X pack. *electrek.* 1 March. Available at: https://electrek.co/2019/03/01/tesla-model-s-model-x-prices-options/.

Lambert, F. (2019b). Volvo delivers its first electric trucks. *electrek*. 21 February. Available at: https://electrek.co/2019/02/21/volvo-delivers-first-electric-trucks/.

Laughlin, R. (2017). Pumped thermal grid storage with heat exchange. *Renewable and Sustainable Energy*, 9. Available at https://doi.org/10.1063/1.4994054.

Lazard (2018). *Levelized Cost of Energy Analysis: Version 4.0*. Available at: https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/.

Li, L., Zhang, X., Li, M., Chen, R., Wu, F., Amine, K. and Liu, J. (2018). The recycling of spent lithium-ion batteries: A review of current processes and technologies. *Electrochemical Energy Reviews*, 1, 461–482.

Liu, H., Chen, C., Lv, X., Wu, X. and Liuy, M. (2019). Deterministic wind energy forecasting: A review of intelligent predictors and auxiliary methods. *Energy Conversion and Management*, 195, 328–345.

Lovell, H. (2017). Are policy failures mobile? An investigation of the Advanced Metering Infrastructure Program in the State of Victoria, Australia. *Environment and Planning A: Economy and Space*, 49, 314–331.

Lutzenhiser, L. (2014). Through the energy efficiency looking glass. *Energy Research & Social Science*, 1, 141–151.

Lv, W., Wang, Z., Cao, H., Sun, O., Zhang, Y. and Sun, Z. (2018). A critical review and analysis on the recycling of spent lithium-ion batteries. *ACS Sustainable Chemistry & Engineering*, 6, 1504–1521.

Maloney, P. (2018). Electric vehicle and stationary storage batteries begin to diverge as performance priorities evolve. *Utility Dive*. 1 August. Available at: www.utilitydive.com/news/batteries-for-electric-vehicles-and-stationary-storage-are-showing-signs-of/528848/.

May, G., Davidson, A. and Monahov, B. (2018). Lead batteries for utility energy storage: A review. *Journal of Energy Storage*, 15, 145–157.

Mulder, F. (2014). Implications of diurnal and seasonal variations in renewable energy generation for large scale energy storage. *Journal of Renewable and Sustainable Energy*, 6. Available at: https://doi.org/10.1063/1.4874845.

Neoen (2017). *Hornsdale Power Reserve*. Available at: https://hornsdalepowerreserve.com.au/.

NREL (National Renewable Energy Laboratory) (n.d.). Concentrating solar power projects by project name. *Concentrating Solar Power Projects.* Available from: https://solarpaces.nrel.gov/projects.

Parkinson, G. (2019). Tesla Big Battery delivered a $22 million profit in 2018. *Renew Economy.* 14 May. Available at: https://reneweconomy.com.au/tesla-big-battery-delivered-a-22-million-profit-in-2018-2018/.

Patel, S. (2013). Spain inaugurates 2-GW pumped storage facility. *Power*. 30 November. Available at: www.powermag.com/spain-inaugurates-2-gw-pumped-storage-facility/.

Pena-Alzola, R., Sebastián, R., Quesada, J. and Colmenar, A. (2011). Review of flywheel based energy storage systems. In *2011 International Conference on Power Engineering, Energy and Electrical Drives, PowerEng2011*. Piscataway, NJ: IEEE, pp. 1–6.

Ratnam, E., Weller, S. and Kellett, C. (2016). Central versus localized optimization-based approaches to power management in distribution networks with residential battery storage. *International Journal of Electrical Power & Energy Systems*, 80, 396–406.

Robson, P. and Bonomi, D. (2018). *Growing the Battery Storage Market 2018: Exploring Four Key Issues.* White paper. Dufresne Research. Available at: https://energystorageforum.com/files/ESWF_Whitepaper_-_Growing_the_battery_storage_market.pdf.

