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# Electrical Energy Storage:

## Technology Overview and Applications

Prepared for the Australian Energy Market Commission

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# Executive summary

Energy storage is seen by many as the next big change facing Australia's electricity system. The technology can solve challenges that range from smoothing the intermittency of renewable generation to providing power quality support, and managing peak demand to reducing customers' electricity bills. Moving beyond the burgeoning enthusiasm associated with energy storage technologies, there is a critical need to understand not just the benefits that energy storage may offer the Australian electricity system, but also the very real economic, regulatory and technical challenges that lay ahead. This report – compiled by the Australian Energy Market Commission and CSIRO – is an overview of the technical aspects of energy storage in Australia, delivering a detailed investigation into the prevailing storage issues facing the energy sector. It provides a deep technical review of key storage technologies, their potential advantages, and the distinct set of challenges that are relevant to each.

While a great range of existing grid-connected energy storage technologies is discussed in popular media, a much smaller subset is commercially available now or likely to be in the near future. Part 1 of this report therefore reviews the broad diversity of storage technologies available. We identify five key storage technologies that are most likely to secure meaningful uptake in the Australian electricity system over the next 15 years, based on technical maturity, supply chain, manufacturing and recent deployment activities. These are advanced lead-acid, lithium iron phosphate, lithium nickel manganese cobalt oxide, zinc bromine flow and sodium nickel chloride molten salt batteries.

Part 2 of the report considers the range of potential benefits that energy storage may provide the electricity grid (from the perspective of grid-side and customer-side), and the capacity of each of the five key technologies to deliver on those benefits. Ultimately, no single storage technology will be able to meet all applications, and each technology has advantages and disadvantages. For example, in providing services such as bulk power provision during times of peak demand, relatively slow-operating, lower energy density storage technologies such as flow or molten salt batteries – which are comparatively cheap – may be perfectly suitable. On the other hand, fast-response services such as frequency support or smoothing of intermittent solar generation will require fast-response batteries with greater cycle life, such as advanced lead-acid or various lithium-ion chemistries.

Fundamentally, the choice of storage technology for a particular application will depend on careful technical design to match its required operational characteristics and nuances with the main goals of its deployment. Importantly, a great deal more real-world deployment experience is required in Australia to understand the optimal fit for storage technologies, quantify technology lifespans and assess the commercial viability of each solution.

When considering the broader potential for mass-market uptake of electrical energy storage across Australia, many challenges remain to be solved before we are likely to see the huge impact of energy storage that is often predicted. In particular:

- Very careful consideration will need to be given to effect of the unique Australian climate on storage technologies. Many storage technologies, including advanced lead-acid and lithium-ion batteries, can be significantly affected by high temperatures that could become common in warmer parts of Australia. While air-conditioning systems may help manage battery life in large-scale deployments, they significantly affect the economics of battery deployment, and are completely inappropriate for small-scale residential energy storage.

- There is a significant need for more data on the relative performance of different battery technologies under a variety of operating conditions, particularly given the significantly different charge/discharge cycles relevant to the various possible storage applications. Such data needs to come from carefully designed trials or experiments that can control for the significant number of factors that will affect system performance.
- While residential-scale energy storage is expected to see significant uptake in coming years, its benefits to the broader electricity system cannot be guaranteed. It could certainly offer many significant benefits to the broader electricity system, but realising such benefits will require careful control of the batteries and their operation. Furthermore, the interplay between battery operation that benefits the end-customer (typically through reducing their electricity bill) and battery operation that benefits the broader electricity system is not straightforward. This will require careful regulation, tariff design or other mechanisms to ensure optimal outcomes.
- Safety regulations or standards are significantly delaying the availability of various energy storage technologies and their potential deployment scenarios. Although technologies such as lead-acid batteries have standards, these do not consider the unique characteristics of other battery types and are not aimed at residential or other non-industrial deployment scenarios.

Energy storage holds great potential to benefit Australia's electricity system, and is likely to significantly affect system operation and the experiences of all stakeholders. We can predict with reasonable confidence the particular energy storage technologies that are most likely to see mass uptake over the coming years. However, many challenges must be addressed before their full benefits will be realised. Ultimately, none of these challenges are insurmountable: the core technologies here are reasonably mature and are starting to see significant uptake in other industries or parts of the world.

The key issues here, which can certainly be addressed, are ultimately related to a lack of real-world Australian experience with each of the technologies across the broad range of potential usage scenarios, or the lag between standards, regulation and the latest technologies now seeing commercial availability. Through further trials and carefully designed technology studies, standards and regulatory work, we can be sure that storage will see the mass uptake and deliver the whole-of-system benefits that are often promised.

# Abbreviations

| Abbreviation | Meaning |
|---|---|
| **AEMC** | Australian Energy Market Commission |
| **AEMO** | Australian Energy Market Operator |
| **AER** | Australian Energy Regulator |
| **CAES** | compressed air energy storage |
| **DoD** | depth of discharge |
| **EV** | electric vehicle |
| **FiT** | feed-in tariff |
| **HV** | high voltage |
| **kW** | kilowatt |
| **kWh** | kilowatt hour |
| **MRL** | manufacturing readiness level |
| **MW** | megawatt |
| **MWh** | megawatt hour |
| **NCAS** | network control ancillary services |
| **NEM** | National Electricity Market |
| **PV** | photovoltaic |
| **SMES** | superconducting magnetic energy storage |
| **SNG** | synthetic natural gas |
| **SoC** | stage of charge |
| **TOU** | time of use |
| **TRL** | technology readiness level |

| | |
|---|---|
| **UPS** | uninterruptible power supply |
| **VRFB** | vanadium redox flow battery |

# Contents

# Part I Energy storage: technology overview

Energy storage has the potential to contribute to stable and efficient operation of the electricity grid, especially with the increasing proportion of renewable generation. Electricity generated from renewable resources is dictated by resource availability – that is, when the sun is shining or the wind is blowing. However, the demand for renewable electricity is governed by factors that do not often align well with the availability of this intermittent resource.

Energy storage technologies therefore provide us with an opportunity to store renewable electricity for later use, thereby matching generation to demand. They also have a wide range of other potential applications, such as managing peak demand and power quality at various levels throughout the electricity network, providing backup power and shaping customer usage in response to tariffs.

To provide such a wide range of applications, energy storage systems require a similarly wide range of characteristics. This part of the report assesses the various strengths and weaknesses of different energy storage types as they apply to potential opportunities within the Australian electricity grid.

## 1.1 Key concepts

**Energy storage** refers to a chemical process or physical media that stores energy to perform useful work at a later time. For example, an air compressor stores air under pressure. The energy held in the pressurised air can be released when required to power any air tools attached to the compressor, such as a spray-paint gun or a tyre inflator.

To further analyse energy storage technologies relevant to Australian electricity systems, we introduce here a few key definitions. The two most important are power and energy.

**Energy** is defined as the measure of the ability to do work or produce a change over time. It is expressed in joules or **kilowatt hours** (kWh). **Power** is defined as the rate at which energy is flowing or the rate at which work is being done. It is expressed in watts or **kilowatts** (kW). Thus a 5-kWh battery can theoretically provide 1 kW of power output continuously for 5 hours, or 5 kW of power for a single hour.

Energy storage technologies are available in many different forms, each of which has different ways of storing energy and using power. For example, pumped hydro systems store energy using water movement driven by pumps, flywheels store energy using mechanical momentum, and thermal systems store energy as heat. A range of energy storage technologies is described in Appendix A.

Another example of an energy storage device is a **battery**. A battery stores energy in the form of chemicals, and releases the energy through chemical changes to do electrical work on demand. Batteries can use different chemistry types to store and then release energy.

There are two types of batteries: primary and secondary**. Primary** batteries are used in devices such as watches, remote controls or children's toys. They are typically single use. **Secondary** batteries are rechargeable, account for approximately 76% of the global market [1] and are the focus of this review. Secondary batteries include lead-acid, lithium-ion (Li-ion) and flow batteries, to name just a few; these and others are described later in Section 1.4 and Appendix A.

The energy storage performance of a battery can be described in terms of **battery capacity** – the total amount of electric charge a battery can deliver at its rated voltage, or the charge stored by the battery. Another term related to battery capacity is **C-rate**, which is a measure of the rate at which a battery discharges (i.e. releases its energy) relative to its maximum capacity. A 1C rate specifies the **discharge current** that will discharge the entire battery in 1 hour. Thus, a battery with a capacity of 100 amp hours (Ah) (amps being a measure of current) operated at a 1C rate should be able to provide 100 amps for 1 hour.

**Battery life** is a measure of battery performance and longevity. It is the amount of time it can run on a full charge, as estimated by a manufacturer in Ah, or as the number of charge and/or deep-charge cycles (see further explanation in Section 1.2) that are possible before it reaches the end of its useful life. Battery life is an important concept to consider when analysing the application and economic feasibility of connecting energy storage to the electricity grid.

## 1.2 Taxonomy of electrical energy storage

Energy can be stored in numerous ways using many different technologies, such as mechanical (flywheels), thermal (hot water), electrochemical/electrical (batteries), or chemical (hydrogen) storage. Some examples of each of these types of energy storage are given in Table 1.

**Table 1 Examples of energy storage methods**

| Mechanical energy storage | Thermal energy storage | Electrical / electrochemical energy storage | Chemical energy storage |
|---|---|---|---|
| • Pumped hydro<br>• Compressed air<br>• Flywheel | • Hot water<br>• Molten salt<br>• Phase-change material | • Supercapacitors<br>• Superconducting magnets<br>• Batteries<br>• Fuel cells | • Hydrogen<br>• Synthetic natural gas<br>• Other chemical compounds e.g. ammonia, methanol |

Each of the energy storage technologies listed in Table 1 has advantages and disadvantages that limit their application for both practical and economic reasons. For example, mechanical technologies such as pumped hydro, compressed air and flywheels have low energy efficiencies. **Energy efficiency** in storage applications refers to the ratio of energy required to store the energy (input) to the use of the energy (output). When this ratio is imbalance or skewed, it results in energy being wasted; hence, the process has low energy efficiency. Pumped hydro and compressed air storage systems can also have slow response times, making them difficult to use when addressing short-term renewable intermittency. These technologies are also restricted by geological and geographical requirements, high investment costs and long construction times. In contrast, electrochemical energy storage systems such as batteries have a fast response time and are easier to deploy, although at significantly lower capacity rates. This is also dependent on the targeted application for energy storage. We investigate some of the benefits of batteries and their applications in greater detail in the following sections of this report.

Energy storage technologies can be connected to the electricity grid for grid-connected applications. These can include meeting shortfalls in renewable generation that arise from moving cloud cover or reduced wind speed, or shifting the energy supply from periods of low electricity demand to periods of high demand (known as time shifting). These scenarios for storage can be applied at various scales, from grid-side applications at large (MW) installations to customer-side residential level (kW). 'Side' refers to the perspective of the grid or customer at the point at which the energy meter is installed. These varying scales of storage and applications require different energy storage response times and characteristics depending on the level, size and mix of grid-connected generation. In addition to grid-connected applications, energy storage can also be used in off-grid scenarios. However, the scope of this report is limited to only grid-connected applications and technologies.

A large number of energy storage technologies are commercially available that can potentially be used for grid-connected applications. In Australia today, batteries, flywheels and pumped hydro storage are the only energy storage technologies with significant deployment for grid-connected applications. Other technologies that are either used overseas, and/or in need of further development, include compressed air, gas, thermal or magnetism-based storage technologies. In this section, we consider the technical suitability of commercially available energy storage technologies for grid-connected applications in Australia.

Table 2 illustrates the particular operational characteristics of a wide range of energy storage technologies, as collated by the United States Department of Energy [2], with information on advanced lead-acid batteries supplied by CSIRO [3]. These technologies are further described in detail in Section 1.4 and Appendix A.

**Table 2 Characteristics of different energy storage technologies. Reproduced from United States Department of Energy data [2] and CSIRO data [3]**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ /$kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ /$kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature °C | Self-discharge %/day | Critical voltage/cell V |
|---|---|---|---|---|---|---|---|---|---|
| **Lead-acid battery** | 3–15 (2000) | 75–300/90–700 | 30–50/75 | min– h | 8–16 h | 5–10 ms | –10 to 40 | 0.1–0.3 | 1.75 |
| **Advanced lead-acid battery** | 3–15 (3000) | 75–300/90–700 | 30–50/75 | min–h | 8–16 h | 5 ms | –10 to 40 | 0.1–0.3 | 2 |
| **Nickel-cadmium battery** | 15–20 (2500) | 150–300/75–700 | 45–80/<200 | s–h | 1 h | ms | –40 to 45 | 0.2–0.6 | 1 |
| **Lithium-ion battery** | 8–15 (500-6000) | 230–340/1300–10000 | 100–250/250–620 | min–h | min–h | 20 ms–s | –10 to 50 | 0.1–0.3 | 3 |
| **Sodium sulfur battery** | 12–20 (>2000) | 90–230/120–160 | 150–240/<400 | s–h | 9 h | 1 ms | 300 | 20 | 1.75–1.9 |
| **Sodium nickel chloride battery** | 12–20 (4000-4500) | 130–160/250–270 | 125/150–200 | min–h | 6–8 h | 100 ms | 270 to 350 | 15 | 1.8–2.5 |
| **Zinc bromide flow battery** | 5–10 (300-1500) | 50–150/1–25 | 60–80/20–35 | s–10h | 4 h | <1 ms | 10 to 45 | 0–1 | 0.17–0.3 |
| **Vanadium redox flow battery** | 10–20 ($13x10^3$) | NA/0.5–2 | 75/20–35 | s–10h | min | <1 ms | 0 to 40 | 0–10 | 0.7–0.8 |
| **Flywheel** | > 20 ($10^7$) | 400–1600/5000 | 5–130/20–80 | 15 s–15 min | <15 min | < 4 ms–s | 20 to 40 | 20–100 | NA |
| **Super/double-layer capacitors** | > 20 ($5x10^5$) | 0.1–10 /40000–120000 | 0.1–15/10–20 | ms–1h | s–min | 8 ms | –40 to 85 | 2–40 | 0.5 |
| **Superconducting magnetic energy storage** | 20 ($10^4$–$10^5$) | 2.600 | 10–75 /0.006 | ms–8 s | NA | < 100 ms | < –200 | 10–15 | NA |
| **Pumped hydro** | 50–100 (>500) | NA/0.1–0.2 | 0.5–1.5/0.2–2 | h–days | 1 min–h | s–min | Ambient | 0 | NA |
| **Compressed air (underground)** | 25–40 (No limit) | NA/0.2–0.6 | 30–60/12 | h–days | min–h | 1–15 min | Ambient | 0 | NA |

h = hours; min = minutes; ms = milliseconds; NA = not applicable; s = seconds

Each parameter listed in Table 2 requires careful consideration when assessing the suitability of energy storage technologies for grid-connected applications. Some of these parameters, as well as further battery terminology that is useful to understanding this report, are explained below.

The **charge cycle** (or 'cycle') is the process of charging a battery and discharging a battery within certain energy and time boundaries. The lifetime of a battery is often denoted by the total number of cycles that a battery can deliver. The **duty cycle** refers to the percentage of the cycle or time that the device is active, thus if a battery is charging for four hours and discharging for two hours of the day its duty cycle would be 25%. The duty cycle of specific energy storage systems is heavily dependent on the application.

The process of fully charging and discharging a battery is called a **deep-charge cycle.** The term is typically used to specify the expected life of a battery. The deep-charge cycle life is the number of completed deep-charge/discharge cycles that the battery can support before its capacity falls below 80% of its original capacity. Flow batteries, as opposed to lead-acid and Li-ion batteries, require deep-charge cycle operation to extend their expected life.

A battery's **state of charge (SoC)** is the equivalent of a car's fuel gauge – it shows how much energy is remaining. The unit of SoC is percentage, where 0% equates to an empty battery and 100% to a full battery. Some battery technologies, such as lead-acid and Li-ion batteries, can be operated at a partial SoC to improve their life expectancy. Understanding of the SoC concept is critical to managing battery life for lead-acid and lithium chemistry batteries. For example, discharging a lead-acid battery to 20% SoC and then later charging it to 80% SoC represents a charge cycle that would have less impact on the expected life of the battery under continued operation than running the same from 100% SoC to 0% and back to 100%. **Depth of discharge (DoD)** is another term describing the amount of charge a battery holds. A battery that is 100% charged has a DoD of 0%. If a battery has delivered 30% of its available energy, and hence has 70% of its energy reserved, then its DoD is 30%. When a battery is 100% empty, its DoD is 100%.

As a battery may stand in a stagnant, non-operating mode, it is common for **self-discharge** to occur. This is where the battery discharges (energy releases) on its own, i.e. in an open circuit, and is reported as percentage per day (%/day).

The amount of energy stored in a given system per unit volume or mass is referred to as the **energy density**. This can be measured in watt-hours per kilogram (Wh $kg^{-1}$) or kilowatt hours per cubic metre (kWh $m^{-3}$). In contrast, **power density** is the amount of power (time rate of energy transfer) per unit volume. Power density can be measured in watts per kilogram (W $kg^{-1}$) or kilowatts per cubic metre (kW $m^{-3}$).

Power and energy density are important characteristics to consider when looking at the needs of particular applications. For example, when cloud cover interrupts solar generation while electrical appliances are operating within a home, an energy storage technology may deliver a high amount of power quickly to cover for the shortfall. The power density is then a measure of the peak power a technology can deliver. In contrast, energy density is a measure of how much energy the technology can store. Many applications require energy, but not necessarily power. For example, a light-emitting diode on an emergency sign does not require high amounts of power, but the energy storage technology must be able to supply that energy for a long time.

Another factor that influences the power delivery of a storage technology is **response time**. This is the time taken for the technology to reach its maximum power output over a given time; i.e. the time to go from dormant status to peak operating mode. The response time can range from milliseconds (ms) to minutes (min) to hours (h).

**Operating temperature** refers to the temperature range a storage technology needs to be kept within for safe or reliable operation, and is particularly relevant for certain battery chemistries. The operation of a battery outside its preferred temperature range can significantly affect performance and lifetime, and increase the risk of explosion. In this report, operating temperature is measured in degrees Celsius (°C).

**Voltage** is the electric energy difference across a circuit. For a battery, this is from the negative to the positive terminals. This difference in electrical energy is used to run an electronic circuit or load, such as a mobile phone. The **critical voltage/cell is** the correct charge voltage of a battery; e.g. for a lead-acid battery, this ranges from 2.30 to 2.45 volts (V) per cell. In this example, setting the critical voltage threshold is a compromise. On one hand, the battery should be fully charged to achieve maximum capacity and avoid sulfation on the negative plate, which can reduce battery longevity. On the other hand, an oversaturated condition causes battery electrical grid corrosion on the positive plate and induces hydrogen gassing, which also significantly limits battery life.

Most energy storage applications have specific power and energy requirements, which can place bounds on the type of energy storage technology deployed. To select the best-suited energy storage technology with the most value, it is vital to assess the needs of the application for which it is required.

### 1.2.1 Energy storage characteristics to consider for the Australian grid

The characteristics of batteries and other energy storage technologies discussed above help define the suitability of those technologies for certain grid-connected applications in the Australian environment. While these applications will be described further in Part 2 of this report, some examples of the impacts of particular storage technology characteristics include the following.

- Lead-acid batteries operate best in temperatures below 40 °C. This makes them potentially unsuitable for peak load reduction applications that coincide with high ambient temperatures. High temperatures will also significantly reduce the life of the battery.
- The fast-discharge characteristic of super/double-layer capacitors make them potentially suitable for co-location with renewable resources, to smooth out ramp rates arising from moving cloud cover for solar, or changes in wind speed for wind turbines.
- Sodium sulfur batteries have a slow recharge time and a high operating temperature, and are therefore potentially unsuitable for daily energy-shifting applications at a residential level.

Although each energy storage technology in Table 2 is suitable for grid-connected applications, no single technology is suitable for all applications. This is due to the vast range of grid-connected applications that different energy storage technologies can meet: for example, responding to high demand at peak times in the grid, smoothing ramp rates of intermittent renewable generation, or shifting load to support the grid. More detail on the grid-based requirements for energy storage in the context of frequency and voltage control in Australian electricity grids is provided in Part 2 of this report.

Importantly, some of the technologies listed in Table 2 are more mature than others, and thus are suitable for immediate deployment for grid applications. Examples of existing larger-scale deployments include advanced lead-acid batteries that have been demonstrated in the Hampton Wind Park, New South Wales, and Li-ion batteries installed on Mackerel Island, Western Australia [4]. However, other technologies require further development, and mass production issues need solving before large-scale deployment is possible. Therefore, caution should be taken when assessing the performance and safety of grid-connected energy storage in given applications.

The Australian environment also presents many challenges to the widespread deployment of grid-connected energy storage, including:

- unique geography, climate and environment
- varying population density
- unique grid structures
- supply chain issues
- availability of local technical expertise
- unique operational and regulatory environment.

Further investigation into the feasibility of grid-connected energy storage in the Australian context is required. In the following section, we discuss current challenges and knowledge gaps identified for deployable technologies.

### 1.2.2 Technical challenges and identified knowledge gaps for energy storage

One of the key questions asked about energy storage is how a particular storage asset will last in use, particularly in the Australian environment. Until now, traditional generation of electricity has relied solely on mechanical processes (e.g. pumps or turbines). In that context, lifetime estimation is relatively straightforward, because it can be determined from factors such as efficiency and materials performance, material mechanical and/or thermal stress parameters, and operation times.

In the context of chemical storage (e.g. advanced lead-acid, Li-ion, flow and molten salt batteries), such traditional lifetime estimation methods cannot be used. Chemical energy storage relies on the conversion of one chemical species into another. These reactions typically occur in systems with other chemicals present, and degradation can occur via many routes, such as:

- materials fatigue
- extra, uncontrolled reactions that are not part of the storage reaction (e.g. sulfation in lead-acid batteries)
- temperature effects on the rate at which reactions occur (especially those related to degradation processes).

Parameters that affect the lifetime of batteries are described below. The combination of the effect of all of these factors then dictates how long a battery will last for in operation.

***Depth of discharge***

The quantity of chemicals changed during the battery operation is dependent on the DoD: the higher the DoD, the more chemical changes occur (both wanted and parasitic). The lifetime of batteries is also strongly related to DoD: the lower the DoD, the greater the lifetime and number of cycles the battery can achieve. For example, a lead-acid battery with a DoD of 5% can provide close to 15 000 cycles at a given temperature and cycle rate. However, under the same conditions, using a DoD of

90% reduces the cycle number to almost 600. The DoD a battery will experience in operation is dependent on the duty cycle and system configuration.

***Charging level***

The charging level of batteries can strongly affect their lifetime and must be optimised for each individual technology. For technologies such as Li-ion, reducing the charge cut-off voltage (i.e. the charging limit) can have the same effect as operating at a lower DoD (i.e. it partially charges the battery). This comes at the cost of operating the battery at lower than its potential capacity. For other technologies, such as lead-acid, reducing the charging level has the opposite effect and decreases lifetime. A high voltage cut-off is required for lead-acid batteries to negate some of the unwanted reactions (e.g. equalisation charging, float charging or sulfation charging to address different issues with the cell).

***Charging rate***

Like charging level, the rate at which the battery is charged strongly influences lifetime. At high rates of charging or discharging, the chemical reactions cannot keep up with the required current being added or drawn from the cell. This results in either incomplete chemical changes (which can lead to degradation reactions in some cases) or reduced cell capacity. For some technology types, such as Li-ion, fast charging/discharging can lead to mechanical fatigue in the crystalline electrode materials. The resulting fragmentation/breakage reduces capacity. High charging rates also increase the cell temperature (see 'Temperature effects' below).

***Voltage limits***

All batteries have a characteristic voltage range in which the desired chemical reactions occur. The limits are dependent on the technology type, but are set at a point between the desired and undesired reactions occurring. Working outside these ranges (i.e. overcharging/discharging) results in unwanted chemical changes and a reduced lifetime. For some technologies, these unwanted reactions can produce gas/explosion hazards if the limits are not strictly adhered to. Typically, the overcharging/discharging process also increases the cell temperature and pressure, which leads to additional problems.

***Cell formation/conditioning***

In typical manufacturing processes, battery electrodes are often not constructed in the optimal state for battery usage, for commercial reasons. To solve this, most manufacturers use a conditioning or formation process based on cycling to optimise the battery cells. The amount of cycles required to form the optimal electrodes is dependent on the battery type and chemical formulation. An incomplete formation step can lead to shorter lifetimes than expected.

***Cell ageing***

During cycling, physical (morphological) changes occur to the electrodes in combination with the chemical changes. In many batteries, these morphological changes are not reversed completely during the cycle and continue to build up during operation of multiple cycles, eventually degrading the electrode. As a consequence, battery lifetime can be shortened. The battery chemistry/type dictates the type of degradative morphological changes occurring.

***Cell interactions***

At the simplest level, a battery consists of two electrodes called a cell. Cell voltages are dependent on the chemistry type, but typically range from 1–4 V. Commercial batteries, which come in sizes of 12 or 24 V or higher, are made by stringing multiple individual cells together in a single package until the desired package voltage is reached. In these multi-cell batteries, the placement of a bad cell (which can result from manufacturing tolerances, variable temperature across the pack, or lower capacity of the cell) can lead to detrimental effects or non-uniform ageing across all of the cells in the pack. Overall, this shortens battery lifetime and is difficult to identify in systems that do not have expensive monitoring electronics.

***System setup***

The configuration of an energy storage system using batteries will have a big impact on battery lifetime. For example, a battery will have a short lifetime if it is directly connected to an intermittent generation source (variable and high DoD) and expected to provide high power/energy (i.e. fast discharging rates) with no cooling system in place. In contrast, a system will have a longer lifetime if it has significantly oversized battery units, allowing each cell to experience a low DoD, a cooling system and suitably buffered intermittent generation. Though the latter system has better performance, it costs much more than the former. The identification of optimal trade-offs here is not trivial.

***Chemical changes***

Unwanted (parasitic) chemical changes can occur in batteries alongside the desired chemical changes needed for battery operation. The rate at which these unwanted reactions occur and the chemical products they form strongly reduces battery lifetime.

***Storage/shelf time***

Many batteries are stored for extended periods of time before being used. Alternatively, while in use, they may be required to be non-operational for long periods (e.g. backup power applications). This storage time can affect some battery chemistries if unwanted chemical changes occur.

***Depletion of active chemicals***

Under different operating or storage conditions, factors such as pressure, temperature and duration of reaction (charging/discharging period) can cause the active chemicals in batteries to break down or combine in different ways. These reactions can significantly shorten battery life. An example of this is the formation of electrolyte breakdown products on lithium battery electrodes during the charging/discharging process. Typically, these products are formed on each cycle and continually deplete the electrolyte solution.

***Quality of battery***

The quality of a battery and its method of manufacture greatly affect its lifetime. In some instances, contamination of materials can exacerbate parasitic reactions. Other contaminants, such as metallic particles from cell manufacturing, can lead to short circuits or additional degradative processes. The performance of some batteries (e.g. lead-acid) can be affected by the quantity of active material (e.g. large quantities, typically for deep-discharge cells) on the electrode, or the electrode geometry and setup.

***Temperature effects***

The chemical reactions that occur in the battery (both wanted and parasitic) are strongly dependent on temperature. Increasing the temperature of the battery during operation or storage periods increases the rate of the chemical reactions. Thus, higher temperature can greatly increase a battery's performance. However, the degradative reactions will also occur at a much higher rate, with the overall effect of reducing the battery lifetime.

***Pressure***

For batteries constructed in a sealed cell format, the increase in internal pressure can have detrimental effects on lifetime. High currents or high ambient temperatures will cause the cell temperature to rise, and the resulting expansion of the active chemicals increases the internal pressure in the cell. Overcharging also causes the release of gases, resulting in an even greater build up in the internal pressure, which can shorten battery lifetime.

***Mechanical stress***

For some batteries, mechanical stresses are placed onto the electrode during the cycling process (e.g. the grids in lead-acid or flow batteries, or the crystal in Li-ion batteries). Over the course of multiple cycles, the electrodes can break apart and detach from the conductive pathways to the terminal, reducing the lifetime of the battery.

***Passivation***

Some of the detrimental parasitic chemical changes that occur in batteries can lead to the formation of insulating solid products, which are deposited onto the electrode surface (e.g. the solid electrolyte interphase in lithium batteries, or lead sulfate in lead-acid cells). Over time, the build up of these products reduces the available electrode area for the desired battery chemical reactions. This reduces the cell's ability to deliver the current and increases its internal resistance, which shortens cell lifetimes. The rate at which this passivation occurs is dependent on factors such as battery chemistry type, duty cycle, DoD and temperature.

***Loss of electrolyte***

Any reduction in electrolyte volume reduces battery lifetime. This can occur through parasitic reactions or venting/leaking of electrolyte. In extreme events, significant loss of electrolyte can cause rapid failure.

***Venting***

Some battery types allow excess gas to vent into the atmosphere. For technologies such as Li-ion this can be a safety feature, where gassing occurs due to irreversible breakdown of chemical components. Any venting leads to loss of electrolyte. For technologies such as sealed lead-acid batteries, which produce some gas as part of the reactions, this loss of gas reduces lifetime.

***Manufacturing tolerances***

Battery life can be affected by variation in materials and cell configurations. Factors such as chemical composition can vary from supplier to supplier and batch to batch. If the change is sufficiently significant, this can affect the battery lifetime. Dimensional changes in electrode/component geometries can also affect cell lifetime. For example, misalignments can cause short-circuiting, or smaller electrodes can lead to excess current being applied to the cell.

The factors described above all play a role in determining battery lifetimes in operation. The actual application of the batteries then feeds into these effects. For example, a battery placed at a utility level will require a specific duty cycle. Typically, these will be large installations with multiple cells and packs, and will have dedicated cooling systems. A residential system (e.g. required for time shifting of renewables) will have far fewer cells, a simpler cooling system (or perhaps none) and a markedly different duty cycle. Thus, the lifetime for the same battery technology type will be very different in each application.

In addition to this, Australia's unique geography and variable climate zones have a range of detrimental effects on an unprotected battery system. Figure 1 demonstrates a new lead-acid battery system being cycled in unprotected Australian summer conditions. Although the technology type should, in principle, last for several years, the consequence of high temperatures causes battery failure after a few months. This example highlights the significant knowledge gap about how batteries operate in Australian climatic conditions and whether ambient temperature control systems are required, and if so, at what level of sophistication.

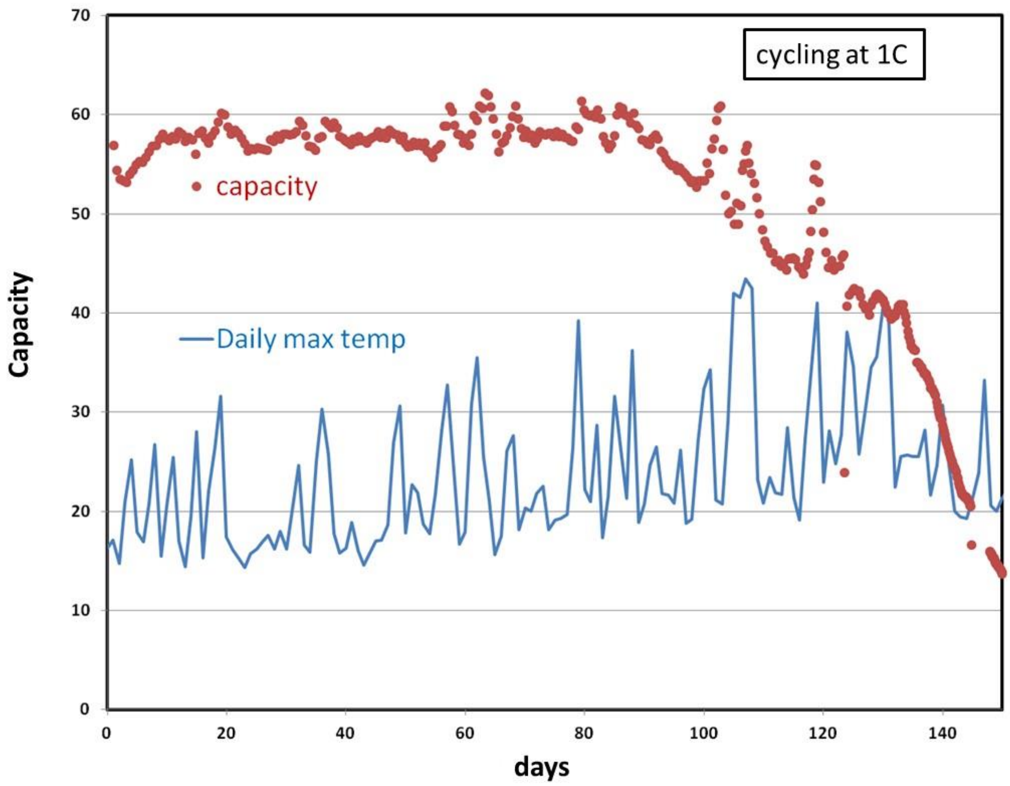



**Figure 1 Example of a new lead-acid battery being cycled in unprotected conditions during a typical Australian summer. The expected several years of life are not reached, with high temperatures leading to premature failure. Note that 1C cycling refers to discharging and charging at a rate that would nominally take 1 hour to fully discharge or charge the battery (see 'C-rate' in Section 1.1)**

In the context of energy storage for the grid, the effect that battery parameters have on technology lifetime creates further significant knowledge gaps due to incomplete or missing research. In particular, a lack of research on the expected duty cycle of various battery technologies hampers determination its effects on lifetime. Although research has been conducted for overseas grid connections, these results cannot directly be transferred into an Australian context, because the

Australian-specific parameters that can change duty cycles or temperature effects have not been accounted for.

The following specific knowledge gaps need to be addressed in an Australian context:

1. Define duty cycles for different grid-connection configurations, such as
   - grid-side (bulk energy shifting, power quality, regulation services, managing intermittency, network upgrade deferral)
   - customer-side – industrial level (power quality, customer energy management, backup power)
   - customer-side – residential level (backup power, customer energy management, bulk energy shifting, power quality).

   After these duty cycles have been identified for each application, standardised evaluation of storage technologies against these conditions is required to ascertain if the technology can be effectively used for this application, as well as the performance/operation limitations.

2. Determine the effect of Australian climatic conditions on battery and energy storage system performance for each of the preceding applications.

3. Establish real-world deployments within Australia to confirm if the technology can deliver sufficient levels of performance to solidify consumer confidence.

4. Compare different manufacturers to gauge quality and performance of technologies, and enable appropriate safety guidelines/regulations for grid-connected systems to be developed.

5. Identify the unique Australian challenges for energy storage systems, e.g. bushfire regulations affecting on-site deployment.

For some of the more mature technologies, such as lead-acid batteries, some of this information is already known due to their long use as backup power and remote area applications. However, for the newer technologies, these knowledge gaps require additional dedicated studies.

## 1.3 Energy storage applications impact: Australia 2015–2030

Given the large number and diverse range of electrical energy storage technologies, a number of specific technologies and application areas were selected for specific consideration in this report. These considerations are taken from the viewpoint of the likelihood of a particular technologies' uptake in the next 15 years.