Rogers, J., Watkins, C. and Hoffman, D. (n.d.). *Overview and History of the Taum Sauk Pumped Storage Project*. Rolla, MO: Missouri University of Science and Technology. Available at: https://web.mst.edu/~rogersda/dams/2_43_Rogers.pdf.

Rogner, M. and Troja, N. (2018). *The World's Water Battery: Pumped Hydropower Storage and the Clean Energy Transition*. IHA working paper. London: International Hydropower Association. Available at: www.hydropower.org/publications/the-world-e2-80-99s-water-battery-pumped-hydropower-storage-and-the-clean-energy-transition.

Romanach, L., Contreras, Z. and Ashworth, P. (2013). *Australian Householders' Interest in the Distributed Energy Market* [survey]. Report no. EP133598. Canberra: Commonwealth Scientific and Industrial Research Organisation (CSIRO). Available at: http://apvi.org.au/wp-content/uploads/2013/11/CSIRO-Survey-Report.pdf.

Scott, P., Gordon, D., Franklin, E., Jones, L. and Thiebaux, S. (2019). Network-aware coordination of residential distributed energy resources. *IEEE Transactions on Smart Grid*, 10, 6528–6537.

Seltzer, M. A. (2017). Why salt is this power plant's most valuable asset. *Smithsonian Magazine*. 4 August. Available at: www.smithsonianmag.com/innovation/salt-power-plant-most-valuable-180964307/.

Singh, M., Lopes, L. and Ninad, N. (2015). Grid forming battery energy storage system (BESS) for a highly unbalanced hybrid mini-grid. *Electric Power Systems Research*, 127, 126–133.

Snowy Hydro (2019). *Snowy 2.0 Project Update*. Snowy Hydro Limited. Available at: www.snowyhydro.com.au/our-scheme/snowy20/.

Sobri, S., Koohi-Kamali, S. and Abdul Rahim, N. (2018). Solar photovoltaic generation forecasting methods: A review. *Energy Conversion and Management*, 156, 459–497.

Sovacool, B. K. (2014). What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Research & Social Science*, 1, 1–29.

Spears, J. (2014). Ontario electricity gets taken for a spin. *The Star*. 7 November.

StreetScooter (n.d.). *StreetScooter*. Available www.streetscooter.com/de.

Sunspec Alliance (2016). *IEEE 2030.5 Common California IOU Rule 21 Implementation Guide for Smart Inverters*. Common Smart Inverter Profile Working Group. Available at: www.pge.com/includes/docs/pdfs/shared/customerservice/nonpgeutility/electrictransmission/handbook/rule21-implementation-guide.pdf.

US DOE (Department of Energy) (n.d.). DOE OE Global Energy Storage Database. Available at: www.sandia.gov/ess/global-energy-storage-database/.

Watson, P., Lovell, H., Ransan-Cooper, H., Hann, V. and Harwood, A. (2019). CONSORT Bruny Island battery trial. Project final report. Available at: http://brunybatterytrial.org/wp-content/uploads/2019/05/consort_social_science.pdf.

Weaver, J. F. (2017). World's largest battery: 200MW/800MWh vanadium flow battery: Site work ongoing. *electrek*. 21 December. Available at: https://electrek.co/2017/12/21/worlds-largest-battery-200mw-800mwh-vanadium-flow-battery-rongke-power/.

Weber, A., Mench, M. M., Meyers, J., Ross, P., Gostick, J. and Liu, Q. (2011). Redox flow batteries: A review. *Applied Electrochemistry*, 41, 1137–1164.

West, N., Watson, P. and Potter, C. (2018). *Pumped Hydro Cost Modelling*. ENTURA-10686B. Cambridge, Tasmania: Entura. Available at: www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Inputs-Assumptions-Methodologies/2019/Report-Pumped-Hydro-Cost-Modelling.pdf.

Zinaman, O., Bowen, T. and Aznur, A. (2020). *An Overview of Behind-the-Meter Solar-Plus-Storage Regulatory Design*. Report/Contract No. IAG-17-2050. USA: National Renewable Energy Lab. Available at: www.nrel.gov/docs/fy20osti/75283.pdf.