The rationale for the selection of specific focus technologies was informed by their technical maturity levels and relevance to the Australian context, but is in no way either an endorsement of these technologies or a prediction of their market uptake. Rather, our intent was to identify a range of technologies that would help focus discussion on how the technical aspects of different energy storage technologies apply to various deployment scenarios.

In considering areas suited to the application of energy storage, the great diversity in Australia's electricity grid must be taken into account. The grid ranges from large and sparsely populated rural areas through to densely populated suburban areas, with a varying mix of conventional generation, wind generation, and increasing amounts of distributed small-scale photovoltaic (PV) systems.

With this diversity comes a wide range of potential applications for energy storage, including:

- **bulk energy storage** – shifting energy between different times of the day (or longer) to manage the differences between availability of generation and requirements of loads
- **regulation services** – providing ancillary services such as grid frequency regulation and more localised services such as voltage regulation
- **backup power** – providing power supply in the event of outages. This can be at an individual customer level or local distribution network (such as a minigrid), or to assist with restarting the wider grid after massive failure
- **network upgrade deferral** – providing targeted locational storage to supplement network capacity where it is insufficient, particularly in scenarios where this occurs very infrequently. This could be used at any level within the electricity network, from managing transmission infrastructure down to low-voltage distribution networks
- **customer energy management** – customers deploying storage to manage their site loads/generation to avoid peak demand or capacity charges
- **power quality** – targeting a range of power quality issues, both at a network and individual customer level. These include helping manage voltage or frequency of the supply, and the rate of change of power on the system
- **managing intermittency of renewables** – smoothing the fast and significant variability in power output of wind and solar resources.

In light of these applications, energy storage presents an opportunity to address the following pressing or growing issues within the Australian electricity system:

- The rapid uptake of air-conditioning within the residential sector has reduced load diversity, increasing the likelihood of significant peak demand changes on hot days.
- The uptake of PV, especially within the residential sector, has significantly reduced daytime loads (even resulting in reverse power flows in some network areas). This has resulted in a wider daily range of power demand in many network areas, causing issues in managing network voltages, and provided broader challenges in protection system design.
- Commercial/industrial electricity charges have significantly increased, particularly related to peak demand or capacity charges.
- Intermittency in generation output due to variations in solar and wind resources will become more significant as increased amounts of renewable energy (specifically PV and wind) are connected to the grid.
- The falling costs of energy storage, with an increasing number of systems marketed directly to consumers and low value of surplus PV generation exported to the grid, coupled with the emerging electric vehicle (EV) market, will likely increase deployments of energy storage by consumers, often behind the meter.

Following these considerations, and in consultation with the Australian Energy Market Commission (AEMC), the following five focus application areas of energy storage were chosen. The specific considerations within each area are noted in parentheses.

1. Large-scale renewable integration (intermittency of large-scale wind and PV systems)
2. Distribution network support (frequency support, voltage management)
3. Commercial and industrial energy management (power quality support, reduction in peak demand and capacity charges)
4. Residential energy management (reduced energy charges, management of peak demand)
5. Electric vehicles (suitability of EV storage systems for residential/commercial applications)

Note that the application terminology discussed above will be considered in more detail in Part 2 of this report. The following subsections give some detail of existing Australian deployments and technical maturity, before presenting the selected technologies in more detail.

Note that when considering this selection, exclusion of a specific technology does not imply that it does not have a role in managing Australia's energy systems. For example, large-scale pumped hydro is technically mature and already deployed at scale, yet is better aligned for bulk energy storage than the five specific application areas that have been chosen for further consideration.

### 1.3.1 Existing Australian energy storage deployments

A range of current energy storage installations in Australia are highlighted in Figure 2. Although this image is not comprehensive, it does demonstrate the range of technologies in use. A comprehensive list is given in Table 3.


**Figure 2 Examples of deployed energy storage systems in Australia**

**Table 3 Summary of deployments of energy storage in Australia and influencing factors for increased uptake**

| Technology type | Location | Commercial influencing factors | Details |
|---|---|---|---|
| **Advanced lead-acid** | King Island, Tasmania | Current ARENA project | 3 MW power, 1.6 MWh usable energy |
| **Advanced lead-acid** | Hampton, New South Wales | Decommissioned | 1 MW wind power smoothing storage |
| **Lithium nickel manganese oxide battery (in polymer battery format)** | TransGrid iDemand, Western Sydney | Operating | 350 kWh demonstrator |
| **Lithium iron phosphate battery** | Mackerel Islands, Western Australia | Operating | 325 kW |
| **Lithium iron phosphate battery** | Queensland | Operating | 25 kW, 4 hours |
| **Lithium polymer battery** | Horsley Park , New South Wales | Operating | 100 kW, 4 hours |
| **Lithium-ion battery (specific chemistry unavailable)** | Newington, New South Wales | Decommissioned | 60 kW |
| **Zinc bromine flow battery** | Elermore Vale/South Wallsend, New South Wales | Demonstrated | 200 kW power and 400 kWh storage |
| **Zinc bromine flow battery** | Scone, New South Wales | Demonstrated | 100 kW power and 200 kWh storage |
| **Zinc bromine flow battery** | University of Queensland, Queensland | Demonstrated | 90 kW power and 240 kWh storage |
| **Zinc bromine flow battery** | CSIRO Mayfield West, NSW | Decommissioned | 100 kW power and 500 kWh storage |
| **Battery**[a] | Cape Barren Island , Tasmania | Non-operational | 163 kW |
| **Battery**[a] | Magnetic Island, Queensland | Demonstrated | Modular 5 kW (20 kWh) batteries |
| **Battery**[a] | Muswellbrook , New South Wales | Operational | 14 kW, 15 kWh |
| **Flywheel** | Marble Bar and Nullagine, Western Australia | Operating | 2 x 500 kW (5 kWh) flywheel energy storage systems |
| **Flywheel** | Coral Bay, Western Australia | Operating | 500 kW, rated power 36 seconds |

| | | | |
|---|---|---|---|
| **Flywheel** | Leinster , Western Australia | Decommissioned | 1 MW |
| **Graphite block (thermal storage)** | Lake Cargelligo, New South Wales | Demonstrated | 3.5 $MW_e$ |
| **Pumped hydro** | Wivenhoe Pocket, Queensland | Operating | 500 MW |
| **Pumped hydro** | Bendeela and Kangaroo Valley, New South Wales | Operating | 80 + 160 MW |
| **Pumped hydro** | Great Lake , Tasmania | Operating | 300 MW |
| **Pumped hydro** | Great Lake , Tasmania | Operating | 1.7 MW |
| **Pumped hydro** | Tumut River, New South Wales | Operating | 250 MW per unit (6 units) |

ARENA = Australian Renewable Energy Agency

[a] Energy storage installation has limited available information on specific technology type used

Most of the deployments described in Figure 2 and Table 3 are larger-scale or field trial demonstrations. The lack of smaller-scale deployments identified by this review is due to the difficulty in obtaining residential-scale installation data, because no accreditation, incentive or registration programs are in place to capture this information. However, the availability of different scales of energy storage in Australia is growing. This is demonstrated through the number of manufacturers of various energy storage systems in the Australian market (see Appendix C). Note that the majority of Australia's storage is manufactured offshore in the United States, Korea, Japan and China.

A number of energy storage technologies have been commercialised to date and many more are still under development. Presently, major battery manufacturers – including Sanyo, Panasonic, BYD, Tesla, General Electric (GE) and FIAMM – are gearing towards the release of residential-scale, grid-connected energy storage systems. This movement will likely promote the growth of the market, echoing trends seen in the solar panel and electronic manufacturing industries. Growth in international and Australian markets is expected to reduce the costs of energy storage through 'learning-by-doing' and economies of scale in production.

#### 1.3.1.1 Overall Australian market-adoption trajectory for energy storage

Various studies in recent years have examined the prospects for the uptake of energy storage in Australia. The Future Grid Forum [5] explored the impact of energy storage on the network and on electricity prices under four different scenarios, where energy storage was considered to be on-site at load, grid-scale and supporting renewable sources of generation. The study found that storage had a role to play in almost all likely future scenarios for Australia's electricity grid.

However, for storage to be used to the extent suggested under these scenarios, a 'megashift' will be required in the storage market. This includes changes upstream in the manufacture of storage technologies and sustained investment in materials. One such example of a significant change in the manufacture of storage technologies (Li-ion batteries in particular) is the Tesla Gigafactory. The projected output of the Gigafactory by 2020 (35 GWh/year of batteries) equals the current global battery manufacturing capacity [6] for such a technology. This type of investment by Tesla and the other major manufacturers is broadly expected to drive technology prices down and thus significantly increase market adoption.

Marchment Hill, when consulting for the Clean Energy Council [7], modelled the impact of energy storage on the Australian electricity sector. They found that storage uptake could reach levels of between 3300 and 1900 MW by 2030, with a similar trajectory to that of PV penetration. This is from the current low level on the residential scale, with 2014 estimates of only 500 grid-connected systems and 4–5 MW of off-grid systems [8]. The Swiss global financial services company UBS calls the current residential PV plus battery storage market in Australia a 'cottage industry' [9], but it has the potential for large cost reductions, and thus the potential to become mainstream. The International Renewable Energy Agency also believes energy storage technology will be deployed to a much greater extent than in the past. Government support has also increased deployments, and hence has helped bring costs down – in particular, for the manufacture of Li-ion battery chemistries [10].

The Australian Energy Market Operator (AEMO) modelled the potential for 100% renewables to supply the entire National Energy Market (NEM) electricity demand from 2030 to 2050 [11]. Unfortunately, trajectories were not modelled, but the study did find that significant amounts of large-scale energy storage were required: ~25–30% of installed generation capacity. The generation technologies considered in this study were biomass, biogas, hydro (including pumped hydro) and concentrating solar thermal. No new hydro plants were assumed to be constructed, thus most of the new potential energy storage required was associated with biogas and concentrating solar thermal generation [11].

More recently, AEMO have released a report that observes the momentum of battery storage and EVs internationally, and recognises the urgency to overcome some of the challenges this will present in the Australian context [12].

From the limited number of studies available, we conclude that while the current market for energy storage may be relatively small, we expect it to grow significantly as renewable energy penetration increases – particularly in the residential and commercial sectors.

### 1.3.2 Assessment of energy storage technologies

With so many different types of energy storage technology, and many more emerging, we have limited the scope of our deeper analysis of energy storage in the Australian context based on the following criteria:

- level of technology readiness (TRL)
- level of manufacturing readiness (MRL)
- demonstrations or commercial deployments
- market trends.

TRL [13] and MRL [14] criteria show the readiness of a technology to be commercialised and deployed; that is, the technical capabilities have been proven in actual application, it is ready 'off-the-shelf', and full-rate, optimised production processes have been demonstrated. As the energy storage market is recognised as emerging, the technologies closest to the higher end of these scales are most likely to reach deployment faster and thus have greater uptake. Demonstrations or commercial deployments of technologies show maturity and give confidence in the technology for the desired applications.

Table 4 summarises our assessment of various energy storage technologies. This includes TRLs, MRLs, present Australian deployments and market trends for energy storage in Australia. Further descriptions of TRLs and MRLs can be found in Appendix B.

**Table 4 Energy storage technology assessment**

| Technology | TRL | MRL | Presently deployed in Australia? | Market trends (e.g. growth, stable, decline) | Other comments | Include in detailed assessment? |
|---|---|---|---|---|---|---|
| **Lead-acid battery** | 9 | 10 | Yes | Marginal growth | Benchmark technology | X |
| **Advanced lead-acid battery** | 8 | 7 | Limited | Anticipate growth | Significant potential as based on well-known technology | ✓ |
| **Nickel-cadmium battery** | 9 | 9 | N/A | Decline | Decline due to environmental issues & memory effect | X |
| **Lithium iron phosphate battery** | 9 | 9 | Yes | Strong growth | Robust chemistry, market leader, increasing number of deployments; e.g. BYD [15], Samsung SDI [16] | ✓ |
| **Lithium nickel cobalt aluminium oxide battery** | 9 | 9 | Near term | Anticipate strong growth | Tesla electrical vehicles | |
| **Lithium nickel manganese cobalt oxide battery** | 9 | 9 | Near term | Anticipate strong growth | Residential and commercial storage, e.g. Tesla Powerwall | ✓ |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Sodium sulfur battery** | 6 | 6 | N/A | N/A | Niche applications | X |
| **Sodium nickel chloride (molten salt battery)** | 8 | 7 | Unknown | Anticipate growth | Anticipated Australian deployments – GE Durathon [17] | ✓ |
| **Zinc bromide flow battery** | 9 | 8 | Yes | Growth | Number of Australian deployments | ✓ |
| **Vanadium redox flow battery** | 8 | 7 | Limited | Stable | Environmental concerns, short life in demonstration | X |
| **Flywheel** | 7 | 8 | Yes | Stable | Off-grid application deployments | X |
| **Super/double-layer capacitors** | 7 | 8 | Yes | Stable | Niche applications | X |
| **Superconducting magnetic energy storage** | 7 | 5 | No | N/A | Complex technology, no deployments in Australia | X |
| **Pumped hydro (includes coastal storage)** | 9 | 10 | Yes | Decline | Limited areas and political sensitivity issues | X |
| **Compressed air (underground)** | 9 | 7 | No | Stable | Limited round-trip efficiency, limited deployment sites in Australia | X |

N/A = not applicable

From this assessment, energy storage technologies with a TRL and MRL of 8–9 (i.e. successfully operated in at least a limited operational environment) were considered further. The technologies that were eliminated at this step were considered potentially unsuitable for grid connection within the scope of this review due to their perceived lack of off-the-shelf readiness, or if their Australian market trends did not show promise of an emerging trend.

### 1.3.3 Energy storage technologies selected for further analysis

The growth in the energy storage market is being driven by the residential sector, as costs reduce and more manufacturers announce new products. Batteries are becoming a popular storage choice in this market; hence, our review focuses on this emerging trend.

The five energy storage technologies selected for deeper analysis in this review are:

- advanced lead-acid batteries
- lithium iron phosphate batteries
- lithium-ion batteries (lithium nickel manganese cobalt oxide)
- zinc bromine flow batteries
- sodium nickel chloride batteries.

Each of these is technologies is described and analysed in depth in the following section. For background detail on other technologies listed in Table 4, please refer to Appendix A.

## 1.4 Analysis of focus energy storage technologies

In this section, we explain the five battery technologies that are the focus of this review. Some background information relevant to all five technologies is given below.

A battery consists of two electrodes: a positive (cathode) and a negative (anode). In between these two electrodes is a layer of electrolyte, which can be made of a liquid, gel or solid material. The electrolyte allows the movement of electrons or ions within the cells during what is known as a redox reaction. The movement of the electrons or ions creates a current flow out of the battery, which allows the device to do electrical work.

Batteries also contain insulating separators to prevent the electrodes from physical contact and potential short-circuiting. Depending on the chemistry of the battery, additional safety features such as pressure relief valves may also be incorporated; the type of feature is specific to the device type. Multiple battery cells can be combined to create battery packs with performance characteristics required for the desired application. The choice of chemical compounds used for the electrolyte and electrodes determines the nature of the battery device, the redox reaction, cell voltages, and energy storage and power capability.

In primary battery systems, once the redox reaction occurs, the electrolyte cannot be regenerated. Secondary battery systems regenerate their chemical compounds back into the original state upon the application of a current (i.e. rechargeable technology). In this review, we only consider rechargeable technologies, which can be charged and recharged from the local grid or by renewable generation, and can also be used by EVs.

### 1.4.1 Lithium-ion battery (lithium iron phosphate)

A large number of technologies come under the broad heading of Li-ion batteries. For reference, an ion is an atom or molecule in which the total number of electrons is not equal to the total number of protons, giving the atom or molecule a net positive or negative electrical charge.

In this and the following section (1.4.2), we will consider two specific technologies: lithium iron phosphate ($LiFePO_4$) and lithium nickel manganese cobalt oxide (NMC) technologies. These two technologies are approaching off-the-shelf readiness for grid-based applications.

#### 1.4.1.1 Basic chemistry

Li-ion batteries operate by the removal of lithium cations (atoms that have lost an electron to become positively charged) from the cathode crystals on the positive side of battery. The lithium cations are then inserted into the graphite layers of the anode during the charge reaction. Upon discharge, the lithium cations are removed from the graphite and inserted back into the cathode material. This is illustrated for a battery system in Figure 3. The electrolytes for Li-ion batteries typically consist of a carbonate-based organic solvent with additives to improve cycling, or a lithium-ion conducting polymer for solid-state devices (known in the industry as polymer batteries or LiPo batteries).

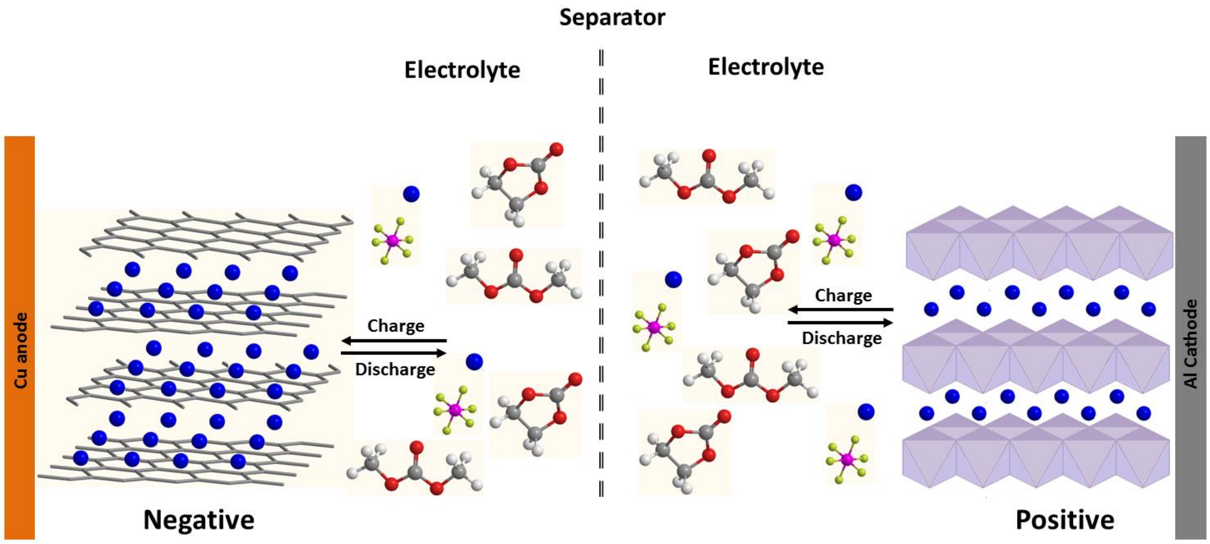



**Figure 3 Schematic of a lithium battery: operation showing the insertion and de-insertion of lithium ions (blue spheres) into the graphite (negative) and cathode (positive) matrixes during charge and discharge. This general schematic describes the majority of rechargeable lithium-ion batteries, regardless of cathode and anode material type**

Since the commercialisation of the $LiCoO_2$ system in 1990 by Sony, a number of different materials have been found to act as the host crystals for the Li-ions. The more prevalent materials are shown in Table 5. Anode materials such as lithium titanates or silicones are also being used in Li-ion batteries; however, at the time of writing, graphite is the most common anode material.

**Table 5 Typical characteristics of typical lithium-ion cathode materials showing maximum discharge voltage and gravimetric capacities**

| Material components | Chemical formula | Discharge voltage | Theoretical gravimetric capacity (Ah/kg) |
|---|---|---|---|
| **Lithium cobalt oxide** | $LiCoO_2$ | 3.6 | 274 |
| **Lithium manganese oxide** | $Li_{1.07}Mn_{1.93}O_4$ | 3.9 | 117 |
| **Nickel cobalt aluminium** | $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ | 3.6 | 265 |
| **Nickel manganese cobalt** | $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ | 4.4 | 170 |
| **Lithium iron phosphate** | $LiFePO_4$ | 3.4 | 170 |

#### 1.4.1.2 Existing technology development/maturity level

$LiFePO_4$ technology is relatively mature in the Li-ion battery technology spectrum, having been commercially available for a number of years for small-scale electronics, transport and power tools [18]. They have also been, and still are, deployed in EVs. The maturity level of this technology for grid-connection purposes is low, and in line with that of alternative technologies in the Li-ion battery spectrum. From a grid-connection perspective, a number of recent installations have demonstrated the use of $LiFePO_4$ batteries. These include a 325-kW $LiFePO_4$ system deployed in the Mackerel Islands in Western Australia, and a 430-kWh battery bank deployed by Transgrid at their New South Wales site through a local supplier, Magellan Power, using a $LiFePO_4$-polymer battery (supplied by Kokam). Large battery manufacturers (some shown in Appendix C) are now beginning to commercialise $LiFePO_4$ batteries for large-scale storage at the 100's of kWh level, as well as introducing them to the residential market in integrated packages. The table in Appendix C also highlights some onshore manufacturers who can assemble pre-made batteries sourced from the battery manufacturers into energy storage systems that can be deployed for grid connection.

#### 1.4.1.3 Technical advantages and disadvantages

Safety is a serious issue in Li-ion battery technologies. Most of the metal oxide electrodes are thermally unstable and can decompose at elevated temperatures. This releases oxygen, which can lead to thermal runaway (i.e. fire). $LiFePO_4$ chemistry was designed to reduce the risk of thermal runaway compared to other Li-ion technologies, and is thus widely regarded as the safest lithium chemistry.

To minimise the risk of thermal runaway, some cell manufacturers equip the batteries with a monitoring unit to avoid overcharging and over-discharging. Usually, a voltage balance circuit is also installed to monitor the voltage level of each individual cell and to prevent voltage deviations among a series of cells.

Li-ion batteries generally have a very high efficiency, typically in the range of 95% to 98% (where efficiency is a measure of how much energy is wasted during a charge/discharge cycle). Nearly any discharge time – from seconds to weeks – can be realised, which makes them a very flexible and universal storage technology. Standard cells with 5000 full cycles can be obtained on the market at short notice, but even higher cycle rates are potentially possible with further development, mainly depending on the materials used for the electrodes.

The operating parameters of Li-ion batteries are set out in Table 6, and their advantages and disadvantages are summarised in Table 7.

**Table 6 Operating parameters of lithium-ion batteries**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Lithium-ion battery** | 8–15 <br> (500-6000) | 230–340/1300–10000 | 100–250/250–620 | min–h | min–h | 20 ms–s | −10 to 50 | 0.1–0.3 | 3 |

**Table 7 Advantages and disadvantages of lithium-ion battery technologies**

| Advantages | Disadvantages |
|---|---|
| • High specific energy density <br> • High power density <br> • No memory effect <br> • Low self-discharge rate <br> • Widely available for many devices and applications <br> • High cell voltage | • High cost <br> • Safety risks such as thermal runaway and fire <br> • Poor recycling options and rate <br> • High temperature has adverse effect on capacity/cycle life |

The main advantages of Li-ion batteries are their high energy storage and power delivery abilities compared with competing batteries with alternative chemistries. However, at present, the market is held back by their high safety risks and manufacturing costs. Li-ion batteries have a high cycle count (longer lifetime) and high energy density, and their response time is appropriate for intermittency management for renewable generation and daily (full cycle, not partial SoC) bulk energy shifting. Concerns for this technology's chemistry in particular are that cycling outside of the operating range leads to significant safety risks of fire from thermal runaway, and that limited (if any) processes are available for recycling the materials.

#### 1.4.1.4 Most common applications/desired outcomes

The Li-ion characteristics of high power and energy storage make them suitable for grid-connected applications, such as power quality, network efficiency, backup power, time shifting, power quality and time shifting of renewables' generation. These applications and Li-ion technology are also mentioned in Section 1.4.2.4 and described in further detail in Part 2 of this report.

#### 1.4.1.5 Current Australian adoption

The Li-ion type of battery has been used for many years in consumer electronics, and thus its current deployment in those types of applications is high. Many large-scale energy storage systems that incorporate this battery chemistry are available to the Australian market, but large-scale uptake of these appears to be limited.

CSIRO understands several Li-ion suppliers are currently exploring opportunities to expand in the Australian market. Battery manufacturers such as BYD and Samsung are now designing and making available complete energy storage systems for the residential and commercial market. These systems include not just the batteries, but also all the associated electronics, inverters and software required for operation. AGL and other energy retailers have announced combined solar and energy storage systems using this type of technology for residential customers, and many commentators suggest there is a very significant potential market for this technology in Australia.

### 1.4.2 Lithium-ion battery (nickel manganese cobalt oxide)

As mentioned in Section 1.4.1, NMC battery technologies are also approaching off-the-shelf readiness for grid-based applications.

#### 1.4.2.1 Basic chemistry

The chemistry of the NMC battery is similar to that of the $LiFePO_4$ battery. The charge/discharge reactions involve the same processes as that shown in Figure 3. The main difference is the addition of a small quantity of nickel and manganese into the $LiCoO_2$ crystal. This increases the pore size where lithium cations reside, which reduces the mechanical stress the crystal faces during the insertion/desertion process and thus improves performance.

#### 1.4.2.2 Existing technology development/maturity level

The NMC battery is a newer technology in the Li-ion battery spectrum. It has been developed specifically to increase the energy storage and power capabilities of the $LiFePO_4$ technology. Commercialisation of this technology has only recently occurred; thus, the maturity level is lower than that of the $LiFePO_4$ battery. Some key challenges still need to be solved for this technology to reach its full potential, such as the need for stable electrolytes that do not break down and cause battery failure at higher operating voltages.

A number of manufacturers are beginning to develop NMC technology for commercial applications. Appendix C lists some of the large manufacturers developing NMC-based solutions specifically for the grid storage market.

#### 1.4.2.3 Technical advantages and disadvantages

The higher energy storage capability of NMC technology verses $LiFePO_4$ technology (for the same sized units) is favourable. However, being a new technology, NMC has more concerns regarding its safety and operational performance compared with the proven $LiFePO_4$ technology.

#### 1.4.2.4 Most common applications/desired outcomes

Due to the high energy and power capabilities of Li-ion batteries (both $LiFePO_4$ and NMC technologies), they can be deployed for a wide range of applications. At the utility level, they can be used for power quality, network efficiency, and off-grid and backup/emergency supply purposes. At the residential/industrial level, they can be used for connection to renewables for time shifting or backup supply, or for power quality applications.

#### 1.4.2.5 Current Australian adoption

The Transgrid iDemand system shows the potential for these types of batteries to become available through this supplier in Australia.

Further, the NMC energy storage systems recently announced by both Panasonic and Tesla could make residential energy storage systems more accessible to Australian households within the next few years. This is potentially a huge market. However, this battery chemistry will be competing with other Li-ion chemistries on the market as well as alternative battery options.

### 1.4.3 Advanced lead-acid battery

An advanced lead-acid battery is a hybrid energy storage device that combines the characteristics of a supercapacitor (described in Appendix A.3) and a conventional lead-acid battery at the materials level within the battery cell, without the need for extra, expensive, electronic control systems and wiring. An advanced lead-acid battery can operate at a high discharge/charge rate and/or partial SoC, while having the safety, recyclability and economic aspects of conventional lead-acid batteries.

#### 1.4.3.1 Basic chemistry

The schematic configuration of the lead-acid cell, a supercapacitor and an advanced lead-acid battery is shown in Figure 4.

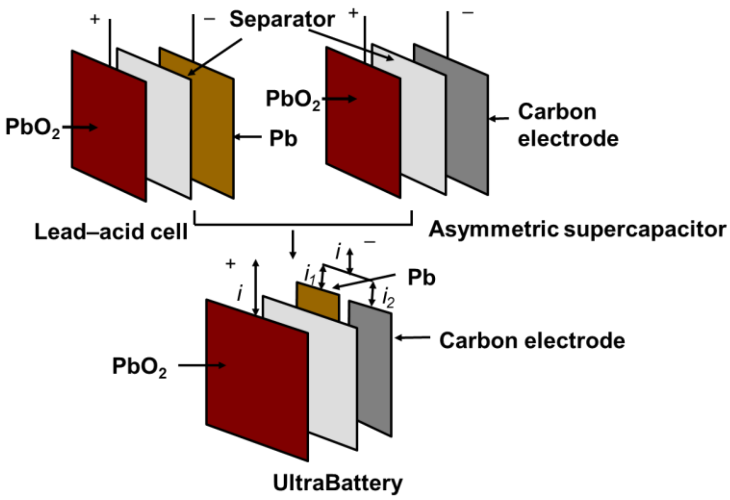



Figure 4 Advanced lead-acid battery chemistry

Figure 4 (top left) shows that a lead-acid cell comprises one lead dioxide positive plate and one sponge lead negative plate. An asymmetric supercapacitor (top right) is formed when a lead negative plate of the lead-acid cell is replaced by a carbon-based negative plate (i.e. capacitor electrode). Since the positive plates in the lead-acid cell and the asymmetric supercapacitor have a common composition, they can be integrated into one unit cell (the 'UltraBattery', bottom of Figure 4) by internally connecting the negative plates of the battery and the supercapacitor in parallel. Both these electrodes now share the same positive plate in the advanced lead-acid battery. This then creates a hybrid device that has properties of both a conventional lead-acid cell and a supercapacitor, and can achieve high power delivery.

To further explain the basic chemistry of the advanced lead-acid battery, we provide some details on a traditional lead-acid battery (shown in Figure 5), which is based on the reactions of lead compounds with sulfuric acid in an electrochemical cell.

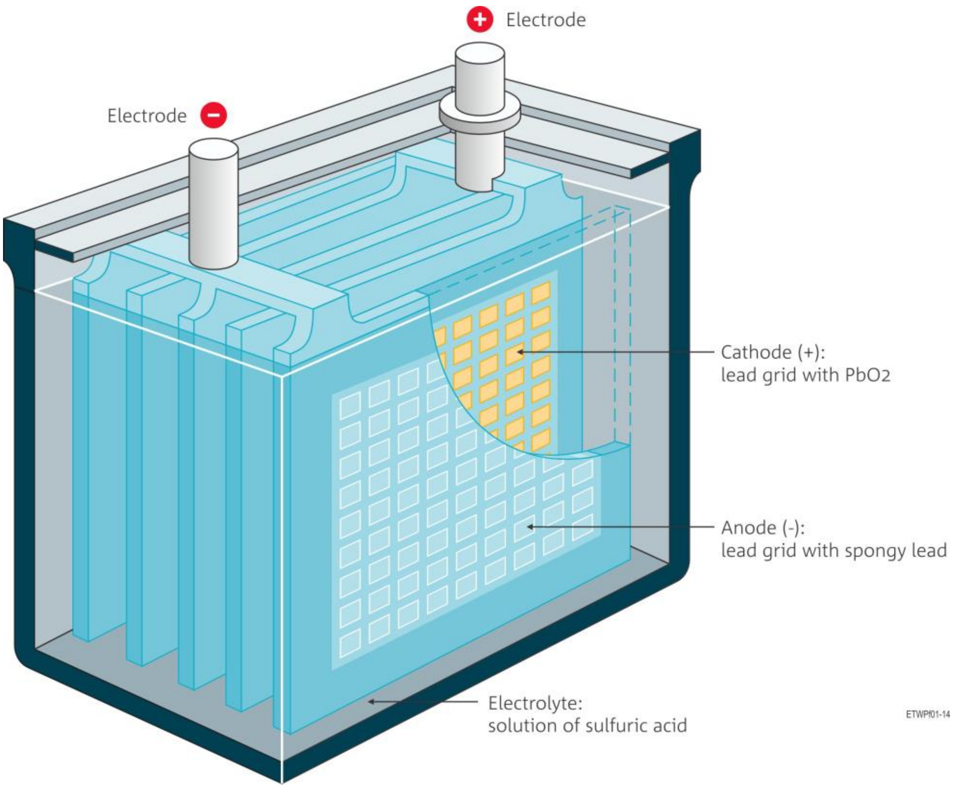



**Figure 5 Construction of a lead-acid battery**

During discharge, the metallic lead at the anode oxidises (loses electrons) and reacts with the sulfate anion. An anion is an atom that has gained an electron to become negatively charged: in this case from the dissociated sulfuric acid electrolyte. The reaction liberates the electrons needed for the external current. At the cathode, protons from the electrolyte combine with the oxygen from the lead dioxide, $PbO_2$, which is reduced (gains electrons). This forms water and frees the lead to combine with the sulfate ions. The four positive charges from the four protons are neutralised by the two negative charges of the sulfate ion and by two additional negative charges from electrons arriving at the cathode via the external load.

Both the power and energy capacities of lead-acid batteries are based on the size and geometry of the electrodes. The power capacity can be improved by increasing the surface area for each electrode, which means using greater quantities of thinner electrode plates in the battery.

Under high-rate, partial SoC cycling applications, traditional lead-acid batteries fail prematurely due to a progressive build up of lead sulfate on the negative plates (sulfation), which is difficult to remove during recharge. Sulfation markedly reduces the effective surface area, so that the plate can no longer deliver and accept the required power.

In contrast, the lifecycle of advanced lead-acid batteries is longer than that of traditional lead-acid batteries because they avoid the build up of lead sulfate due to the supercapacitor's activated carbon electrode, which reduces sulfation.

#### 1.4.3.2 Existing technology, development, maturity and applications

Advanced lead-acid batteries are currently being used in hybrid EVs and renewable energy storage solutions, including integration into electricity grids. Advanced lead-acid batteries have demonstrated that the technology has a similar working potential to that of the conventional lead-acid battery, and can be manufactured in existing lead-acid battery factories.

One well-known version of the advanced lead-acid battery is the UltraBattery, developed by CSIRO. The UltraBattery technology has been licensed to the Furukawa Battery Co., Ltd, Japan and the East Penn Manufacturing Co., Inc., United States.

Existing applications for advanced lead-acid batteries include:

- Duke Energy's project with 24-MWh battery with a 36-MW charge/discharge limit, grid-connected in the United States [19]
- Hydro Tasmania's project with a 1.6-MWh battery with a 3-MW charge/discharge limit, grid-connected at King Island Renewable Energy Integration in Australia [20]
- a demonstration 500-kWh battery with a 1-MW charge/discharge limit, grid-connected at Hampton Wind Farm in Australia [21]
- a 2.1-MWh battery with a 3-MW charge/discharge limit, grid-connected at Pennsylvania-Jersey-Maryland Interconnection in the United States [22]

For further details of manufacturers of advanced lead-acid batteries, see Appendix C.

#### 1.4.3.3 Technical advantages and disadvantages

The operating parameters of advanced and conventional lead-acid batteries are compared in Table 8, and the advantages and disadvantages of advanced lead-acid systems are summarised in Table 9.

**Table 8 Operating parameters of advanced and conventional lead-acid batteries**

| Parameter → | Typical life time | Power density | Energy density | Typical discharge time | Recharge time | Response time | Operating temperature | Self-discharge | Critical voltage/cell |
|---|---|---|---|---|---|---|---|---|---|
| Technology ↓ | Years (cycles) | $Wkg^{-1}$ $/kWm^{-3}$ | $Whkg^{-1}$ $/kWhm^{-3}$ | | | | °C | %/day | V |
| **Lead-acid battery** | 3–15 (2000) | 75–300/90–700 | 30–50/75 | min– h | 8–16 h | 5–10 ms | −10 to 40 | 0.1–0.3 | 1.75 |
| **Advanced lead-acid battery** | 3–15 (3000) | 75–300/90–700 | 30–50/75 | min–h | 8–16 h | 5 ms | −10 to 40 | 0.1–0.3 | 2 |

**Table 9 Advantages and disadvantages of advanced lead-acid batteries**

| Advantages | Disadvantages |
|---|---|
| • Low cost<br>• Low self-discharge<br>• Rapid response<br>• Has one of the highest recycling rates compared to other batteries | • Relatively low specific energy density<br>• Need to be kept at charged state<br>• Uses toxic lead and corrosive acid<br>• Shorter cycle life at higher temperatures |

The main advantages of the advanced lead-acid battery technology are its low cost (compared to competitive technologies), commercial availability and the fact that it is based on well-known lead-acid batteries. Its disadvantages are mainly related to the high toxicity of the components and low energy density compared with newer technologies, such as nickel metal hydride or Li-ion cells. Additional advantages of the advanced technology over the standard lead-acid battery include a greater number of possible cycles and thus longer expected battery life. This battery technology can also operate in a high-efficiency partial SoC range, with reduced sulfation compared with a traditional lead-acid battery. Combined with the fast response made possible by the supercapacitor, this makes the advanced lead-acid technology particularly suitable for applications such as managing intermittency from renewable generation and regulation services. Given the well-established recycling processes for lead-acid batteries, environmental concerns about the toxic and corrosive disadvantages of the materials can be largely mitigated.

#### 1.4.3.4 Most common applications/desired outcomes

The advanced lead-acid battery technology was originally designed to operate in vehicles, where partial SoC cycling is key. However, this design feature also lends itself to grid-connected applications. The advanced lead-acid battery is thus suited for applications that require both high power and energy, such as:

- backup power
- off-grid/remote applications
- power quality
- time shifting of renewables generation.

#### 1.4.3.5 Current Australian adoption

Limited data is available to predict the market-adoption trajectory of advanced lead-acid batteries. However, with one demonstration project and one current operating installation in Australia, and with various manufacturers producing this technology, the technology has the potential to be adopted here at a greater scale.

### 1.4.4 Zinc bromine flow battery

A flow battery stores energy in one or more species of ions dissolved into liquid electrolytes. The electrolytes are stored externally in tanks and pumped through electrochemical cells, which convert chemical energy directly to electricity and vice versa during operation.

The power capacity of a flow battery is defined by the size and design of the electrochemical cell, whereas the energy capacity depends on the size of the tanks. With this characteristic, flow batteries can be fitted to a wide range of stationary applications. Flow batteries are classified into hybrid flow batteries and redox flow batteries (a redox reaction, or oxidation-reduction reaction, is a chemical process that occurs in acid-base reactions). The zinc bromine (Zn-Br) flow battery is a type of hybrid flow battery (Figure 6).

#### 1.4.4.1 Basic chemistry

In a Zn-Br flow battery, the electrolyte solution for the anode reaction (anolyte) consists of an acid solution of $Zn^{2+}$ ions. During charging, Zn is deposited at the electrode, and at discharging, $Zn^{2+}$ goes back into solution. A solution of bromide ions in acid is used for the electrode solution for the cathode (catholyte). The charging process converts the bromide ions into bromine liquid. Since the bromine liquid is not readily dissolvable into the acid solution, a range of additives (the nature of which depends on manufacturer) are used to allow the bromine to stay in solution, and thereby take part in the discharge process where it is converted back into bromide ions.

The two electrode chambers of each cell are divided by a membrane, typically a microporous or ion-exchange variety. This helps to prevent bromine from reaching the positive electrode, where it would react with the zinc, causing the battery to self-discharge. To further reduce self-discharge and to reduce the vapour pressure of bromine, complexing agents are added to the positive electrolyte. These react reversibly with the bromine to form an aqueous solution and reduce the free $Br_2$ in the electrolyte. The working electrodes in the Zn-Br battery are based on carbon-plastic composites.

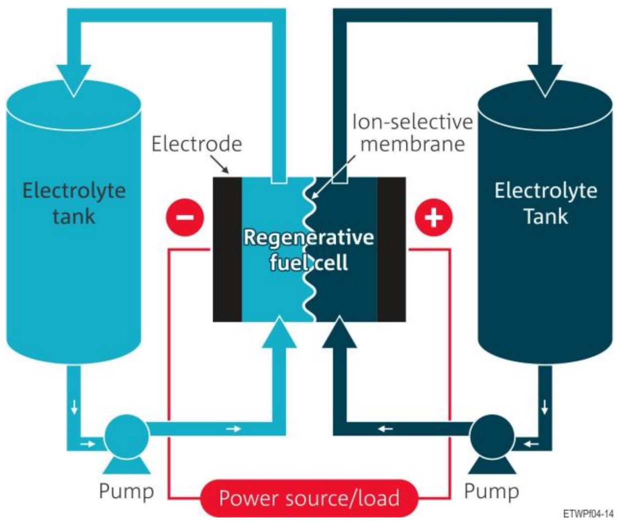



**Figure 6 Schematic of a hybrid flow battery showing the anolyte and catholyte tanks and fuel cell components**

#### 1.4.4.2 Existing technology development, maturity and applications

Originally developed by NASA in the early 1970s as energy storage systems for long-term space flights, flow batteries are now receiving attention for storing electrical energy for hours or days, with a power of up to several MW [23].

Various companies are working on the commercialisation of the Zn-Br hybrid flow battery. In the United States, ZBB Energy Corporation and Premium Power sell trailer-transportable Zn-Br systems with unit capacities of up to 1 MW/3 MWh for utility-scale applications [24]. In Australia, Redflow have developed a Zn-Br system for electrical energy storage applications [25].

In the United States, flow battery projects with up to 500 kW rated power have been used in demonstrations for load shifting, peak shaving, renewable system integration and voltage support.

In Australia, Redflow have produced 5 kW/10 kWh modules that have been used in demonstrations for renewable energy time shifting and capacity firming (i.e. maintaining a fixed level of generation for a period of time from intermittent generation sources) at a number of sites. These include the

90 kW and 120 kW systems at the University of Queensland and Smart Grid projects in Newcastle and Scone [26]. A few years ago, ZBB Energy Corporation supplied a 100 kW system for renewable energy grid integration testing at a CSIRO site in Newcastle, at a cost of US$3 million. Key manufacturers of flow batteries (both redox and hybrid variants) are listed in Appendix C.

#### 1.4.4.3 Technical advantages and disadvantages

The operating parameters of Zn-Br flow batteries are shown in Table 10, and the advantages and disadvantages of Zn-Br flow batteries are summarised in Table 11 .

**Table 10 Operating parameters of zinc bromide flow batteries**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ / $kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ / $kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Zinc bromide flow battery** | 5–10 (300-1500) | 50–150/1–25 | 60–80/20–35 | s–10h | 4 h | <1 ms | 10 to 45 | 0–1 | 0.17–0.3 |

**Table 11 Advantages and disadvantages of zinc bromide batteries**

| Advantages | Disadvantages |
|---|---|
| • Fast response<br>• Easily scalable<br>• Long cycle life<br>• Parts can be replaced individually<br>• Tolerance to overcharge/over-discharge | • Still in development and demonstration stage<br>• High cost<br>• Complicated with multiple components<br>• Low specific energy density<br>• Limited electrolyte stability<br>• Require external power to operate |

Zn-Br batteries can theoretically be 100% discharged every day without being damaged, and this can be repeated for more than 2000 cycles. The technology is scalable, due to the ease of connection of multiple modules, and has lower safety risks than technologies such as Li-ion. However, the technology is still in a developmental stage. The mechanical nature of the storage technology (e.g. pumps) means that maintenance will be required during operational lifetimes, which could discourage some consumers. The technology also has a lower energy density than other battery types.

The technical characteristics of flow batteries, such as typical long discharge time and recharge time, make this technology type appropriate for daily energy shifting, providing backup power in the event of outages, bulk energy storage or regulation services. However, these battery systems have some environmental and safety concerns regarding bromine leaching and the toxicity of vanadium.

#### 1.4.4.4 Most common applications/desired outcomes

Flow battery technology can be used for time shifting, network efficiency and off-grid applications at the utility level. At the industrial/residential level, the technology is suited for connection to renewables and time-shifting applications. The inherently larger footprint of the technology compared with competing technologies may lead to residential consumers investing in alternative technologies with smaller footprints (e.g. lead-acid batteries).

#### 1.4.4.5 Current Australian adoption

The Australian deployments to date (outlined in Section 1.4.4.2) have been limited to demonstrations and trials [27] of this technology; however, flow batteries are also available commercially at the residential, commercial and utility scale. The current market trajectory for flow batteries looks promising. An onshore manufacturer with a business dedicated to the emerging renewables storage market is likely to grow this market. The technology can compete with other technologies and is likely to have a market share in the future. The technology still needs to be proven in large-scale deployments to entice utilities and consumers to purchase the product.

### 1.4.5 Sodium nickel chloride battery

Sodium nickel chloride (Na-$NiCl_2$) batteries are a type of molten (liquid) salt battery. They consist of molten $NiCl_2$ at the positive electrode/cathode and molten Na at the negative electrode/anode [28]. The active materials are separated by a solid beta alumina ceramic electrolyte. The battery temperature is kept around 300 °C to keep the electrodes molten. If the temperature drops and the electrodes solidify, then the battery ceases to operate. This high temperature introduces a time lag where a heating step is required before the battery can operate if it has cooled (e.g. for shipping or maintenance). Typically, the heating time from room temperature is 9–13 hours.

#### 1.4.5.1 Basic chemistry

The battery operates by converting Na ions (from molten $NaCl_2$ in the electrolyte) into liquid Na metal and vice versa at the anode. Simultaneously, at the cathode, Ni metal is converted into $NiCl_2$ (and vice versa) during the charging/discharging processes.

#### 1.4.5.2 Existing technology development, maturity and applications

The Na-$NiCl_2$ battery was developed in 1985 by ZEBRA (the Zeolite Battery Research Africa Project) at the Council for Scientific and Industrial Research in Pretoria, South Africa.

Since around 1990, Na-$NiCl_2$ batteries have been manufactured by a number of companies from Japan, Italy and the United States, with a minimum module size of 50 kW and typically 300–360 kWh. Key manufacturers of molten salt batteries are listed in Appendix C.

It is not practical at present to use only one isolated Na-$NiCl_2$ module. Since 20 modules are typically combined into one battery, the minimal commercial power and energy range is in the order of 1 MW and 6–8MWh. These batteries are suitable for bulk storage applications with daily energy cycling. Two major manufacturers, GE and FIAMM, have developed Na-$NiCl_2$ battery technologies specifically for the emerging grid storage market in Australia.

At the time of writing, we are not aware of any large-scale deployments of the molten salt battery technology within Australia. FIAMM, through its local representative LC Engineering (Queensland) has developed a standalone molten salt battery generator for the mining industry, but it is unclear whether these modules have been sold or deployed. GE is apparently soon introducing its variant into the Australian marketplace, but it is not yet commercially available.

### 1.4.5.3 Technical advantages and disadvantages

The operating parameters of sodium sulfur (Na-S) and Na-$NiCl_2$ batteries are compared in Table 12, while the advantages and disadvantages of Na-$NiCl_2$ batteries are summarised in Table 13.

Na-$NiCl_2$ batteries reach typical life cycles of around 4500 cycles and have a discharge time of 6 to 8 hours. They have an efficiency of about 75% and have a fast response time.

The main drawback is that a heat source is required to maintain the required operating temperatures. This uses the battery's own stored energy, thereby partially reducing the battery performance. In daily use, the temperature of the battery can almost be maintained by just its own reaction heat, with appropriately dimensioned insulation.

**Table 12 Operating parameters of sodium sulfur and sodium nickel chloride batteries**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ / $kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ / $kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Sodium sulfur battery** | 12–20 (>2000) | 90–230/120–160 | 150–240/<400 | s–h | 9 h | 1 ms | 300 | 20 | 1.75–1.9 |
| **Sodium nickel chloride battery** | 12–20 (4000-4500) | 130–160/250–270 | 125/150–200 | min–h | 6–8 h | 100 ms | 270 to 350 | 15 | 1.8–2.5 |

The high operating temperature, recharging time and energy density of Na-$NiCl_2$ batteries make them very suitable to bulk energy-shifting and large-scale systems. The fast response time also adds to the capability to mitigate intermittency when co-located with renewable generation installations. Due to the high temperatures, there are obvious safety risks to be considered when operating this technology.

**Table 13 Advantages and disadvantages of sodium nickel chloride batteries**

| Advantages | Disadvantages |
|---|---|
| • Can withstand high temperatures <br> • Long cycle life <br> • Fast response <br> • Long discharge time <br> • Quite mature and commercially available <br> • Can be used for electric vehicles | • Expensive <br> • Use hazardous material <br> • Hard to construct <br> • Needs parasitic power to maintain molten operating temperature (300 °C) |

### 1.4.5.4 Most common applications/desired outcomes

Na-$NiCl_2$ batteries are suited to industrial-scale connection to renewable energy and time-shifting applications, as well as off-grid energy generation. Some manufacturers have developed the Na-$NiCl_2$ battery for residential applications for time shifting of renewables generation, making energy available when the consumer requires it. Advantages of this technology over others in this application is that there is no need for air conditioning and the system can operate in extreme temperature conditions. However, the system requires parasitic power to maintain molten operating temperature thus the residential application where use may be irregular and have low duty cycles might not be best suited to this technology. Aside from this Na-$NiCl_2$ batteries are relatively maintenance free and have a long cycle life.

#### 1.4.5.5 Current Australian adoption

As described above, there are currently no Australian deployments of Na-$NiCl_2$ energy storage technology, however there is interest for entry into the Australian market [17]. Some global manufacturers have targeted applications for this technology including telecommunications and electric vehicles which indicate growth in demand for this technology type and potential for the stationary energy storage application.

## 1.5 Summary

Many energy storage technologies are available today. At the time of writing, the technologies reviewed in the preceding sections are currently best placed in terms of technology, manufacturing readiness assessment and proven real-world trials.

The identified five key energy storage technologies are summarised in Table 14. From this table, we can see that each energy storage technology has its own advantages and disadvantages, with no one particular technology being the overall winner.

Currently, advanced lead-acid technology is believed to be one of the best options for electrical energy storage in the short to medium term, mainly due to its availability, safety record, high recycling rate and low cost.

For Li-ion, flow and molten salt battery technologies, supply chains are emerging and potential end-of-life processes are being developed. Though in the short term (1–2 years) early adopters may deploy these technologies, the medium term (2–5 years) is when large-scale deployments of these particular technologies are expected to occur once supply chain, pricing, operation and maintenance and end-of-life processes are identified, developed and implemented.

**Table 14 Summary of typical parameters of five identified energy storage technologies**

| Parameter | Advanced lead-acid battery | Lithium iron phosphate battery | Lithium nickel manganese cobalt oxide battery | Zinc bromide flow battery | Sodium nickel chloride battery (molten salt) |
|---|---|---|---|---|---|
| **Depth of discharge (%)** | 40–50 | 50–90 | 50–90 | 100 | 20–90 |
| **Cycle life (no. cycles)** | 1000–10000 | 3000–6000 [a] | 750–8000 | 300–1500 | 4000–4500 |
| **Cycle life determination conditions** | 1000 cycles at 100% and 10 000 cycles at 5% DoD at 1C rate[b] | 100% DoD at 1C rate. 6000 cycles at 25 °C and 3000 at 60 °C | 750 cycles at 100% DoD and 8000 cycles at 80% DoD and 1C[c] | 100% DoD at C/8 rate[d] | 80% DoD at C/5 rate[e] |
| **Lifetime (years)** | 10 | 5–10 | 8 | 5–10 | 10–15 |
| **Round-trip efficiency (%)** | 90–98 | 89 | 95 | 75 | 85 |
| **Suitable application (energy, power or both)** | Energy | Both | Both | Energy | Energy |
| **Typical charge time** | 3–5 hours | Mins–hours | Mins–hours | 4 hours | 9–13 hours |
| **Typical discharge time** | 2–3 hours | Mins–hours | Mins–hours | Secs–hours | Secs–hours |
| **Operating temperature (°C)** | –10 to 32 | 0 to 45 | –10 to 50 | 5 to 45 | 270 to 350 battery internal, with –40 to 60 ambient temperature |

**a** Based on BYD $LiFePO_4$ battery specifications, which are typical for the technology type

**b** Calculated from S. Ferreira, W. Baca, T. Hund, & D. Rose, 2012. Life Cycle Testing and Evaluation of Energy Storage Devices. Albuquerque, USA: Sandia National Laboratories

**c** Data for cycle life to 60% of initial capacity. For comparison, 2500 cycles are achieved for 80% of initial battery capacity as determined from Kokam technical specifications

**d** Rate calculated from cycle life testing data presented in 'An Assessment of the State of the Zinc Bromine Battery Development Effort by Garth P. Corey (29 October 2010)

**e** GE Durathon states 4000 cycles lifetime, but cycle life testing conditions not reported. Fiamm SoNiCk has 4000 cycles at 80% depth of discharge (DoD) and C/5 rate

# Part II Energy storage: status and applications

In Part 1 of this report, the technical characteristics, strengths and weaknesses of a wide range of energy storage technologies were considered as they apply to opportunities within the Australian electricity grid. From this high-level assessment, five technologies were chosen for more focused consideration. These are:

- advanced lead-acid batteries
- lithium iron phosphate ($LiFePO_4$) batteries
- lithium nickel manganese cobalt oxide (NMC)
- zinc bromine flow batteries
- sodium nickel chloride batteries.

Energy storage can play many roles in the Australian electricity system, and thus deliver multiple benefits. However, no single energy storage technology can fulfil all these roles. Therefore, a mix of technologies or a trade-off in performance and lifetime may have to be accepted.

For the scope of this report, we focus on the electric power grid that connects the eastern side of Australia (Queensland, New South Wales, Victoria, South Australia, the Australian Capital Territory and Tasmania). This grid forms the National Electricity Market (NEM) and is operated by AEMO.

To manage energy in the Australian electricity system, energy storage can be used in various ways across the supply chain. For example, **bulk energy storage** shifts energy between different times of the day (or longer) to manage differences between availability of generation and requirements of loads. Technologies appropriate for this application are typically focused on price and energy density. To **manage intermittency of renewables** – smoothing out the fast and significant variability in power output of wind and solar resources – faster response technologies should be deployed, where power density may be a greater consideration than energy density.

Energy storage may also be used to provide **regulation services**. These are ancillary services that support power quality in the electricity networks, such as frequency regulation, but may also include more localised services, such as voltage regulation. In these applications, a fast response is again a key requirement. Energy storage can also be used to provide **backup power** in the event of outages. This can be at an individual customer level, at the local distribution network level (such as a microgrid), or may be used to assist with grid black-start capability. For backup power, the key storage characteristics vary across deployments.

The use of large-scale energy storage at targeted locations can supplement network capacity for **network augmentation deferral**. Network augmentation deferral could be used at any level within the electricity network, from managing transmission infrastructure down to low-voltage distribution networks. Key characteristics here tend to focus more on price, reliability and temperature constraints, rather than response times.

Finally, **customer energy management** involves customers deploying storage to manage their own site loads/generation to avoid peak demand or capacity charges. This application is a significant driver for energy storage uptake in Australia, and could be met by a range of battery technologies. Electric vehicles (EVs) may also play a dual role in the future, providing a storage device to assist with home energy management in addition to transportation.

The following sections further explore how different energy storage technologies can be used in these different applications.

## 2.1. Suitability of focus technologies to application areas

With a diverse range of possible application areas for energy storage, no single technology solution is best in all cases. Rather, technical selection criteria need to consider the specific application need and how it aligns with the strengths of different technology options. For the five focus storage technologies identified in Part 1 of this report, the general fit of each with the application areas introduced in the previous section are summarised in Table 15. Note that while this table provides general guidance on technology applicability, a detailed assessment is needed before embarking upon any specific application.

**Table 15 Summary of general applicability of focus battery technologies to application areas**

| | Application | Advanced lead-acid | Lithium iron phosphate | Lithium nickel manganese cobalt oxide | Zinc bromide flow | Sodium nickel chloride molten salt |
|---|---|---|---|---|---|---|
| **Grid-side** | Large-scale renewable integration | ✓✓✓ | ✓ | ✓ | ✓ | ✓✓✓ |
| | Distribution network support | ✓✓ | ✓✓ | ✓✓ | X | X |
| **Customer-side** | Commercial and industrial energy management | ✓✓✓ | ✓✓ | ✓✓ | ✓✓ | ✓ |
| | Residential energy management | ✓✓ | ✓✓✓ | ✓✓✓ | ✓ | ✓ |
| | Electric vehicles | ✓ | ✓ | ✓✓ | X | X |

Key: X = very low (if any) applicability; ✓ = low applicability; ✓✓ = moderate applicability; ✓✓✓ = high applicability

Factors that were considered in developing the above summary table are further explored in the remainder of this section.

### 2.1.1. Grid-side applications and outcomes

Grid-side applications of energy storage involve deployments that support large-scale generation and the transmission network, through to power quality support within distribution networks.

Key grid-side applications are explained below, and their considerations summarised in Table 16.

***Bulk energy storage***

At the transmission level, bulk energy shifting allows more efficient use of transmission and generation infrastructure, and can be used to manage energy flows between regions. An example of this is shifting generation output from a solar generation system, such as solar thermal or photovoltaic (PV), into the late afternoon/evening to better align with demand. This also improves the use of generation and transmission infrastructure associated with the plant.

In this application, the energy storage system is able to charge and discharge over many hours, so does not require either high power levels or a fast response. Technically, this is well suited to the typical characteristics of flow or $LiFePO_4$ batteries; but, subject to transmission constraints, it could also be achieved using existing pumped hydro systems.

***Regulation services***

Within the National Energy Market (NEM), regulation services are managed by the Australian Energy Market Operator (AEMO) through the frequency control ancillary services (FCAS) markets, while network support and control ancillary services (NSCAS) are procured by transmission network service providers. FCAS and NSCAS include dispatch and automatic regulation of frequency and voltages at a transmission level, including generation/load balancing between regions. The fastest of these services is the six-second-frequency response, though all these services require a reasonably fast response. This makes them mostly unsuitable for energy storage systems that have a significant start-up time. Because these services are centrally controlled, they are most accessible to large-scale technologies (MW level), though they could be accessed by an energy service provider aggregating the response of a large number of smaller systems. Technically, regulation services are well suited to the typical characteristics of Li-ion or advanced lead-acid systems, though they are currently mostly provided by existing conventional generation.

***Network augmentation deferral***

At the transmission level, bulk energy storage can be used to help balance energy flows between regions and to reduce the diurnal generation cycle of renewable generation (such as solar or tidal). In these cases, this provides higher usage of network assets and can also avoid or defer the need for network upgrades. Similarly, within distribution networks, grid-side storage can be targeted to meeting demand peaks that may only last a few hours per year, but would otherwise require network augmentation to satisfy. In these cases, there may only be a small number of times per year where the energy storage system is required to operate, but during these times (which will often be aligned with extreme temperatures), reliable operation is essential. Technically, this is well suited to the typical characteristics of $LiFePO_4$ or advanced lead-acid systems, but may also be achieved by demand management schemes.

***Power quality***

With the increasing uptake of air-conditioning and widespread deployments of PV systems, distribution networks (especially in residential areas) are facing both higher peaks and lower troughs in demand. This is challenging the existing approaches to distribution-level voltage management. Voltage support functions can include basic real and reactive power regulation, but may also include fault ride-through functionality designed to help support the network during transient events – such as a voltage sag associated with start-up of a large load. Furthermore, the interaction between PV generation and loads can lead to increased harmonics, phase imbalance and low power factors. These factors are often highly location specific, require a fast response and need to be addressed at that point within the distribution network (and possibly on the customer side). Technically, this is well suited to the typical characteristics of Li-ion or advanced lead-acid systems. Since these would need to be distributed through the network, their small size and low maintenance are valuable attributes.

A similar situation exists with large-scale wind and PV generation systems, where output variability can impact power quality. Here, the integration of energy storage offers the potential to manage network power quality.

### *Managing intermittency of renewables*

Solar and wind resources can vary significantly over very short periods of time. At a single location, cloud cover can increase or reduce solar generation between full and no output within seconds. Fortunately for wind farms, large-scale PV and small-scale distributed PV, the aggregation of a number of generating units – all with slightly different conditions – significantly reduces this variability. Storage can supplement the benefits of such diversity by further smoothing renewable generation output, reducing the need for network regulation services, improving local power quality and making better use of network infrastructure. One approach to managing the intermittency of renewables is to impose ramp-rate constraints as a connection requirement. This is done to keep the rate at which renewable generation output power changes below a level that network equipment and other generators can respond to (such as through the regulation services, as above). Renewable resource variability is fast and occurs frequently, so storage systems with high power output and a long cycle life are best suited to this application. This fits the typical characteristics of Li-ion or advanced lead-acid systems, but could also suit technologies such as flywheel systems.

**Table 16 Considerations for grid-side energy storage systems**

| Application area | Specific considerations | Storage technologies |
|---|---|---|
| **Bulk energy storage** | High energy rather than power<br>Slow response is sufficient<br>Medium cycle life | Flow battery<br>Lithium iron phosphate |
| **Regulation services** | Fast response time<br>High power<br>Low cycle life is acceptable | Li-ion<br>Molten salt<br>Advanced lead-acid |
| **Network augmentation deferral** | High reliability<br>Low cycle life is acceptable | Advanced lead-acid<br>Lithium iron phosphate |
| **Power quality** | Fast response time<br>High power<br>Medium cycle life | Li-ion<br>Advanced lead-acid |
| **Intermittency** | Fast response time<br>High power<br>Long cycle life required | Li-ion<br>Advanced lead-acid |

More detailed requirements for a number of examples of grid-connected energy storage system applications, as identified by Fraunhofer and the International Electrotechnical Commission (IEC), are shown in Table 17.

**Table 17 Grid-side applications – energy storage requirements [29]**

| Application | Description | Size | Discharge duration | Cycles | Desired lifetime |
|---|---|---|---|---|---|
| **Large-scale renewables integration** | Wind integration (intermittency, power quality – ramp and voltage support) | 1–10 MW distributed<br>100–400 MW centralised | 1–30 min | 5000/year (10,000 full energy cycles) | 20 years |
| | Wind integration (bulk energy storage) | 100–400 MW | 5–10 hour | 300 to 500/year | 20 years |
| | PV integration (bulk energy storage, intermittency, power quality) | 1–2 MW | 15 min – 4 hour | <4000 | 15 years |
| **Stationary T&D support** | Urban and rural T&D – network augmentation deferral | 10–100 MW | 2–6 hours | 300–500/year | 15–20 years |
| **Distributed energy storage systems** | Utility sponsored on utility side of meter, feeder line, substation (power quality) | 25–200 kW 1-phase<br>25–75 kW 3-phase | 2–4 hours | 100–150/year | 10–15 years |

AC = alternating current; PV = photovoltaic; T&D = transmission and distribution

### 2.1.2. Customer-side applications and outcomes

Customer-side applications of energy storage involve deployments by the end user (residential, commercial or industrial) within their site. The storage can be targeted towards solving specific power quality or reliability issues, providing independence from the grid or reducing energy costs. In managing their local energy needs and responding to market signals, a customer-side deployment may also provide grid services.

Key customer-side applications are described below and their considerations are summarised in Table 18.

***Bulk energy storage***

At a customer level, bulk energy shifting allows energy to be moved to periods of maximum economic benefit, reducing tariff charges. As with the grid-side scenario, the energy storage system is able to charge and discharge over many hours, so does not require either high power levels or a fast response. Technically, this is well suited to the typical characteristics of $LiFePO_4$ batteries; because of the smaller scale, technologies such as flow or molten salt batteries are less attractive. Other customer-side options include load management, such as pre-cooling air-conditioning strategies, or thermal storage, such as ice slurries.

***Backup power***

Customers located in areas with frequent outages or with critical loads may elect to install their own backup energy storage system. Where the customer remains grid-connected, these systems will only be used infrequently, so a solution with a lower efficiency and cycle life is adequate. If the energy storage system is intended for a short duration to bridge the time needed to start up a backup (fossil-fuel-based) generator, then a high-power, low-energy system is appropriate. However, if the energy storage system is the sole backup, then it will be sized for a much longer discharge time, and the energy capacity of the system becomes more relevant. Technically, this is well suited to the typical characteristics of Li-ion, $LiFePO_4$ or advanced lead-acid battery systems.

***Maximum demand management***

Responding to tariff and market incentives will be a significant driver for the customer-side adoption of energy storage systems. For commercial and industrial customers, there is a particular opportunity to manage capacity charges, which may only involve demand reduction or use of energy storage a few times per year at peak times. In this case, an energy storage system does not require high energy or power output, and does not need to be highly efficient or have a long cycle life. This may be a co-benefit of a storage system deployed primarily for another purpose. Where a customer-side deployment is instead based around a daily energy cycle – such as managing time-of-use (TOU) tariff – then a much greater cycle life and efficiency system would be required, e.g. Li-ion or advanced lead-acid batteries.

***Power quality***

Large-scale commercial and industrial customers, in particular, have specific requirements for the characteristics of loads. This forms part of their connections agreement. In addition to the compliance issue, measures such as power factor correction can reduce capacity charges. Many energy storage systems can manage both real and reactive power, reducing capacity charges even further.

Some customers will also have equipment that requires higher power quality than that provided by the grid: e.g. semiconductor manufacturing facilities. Furthermore, customers (particularly residential) with on-site generation, such as PV, can at times find that their system is unable to generate or export due to high network voltages. For these customers, energy storage power quality functions may allow them to continue to operate/generate, rather than lose the expected revenue from their generation system.

Several power quality functions – including power factor corrections and managing phase imbalance – are achieved primarily by the inverter associated with a battery. Other functions require fast, infrequent use of the energy storage system. Hence, for power quality applications, the efficiency and cycle life are less important than fast availability of full power when required. Technically, this is well suited to the typical characteristics of Li-ion or advanced lead-acid battery systems.

***Managing intermittency of renewables***

At a customer level, the variability of renewable generation may be reduced as a connection requirement by the distribution network service provider, such as through a ramp rate specification. This may also be required where there are restrictions on export of energy to the electricity network, or economic incentives to avoid exporting energy. Since a single customer site is unlikely to be large enough to benefit significantly from the diversity seen at grid level, customer-side intermittency smoothing requires storage with faster response and higher power proportional output than would be required by the grid. This fits the typical characteristics of Li-ion or advanced lead-acid systems, while solutions such as flywheels that may be deployed grid-side are less likely to be viable on the customer side.

**Table 18 Considerations for customer-side energy storage systems**

| Application area | Specific considerations | Storage technologies |
|---|---|---|
| **Bulk energy storage** | High energy rather than power<br>Slow response is sufficient<br>Medium cycle life | Flow battery<br>Li-ion<br>Advanced lead-acid |
| **Backup power** | High energy rather than power<br>Slow response is sufficient<br>Shorter cycle life is adequate | Li-ion<br>Lithium iron phosphate<br>Advanced lead-acid |
| **Customer energy management** | Fast response time<br>High power<br>Long cycle life required | Li-ion<br>Lithium iron phosphate<br>Advanced lead-acid<br>Flow battery |
| **Power quality** | Fast response time<br>High power<br>Medium cycle life | Li-ion<br>Advanced lead-acid |
| **Intermittency** | Fast response time<br>High power<br>Long cycle life required | Li-ion<br>Advanced lead-acid |

More detailed requirements for a number of example customer-side energy storage system applications, as identified by Fraunhofer and the IEC, are shown in Table 19.

**Table 19 Customer-side applications – energy storage requirements [29]**

| Application | Description | Size | Discharge duration | Cycles | Desired lifetime |
|---|---|---|---|---|---|
| **C&I power quality** | Solution to avoid voltage sag and momentary outage (power quality) | 50–500 kW<br>1 MW | < 15 min<br>> 15 min | <50/year | 10 years |
| **C&I power reliability** | Provide UPS bridge to backup power, outage ride | 50 kW – 1 MW | 4–10 hours | <50/year | 10 years |

| | | | | | |
|---|---|---|---|---|---|
| | through (backup power) | | | | |
| **C&I energy management** | Reduce energy costs, increase reliability. Size varies by market. (Customer energy management, bulk energy storage) | 50 kW – 1 MW (small footprint)<br>1 M | 3–4 hours<br>4–6 hours | 400–1500/year | 15 years |
| **Residential energy management** | Efficiency, cost savings (customer energy management, bulk energy storage) | 2–5 kW | 2–4 hours | 150–400/year | 10–15 years |
| **Residential backup** | Reliability (backup power) | 2–5 kW | 2–4 hours | 150–400/year | 10 years |

C&I = commercial and industrial; UPS = uninterruptible power supply

### *Electric vehicles*

A potential opportunity to use energy storage in managing demand on the distribution network is to use capacity already purchased as part of EVs, targeting any of the customer-side applications noted above. Although EV uptake in Australia has been slow to date, in terms of energy storage, EV batteries can hold a significant amount of energy. The 24 kWh of the Nissan Leaf, or 85 kWh of the Telsa model S, are much greater than a typical residential battery system currently available of around 7 kWh.

EVs connect to the customer-side of the electricity system either directly (using an on-board AC charger) or through dedicated EV supply equipment (EVSE). There are various types (levels) of charging systems, with a number of competing technologies and standards in use, both internationally and within Australia. As an example, the IEC define four charging modes (IEC61851-1 2001):

- Mode 1 charging: connection of the EV to the electricity system via standard sockets, up to 16 A. This is a slow charge mode that does not require any special equipment and in Australia would typically be limited to 10 A (2.4 kW)
- Mode 2 charging: connection of the EV to the electricity system via standard sockets, plus the addition of a control signal (possibly between the EV and an in-cable controller)
- Mode 3 charging: connection of the EV to the electricity system via dedicated and permanently connected EVSE with control signal between the EV and EVSE
- Mode 4 charging: indirect connection of the EV to the electricity system via a dedicated and permanently connected EVSE with an off-board charger and control signal between the EV and EVSE. This would typically be a direct current, super-fast charger.

For Mode 2–4 charging, a control signal is used to provide various safety checks and allow setting of the charging rate. The controls may also allow real-time adjustment of the charging current, though this is not a mandatory requirement of IEC61851.

Without clear standards for EV charge management in response to electricity network conditions, the ability of EVs to actively contribute to managing customer-side applications is limited. The main benefit seen to date is that consumers are willing to alter their charging profiles considerably on the basis of financial incentives. For example, in United States trials[1], charging occurred predominately during a special EV overnight off-peak tariff in San Francisco, while in Australia, the Western Australian EV trial[2] saw charging predominately during daytime. In the future, vehicle-to-grid and vehicle-to-home standards may become available to export energy from an EV to support customer-side applications. However, such systems are still in early development.

It is unclear whether EV owners would want, or if vehicle manufacturers would allow, vehicle batteries to provide power and energy to the grid. The concern here is primarily that the additional use would degrade the batteries, or that they would be left in a state of partial (or low) charge when the vehicle is next required. Additionally, EV batteries are generally not appropriate for daily load cycling – only requiring reasonably low lifetime charge cycles (1000–2000) to meet typical driving requirements. Where an opportunity may emerge here is in addressing critical network peaks. Since these occur only infrequently, the impact on EV battery life is likely to be low. Lithium batteries (including NCM and $LiFePO_4$), with their reasonably high gravimetric specific energy (Wh/kg), are well suited to use in EVs, while advanced lead-acid batteries are also suited to hybrid vehicles where lower energy capacity is required.

***Residential off-grid applications***

Residential energy storage can be applied in completely off-grid applications, where in combination with an alternative generation supply, such as rooftop PV, it can replace any grid-connected electricity supply. In this case, ensuring a reliable electricity supply is a significant challenge to PV customers seeking to go off-grid, considering the daily variability of solar irradiance, temporary cloudy weather, and the time required to repair or replace equipment that malfunctions (e.g. an inverter). Such customers may choose to install redundant inverters and a battery with a capacity, charge/discharge rating and round-trip efficiency sufficient to ensure that electricity demand is met when solar irradiance is very low. This would typically require a battery capacity several times greater than that required by a grid-connected customer.

## 2.2. Network optimisation with distributed renewable generation

Australia currently has around 4 GW of installed PV solar and 3 GW wind generation capacity. While wind generation is predominately large scale, Australia has more than one million individual PV installations, mostly concentrated in residential areas, and therefore connected to the low-voltage distribution network.

Figure 7 provides a simplified representation of the electricity system, showing large-scale conventional centralised generation, plus large-scale renewables and industries connected through the transmission network. Smaller industries, plus commercial and residential customers, typically connect through the low-voltage distribution network.

[1] http://www.theevproject.com

[2] http://www.therevproject.com/waevtrial/

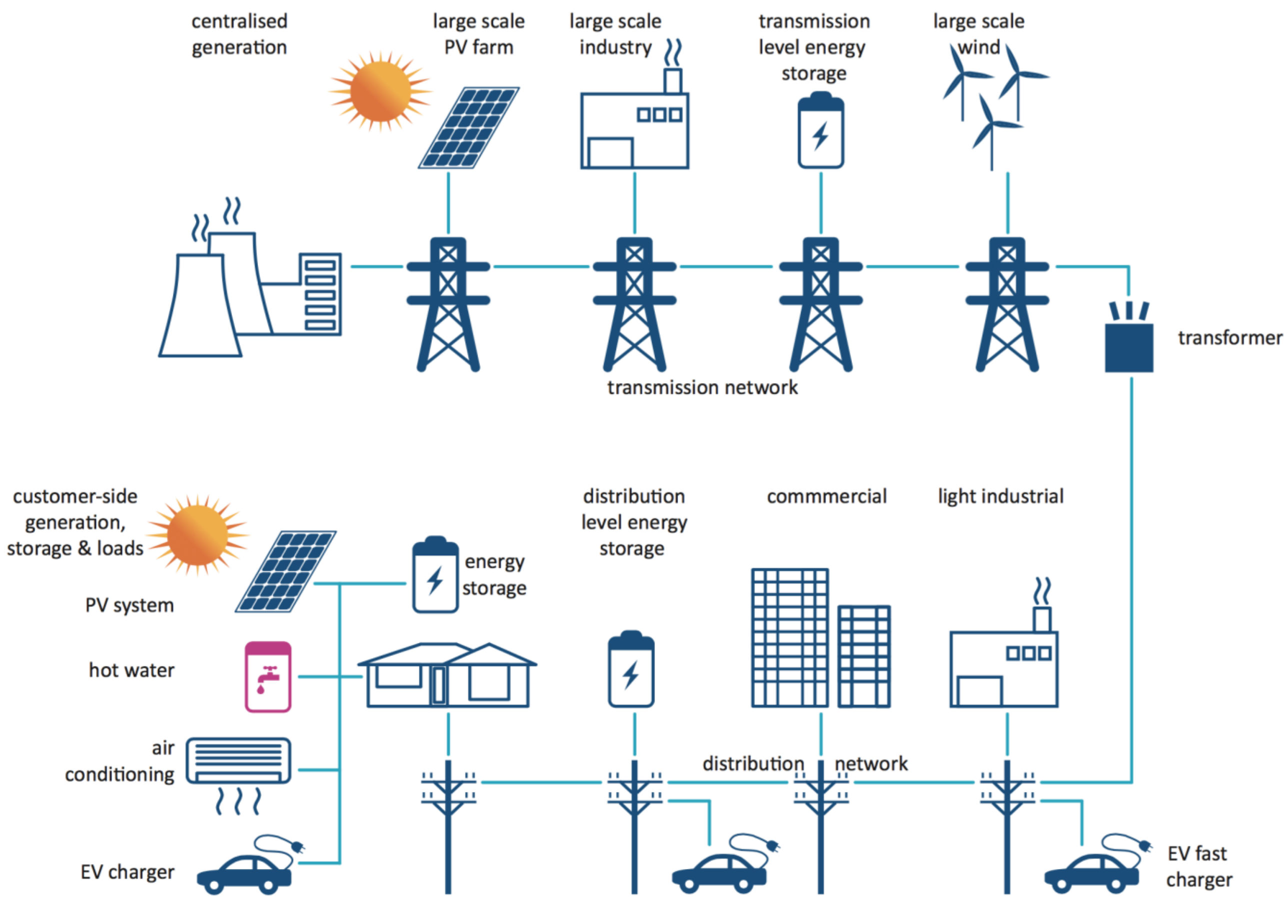



**Figure 7 Simplified diagram of electricity network**

A strong transmission network is important to allow transport of energy between regions. As a larger number of intermittent renewable generators enter the market, output variability can be managed with energy storage and load shaping, but it is also significantly reduced due to the diversity of generators. A strong transmission system allows:

- diversity between generators to be exploited, significantly reducing the need to manage power quality
- energy storage to be chosen to manage bulk energy shifting, rather than power quality management – e.g. a flow battery with lower power output and slower response, but potentially lower cost, could be used
- storage to be located more centrally, and in areas with milder climatic conditions – e.g. allowing the use of Li-ion, which may otherwise be unavailable in peak summer/winter conditions that may be outside high/low thermal operational limits. Larger-scale centralised storage also simplifies system maintenance and management.

On the other hand, large numbers of small-scale renewable generators connected to distribution networks can create further challenges for electric power system operators. More specifically, the distribution grid was originally designed for one-way power flow from the high-voltage substation to low-voltage customers. At times when residential PV generation exceeds demand, a PV system will deliver excess energy to the distribution grid (i.e., reverse power flow). Significant reverse power flow in the distribution grid potentially degrades the effectiveness of existing protection and voltage control schemes (e.g. line drop compensation). Load coordination and energy storage at the residential scale could address this problem by absorbing excess energy and preventing reverse power flows, then dispatching this stored energy at later times of peak demand. This application is also dependent on the maturity of the energy storage technology and its supporting infrastructure. For example, the algorithms that control grid-connected battery charging and discharging schedules potentially require supporting communication-based infrastructure.

### 2.2.1. Integrating storage into distributed generation systems

In the short term, the Australian market for energy storage uptake is anticipated to be predominantly driven by the residential sector from customer-side demands. The technologies appropriate for this application are already being deployed through multiple pilot trials and installations.

Initial customer-side uptake of energy storage is expected to be in situations where energy storage can be used to provide an arbitrage between low and high energy costs; e.g. in TOU energy tariffs, or to save solar energy to service higher-cost peak loads later in the day. This movement is happening now, with a number of manufacturers announcing residential energy storage products for the Australian market, and deployment partnerships being formed between manufacturers and electricity market players – targeting both retail and network opportunities. The suitability of these systems for operation in the Australian climate during peak loads requires further investigation. Some trials (such as the Ausgrid Smart Grid Smart City project) have already found that energy storage systems may not be operable during extreme temperature events, when they are most needed for peak demand management. Though the potential temperature limitations of this particular chemistry may be mitigated with air conditioning or other suitable environmental controls, this is likely to be unsuitable for small residential deployments due to the high per-unit cost.

The impact of energy storage on the customer side remains to be seen from the distribution network service provider (DNSP) and grid operator's perspectives. Distributed energy storage behind the meter may not be available for network management with both customer and retailer objectives potentially misaligned with network needs at times. This could potentially lead to further complications in forecasting and balancing supply and demand.

There are a number of common topologies for integrating distributed generation with energy storage, as shown in Figure 8.

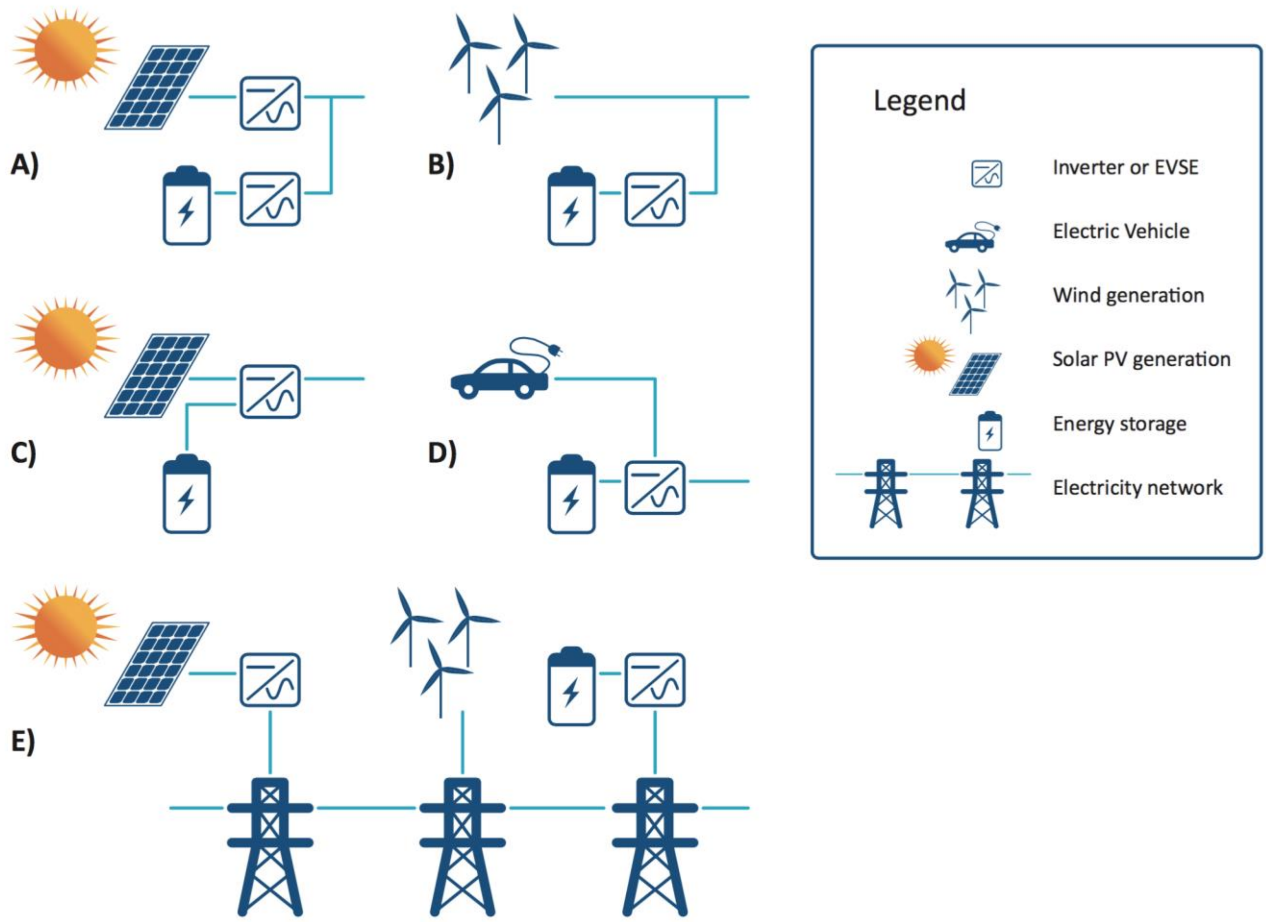



**Figure 8 Distributed generation and energy storage connection configurations**

Features A–E of the topologies shown in Figure 8 are explained below.

***A) Alternating current (AC)-coupled solar PV***

This configuration is likely to be widely deployed by residential and other consumers. A significant benefit of this arrangement is that an existing PV system can be easily augmented with an independent energy storage system. Using the AC mains wiring to connect the PV and energy storage system also simplifies electrical isolation if working on the system, and can minimise the amount of direct current (DC) wiring, particularly with micro-inverter systems. One issue with this configuration is that coordinating control of the storage with the PV system or site loads can be challenging, particularly when using the energy storage to manage power quality requiring a high-speed response. Another issue is that separate inverters are required for both the PV and energy storage systems. This duplication of hardware can increase the capital cost of the system. All of the focus energy storage technologies are appropriate for configuration in this way.

***B) AC-coupled wind***

This is a minor variation on case (A). Large-scale wind turbines are typically either synchronous generators or doubly fed induction machines that generate AC. A separate inverter system is therefore required when integrating energy storage. All of the focus energy storage technologies can be configured in this way.

*C) DC-coupled PV*

An alternate method of integrating energy storage and PV is to put them on the DC side of the inverter, which avoids the duplication of power electronics seen in case (A). This is particularly effective where the energy storage system can be arranged to have a very similar DC voltage to the PV array, and is commonly seen with Li-ion, $LiFePO_4$ and lead-acid batteries. In the case of lead-acid or $LiFePO_4$, the battery is usually reasonably low voltage (e.g. 48 V), housed separately to the inverter, and accessible to the consumer – which may pose a safety risk. In the case of Li-ion, a higher-voltage battery is typically used (several hundred volts) and the inverter/battery are housed together as an integrated unit. This simplifies installation, including easy upgrading of an existing PV system to integrated PV/storage. Because the battery and PV are integrated on the DC side of the inverter, the combined PV/storage output is easily controlled.

*D) DC-coupled EV charging*

Not generation as such, but a similar approach to case (C), can be used with EV charging (or in the future, vehicle-to-grid) applications. In this case, the (fixed) storage system can also be used in conjunction with other distributed generation. The main reason for including energy storage into an EV charger is to reduce electricity network power draw, and hence reduce costs. This is particularly important with Mode 4 charging, as shown in Figure 8, when DC fast charging is supported at rates of up to 50–75 kW. To support fast DC charging of an EV, and have low standby losses between charges, Li-ion would be an appropriate storage technology.

*E) Grid-coupled storage*

As an extension to cases (A) and (B), distributed generation can also be coupled to energy storage via the electricity network, rather than solely within a single customer site. A major benefit of grid-coupled generation and storage is that the diversity of generation can be taken advantage of with minimal control/coordination, and with slower responding storage technologies, while still achieving the same aggregate-level response. Although all storage types are appropriate for this application, molten salt and flow batteries could be better suited, due to their economics and the relatively modest response times required.

An example of integrated renewable generation and energy storage is the advanced lead-acid UltraBattery, which has been successfully implemented with distributed generation in many projects including large-scale MW applications [30]. At the Hampton Wind Farm in New South Wales, the UltraBattery was used for wind smoothing to constrain the 5-minute ramp rate of wind generation. The Hampton Wind Farm project aimed to demonstrate that higher penetrations of generation were possible from wind and other renewable energy sources. The variability of the wind generation was improved by more than one order of magnitude with the inclusion of the UltraBattery, as shown in Figure 9.

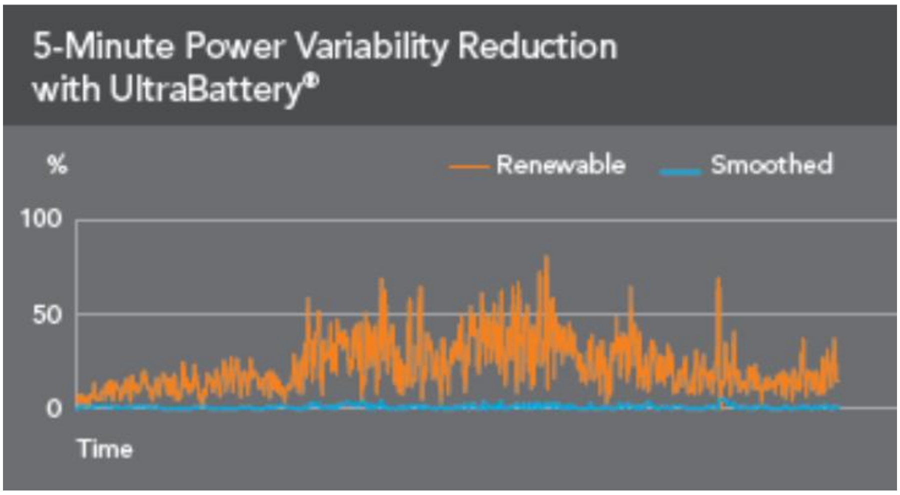



**Figure 9 Five-minute power variability reduction with the UltraBattery at Hampton Wind Farm [30]**

In New Mexico (United States), as part of the Public Service Company of New Mexico Prosperity Energy Storage project, the UltraBattery was integrated with a 500-kW solar PV plant to demonstrate its ability for smoothing and reducing peak load. The project is one of the largest PV installations with integrated energy storage in the United States. The addition of the UltraBattery reduced the peak load on the feeder by 15% through energy shifting [30].

#### 2.2.2. Reverse power flow in distribution networks

Increasing the penetration of renewable generation sources in the NEM could pose additional complexities for network operators, since the effects of renewable generation sources on the eastern Australian electrical grid are not known to any great extent. In 2013, a desktop study conducted by AEMO examined the impact of 100% renewable generation on the NEM [11]. While the study explored these issues, several questions remain, including the:

- effect of power quality in frequency control and voltage rise
- operation of protection equipment under reverse power flow
- effect on network asset lifetimes under new operational regimes.

These potential network issues are driving strong interest in energy storage, since storage technologies may reduce or eliminate reverse flows. However, the operational limits of battery technologies require careful consideration with respect to facilitating a greater level of grid-connected renewable generation. In particular, the operating conditions of battery technologies subject to Australian climatic conditions must be considered to ensure that a high-quality, secure electricity supply is provided to consumers.

## 2.3. Safety considerations for grid-connected energy storage

Safety procedures are required to minimise risks to life and property when grid-connecting and operating energy storage in different locations of the electrical power system. The procedures should be tailored to integrate with existing electrical standards and protection schemes. They must also take into account energy storage technology-specific operating conditions and safety requirements.

Relatively few Australian standards and regulations consider safety protocols for the variety of energy storage technologies considered in this report. This deficiency poses safety risks and may hinder the uptake of these emerging technologies in Australia. Existing standards are largely focused on mature technologies, such as traditional lead-acid (AS 4029) and nickel-cadmium (AS 3731) batteries. AS 4086 and AS/NZS 4509 cover the application of secondary batteries for standalone power systems that are not designed for grid connection. Within the low-voltage distribution network, grid-connection standards for energy storage systems predominately fall under the AS/NZS 4777 series of standards for grid-connected inverter systems. A new standard (AS/NZS 5139) is currently under development to address the safety of battery systems for use with inverter energy systems.

Consumers are often unsure whether they are required to advise their distribution network service provider if they have installed an energy storage system. The number of sufficiently trained and accredited energy storage installers is also limited, particularly for the newer Li-ion battery technologies such as $LiFePO_4$ and NMC. This could pose safety risks for both customers and installers not familiar with the potential issues discussed in Section 1.4.1.3 and the associated measures to reduce risk and handle hazards. Energy storage technologies that pose a potential fire risk (such as Li-ion) require fire barriers and/or fire extinguishers in close proximity to contain hazards in event of emergency. Safety clearances may be required to ensure flammable materials do not fuel these instances. Isolating the hazard from the electrical network in a timely fashion is also critical to minimise the risk to life and property. The current standards and regulations are not sufficient to ensure that these risks are minimised. They must be updated to address these issues and facilitate the uptake of emerging energy storage technologies and the safe connection of these to the grid.

Within different application spaces, there are safety risks related to the particular application in addition to the chemistry specific considerations. These include:

***Grid-side network support and large-scale renewables integration***

Large-scale deployments of energy storage technologies are likely to contain significant quantities of materials, so the consequence of a major failure is potentially greater. Electrically, these systems will typically connect to the electricity network at MV (medium voltage) level (>1000V) and can support high fault currents, which could include significant and sustained direct current (dc) arcing.

At this scale, many vendors offer containerised solutions that have a number of benefits including: integrated fire-suppression systems; dedicated thermal condition management system (including heating, cooling and ventilation), which can both reduce failure rates and improve system availability; remote system monitoring and alarms; and an integrated design approach where systems have been tested as an integrated whole rather than just individual components. The use of modular systems, ideally physically well separated, can reduce the propagation of faults (via thermal, electrical or fire) to other adjacent systems.

Managing the physical security of energy storage systems for both grid-side distributed energy management and large-scale renewables integration could prove challenging as these are high-value assets with considerable safety risks to unauthorised access – including electrical, chemical and thermal.

***Commercial and Industrial energy management***

Electrical energy storage systems installed within commercial and industrial sites need to comply with the Building Code of Australia (BCA). This code for commercial/industrial buildings (classes 2-9) includes provisions requiring such systems to be separated from the remainder of the building with fire rated construction. It is however, unclear if these requirements are being applied in practice. There is a clear risk where such provisions have not been followed, which in addition to the potential spread of fire, could also result in the venting of toxic or flammable gases into workspaces.

At the moderate scale (>100kWh) that is expected to be applicable to commercial/industrial installations, systems are likely to be sold as an integrated solution, which will benefit from remote system monitoring and alarms and integration into existing building energy management systems. Unlike grid-side and large scale renewable integration systems, these systems are likely to be installed adjacent to occupied spaces where the consequence of failure – including spillages, venting of gases or even fire, will have far greater consequences.

There is a risk that rather than installing appropriately rated ventilation and climate control equipment and fire suppression systems, existing building controls may be assumed to be adequate. This risks over-temperature operation of the energy storage system. Conventional fire suppression using water sprinklers may cause bunding, intended to contain chemical spills, to overflow. Water, used in these emergency measures to contain or reduce hazards, may react chemically if exposed to materials in some energy storage technologies (i.e. lithium).

In the event of untrained or unauthorised personnel accessing the system, there is a significant risk of exposing themselves to chemical, thermal and electrical hazards.

***Residential energy management and backup***

Regulations concerning the installation of residential energy storage systems are not well developed, vary by state according to local building codes and may include additional requirements by the electricity distributor. This lack of clarity of approach is leading to a diversity of installation methods, which is likely to cause confusion for homeowners and first-responders in the event of an incident. The Clean Energy Council has established a *Storage Integrity Working Group* whose role is to ensure Australia has the appropriate standards, accreditation programs and product stewardship systems in place to manage the safety and quality of energy storage systems.

It is anticipated that residential energy storage systems will be installed in both indoor and outdoor locations. For indoor installations, venting of gases (possibly as a result of cell failure) and installation adjacent to flammable materials are of concern. While these risks are lower for outdoor installations, more extreme environmental conditions – including high/low temperatures and water ingress, increase the likelihood of cell failures. In all cases, a move towards a safe-fail design and installation philosophy is warranted.

Another issue is the potential for consumers to be exposed to contact with dangerous voltages, especially in systems where batteries are not internally integrated into the energy storage system. Many off-grid style energy storage systems have been deployed with 12, 24 and 48 volt battery systems, though newer systems are starting to use higher system voltages (>100V) that could leave exposed conductors at these higher voltage levels if unaccredited installation methods are used.

At the residential level, system monitoring including alarm notifications is not guaranteed to always be rigorous, which reinforces the need for safe-fail design. This design approach needs to extend to hardware and software safety protocols to ensure accidental (or malicious intentional) wrong settings or updated software versions do not compromise the integrity and safe operation of the system.

***Electric vehicle charge control***

The United Nations Economic Commission for Europe (UNECE) have established particular safety requirements for electric vehicles, enabling a consistency of approach across Europe, and also internationally. These are specified in UNECE regulation 100 - *Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train*. These regulations cover electric vehicle specific safety considerations including: electrolyte leakage, cell rupture, fire and explosion under a range of component and system level tests. These acount for both normal and dynamic operation and vehicle crash testing.

For grid integration of electric vehicles, managed charging (such as modes 2 to 4 per IEC61851-1 2001) includes a number of system safety checks that are undertaken before charging is enabled. These include verification that the vehicle is properly connected and continuous checking of the protective earth conductor. Mode 1 charging, where an EV is charged by directly plugging into a standard power outlet, is likely to be common within the residential sector and there is risk that they may not have these safety features.

Other EV charging specific risks include potential for fire propagation to adjacent vehicles, unclear electrical isolation procedures and identification of appropriate actions for first-responders in the case of an incident.

Specific key safety risks associated with each of the focus energy storage technologies are outlined below.

***Advanced lead-acid batteries***

Advanced lead-acid batteries share many of the same safety risks as conventional lead-acid batteries. First, the risk of fire is very low. The electrolyte solution in advanced lead-acid batteries is non-flammable, with flame-retarding tendencies [31]. However, overcharging lead-acid batteries may electrolyse the water and produce hydrogen and oxygen [32]. In extreme cases, if protective valves fail (e.g. due to accumulation of dirt or debris), the resulting pressure build up can trigger an internal explosion. Additionally, in the event of a leak or explosion, the sulfuric acid contained in the electrolyte can cause severe chemical burns to those nearby [32]. Personal protective equipment should be worn when working near lead-acid batteries in these situations.

***Li-ion batteries***

Serious safety risks are associated with Li-ion battery technologies such as $LiFePO_4$ and NMC batteries. The cell components of Li-ion batteries can oxidise if overheated or overcharged, leading to thermal runaway and cell rupture [33]. Thermal runaway can cause a cascade of cell failures and, in extreme cases, fire if the battery is hot enough to ignite the electrolyte. Thermal runaway can also occur if the battery is short-circuited due to mechanical pressure (i.e. if it is punctured or crushed).

Li-ion battery packs typically contain safety features to reduce the risk of thermal runaway, such as pressure relief valves or insulating separators. In general, $LiFePO_4$ batteries are considered safer than other Li-ion chemistries, due to their higher thermal stability and reduced risk of thermal runaway [34], [35].

***Zinc bromine flow batteries***

The safety risks associated with zinc bromine (Zn-Br) flow batteries are lower than battery technologies such as Li-ion. The risks depend primarily on the charge state of the battery. When uncharged, Zn-Br batteries pose very low risks [36]. The electrolyte is only mildly acidic (pH 2–5) [36] compared with other electrolytes and it contains no heavy metals. Bromide compounds are also widely used as fire-suppression liquids and are added to plastics for their fire-retardant properties [37], [38]. However, Zn-Br is corrosive and prolonged exposure to skin can cause burns and irritations. However, since Zn-Br is highly soluble and easily diluted to counteract these effects, Zn-Br batteries are generally considered to be a low risk [36].

During charging, the electrolyte solution of Zn-Br flow batteries is split into zinc metal and elemental bromine. Since bromine is a highly reactive and volatile liquid, Zn-Br batteries such as those manufactured by ZBB Energy Corporation and Redflow include a specific complexing agent that decreases the vapour pressure and binds the bromine into a non-volatile liquid with considerably lower reactivity [36], [38]. This improves the overall safety of the battery. The risks to life and property from accidental spills can also be minimised by fully discharging the battery before transport or handling. Personal protective equipment should be worn when handling electrolyte leaks.

***Sodium nickel chloride batteries (molten salt)***

The safety risks posed by sodium nickel chloride ($Na\text{-}NiCl_2$) batteries are largely due to the high operating temperatures (typically around 300 °C) required to keep the electrodes molten. This complicates sealing and thermal management of the batteries [39] and poses potential burning risks to personnel in the event of a leak. $Na\text{-}NiCl_2$ batteries are also sensitive to short-circuiting due to their three-layer construction [39].

## 2.4. Issues in applying international experiences to Australia

The Australian environment, geographical size and distance between neighbouring urban and rural load centres presents complexities for Australian electric power system operators in managing supply and demand. These complexities potentially motivate the integration of grid-connected energy storage, but may also affect its performance.

Australia has four main electricity grids, which consist of transmission and distribution assets [40]. Each of these electricity grids:

- covers a large geographical area
- services a country with low average population density
- features many long constrained power lines
- has higher impedance than those in Europe

- has low levels of interconnection
- is subject to Australia's often extreme weather and environmental conditions
- operates under challenging market dynamics [41].

### 2.4.1. Single wire earth return networks

In Australia, it is typical for rural distribution networks within the NEM to incorporate single wire earth return (SWER) feeders, which are relatively unusual internationally. SWER systems operate on the principal of using the ground as a return path for the current drawn by loads. By using significantly less infrastructure, they are cheaper to install than more conventional connections with similar capacity. In cases where augmentation on SWER networks is required, battery storage could potentially reduce costs.

In rural areas of Queensland, more than 65 000 km of SWER networks have been installed to supply approximately 26 000 customers [42]. These networks are often located at the end of single-phase networks, with high impedance lines. As such, maintaining voltages delivered to customers within a +10%/–6% tolerance (as defined in the Australian Standard AS 60038) is not straightforward [43] [44]. More specifically, voltage rise during light-load periods on SWER networks is prevalent due to the charging effect of the line capacitance, otherwise known as the Ferranti effect [42]. During high-load periods, losses on the SWER network are often significant due to high line impedances, leading to voltage drops below the required level at residential premises.

When voltages fall outside a +10%/–6% tolerance at a residential location, a distributor is typically required to improve the quality of the delivered voltage. Approaches include active network components, such as on-load tap-changing transformers, voltage-regulating transformers and shunt capacitors that switch on and off as required. Augmenting parts of the SWER network to lower the line impedance is also a common approach to reducing line drop during peak load periods. Alternatively, grid-connecting battery storage in the vicinity of residential load centres – with charge rates to increase the load during 'no load' periods and discharge rates to reduce peak loads – may avoid augmentation costs in SWER networks.

### 2.4.2. Climate conditions

Due to the size of the Australian continent, the climatic conditions within Australia vary significantly. In northern Australia, tropical climates with rainy periods during summer and dry and warm weather during winter are typical. In southern Australia, summer is typically mild and winter is cool, similar to climatic conditions in the United Kingdom. In the mid-east of Australia, both very hot summers and cool winters are typical. Heat waves during summer are common, with ambient temperatures often exceeding 40 °C.

Across the NEM, extreme weather events also typically lead to peaks in electricity demand [45] [46]. When peak demand is forecast to exceed a capacity limit (e.g. a thermal rating of an overhead conductor), the grid is often augmented. Locating grid-connected battery storage near loads could defer these network augmentation costs by providing additional local capacity at times of peak demand. On the other hand, these peak loads often occur during particularly extreme heat waves or on very cold days. Energy storage technologies with operating temperatures below or above such extreme ambient temperatures are potentially unsuitable for managing peak loads. Moreover, performance degradation of battery technologies operating close to their maximum or minimum operating temperature may limit the full potential of energy storage to address grid-side applications of peak load reduction. For example, the Smart Grid Smart City trial [27] observed that Zn-Br flow batteries did not perform peak load reduction as expected on a day that reached 45 °C. Thus, understanding the grid application of peak load reduction and the operating temperature of different energy storage technologies is critical for selecting an appropriate solution.

## 2.5. Summary

While there are a large number of energy storage technologies, each with different levels of technological maturity, there is a similar diversity of applications within both the grid-side and customer-side of the electricity system. Technologies therefore need to be selected that are appropriate for specific deployment applications.

While many technologies might seem suitable for grid-side applications, many others still require further development or investigation into the feasibility of mass production for large-scale deployment in grid or stationary energy applications. That being said, a number of grid benefits can be predicted from the more well-known storage technologies, particularly when considering the five key technologies examined in Part 1 of this report.

In particular, grid-connected energy storage can:

- help manage peak demand and related costs on the electricity grid
- help integrate intermittent renewable energy generation into the grid
- improve the power quality or reliability of the grid.

Key considerations in assessing the suitability of energy storage systems are summarised in Table 20 for a range of applications. Note that even within a technology class, there are significant differences between specific systems.

**Table 20 A more detailed examination of the current status of each shortlisted energy storage technology**

| | Advanced lead-acid battery | Lithium iron phosphate battery | Lithium nickel manganese cobalt oxide (NMC) battery | Zinc bromide flow battery | Sodium nickel chloride molten salt battery |
|---|---|---|---|---|---|
| **Grid-side applications** | Intermittency and bulk (daily) energy shifting | Intermittency and bulk (daily) energy shifting | Intermittency and bulk (daily) energy shifting | Daily energy shifting | Intermittency and bulk (daily) energy shifting |
| **Customer-side application** | Backup supply and power quality | | | | |
| **Combined with distributed generation** | Suitable/established for widespread co-location with PV and wind | Common technology offered for PV/storage at residential level. Co- | Li-ion (NMC and other similar derivatives) are used in integrated PV inverter/storage | Suitable/established for widespread co-location with PV | Only appropriate for large-scale systems, suitable for |

| | | | | | |
|---|---|---|---|---|---|
| | | located with large-scale windfarm | systems (Samsung, Panasonic) | | co-location with wind |
| **Existing grid-side integration issues** | Control and coordination require further investigation | | | | |
| **Performance and lifespan** | Improvement on traditional lead-acid | High specific energy density, high power density, up to 6000 cycles | | 300–1500 discharge life cycles | 4000–4500 discharge life cycles |
| **Application issues and/or gaps in knowledge** | Low specific energy density, shorter life cycle at higher temperature | High operational temperatures have an adverse effect on capacity/life, poor recycling | Operational temperature (especially for charging) below ambient, poor recycling | Operational temperature (especially to discharge) below ambient, parasitic losses | Very high operational temperature, parasitic losses |
| **Safety issues** | Hydrogen evolution, uses toxic lead and corrosive acid | Thermal runaway potentially leads to fire | Thermal runaway potentially leads to fire | Bromine leaching | Potential risk of burns |

It is clear that no single storage technology can provide each of the above functions. Each application has unique characteristics: some will require fast response, others slow; some need high power, but low energy; and some have more modest power requirements, but require bulk energy provision. Similarly, some storage systems are relatively slow responding, but provide comparably cheap kWh prices, while others are fast responding, but can only operate economically in low-energy applications. Ultimately, implementing the optimal storage system for a particular application will require careful consideration of the operational characteristics of the application itself, and matching these to the operational characteristics of the available storage systems.

Our knowledge of the suitability of different energy storage technologies for Australian deployment is still limited. Understanding the potential for grid-connected energy storage is made more complex by the country's unique climate and environmental considerations, population densities and electricity network topologies.

Specific issues arising now include the following.

- Mainstream residential energy storage products have only just entered the market, so there is little experience of their potential impact – e.g. will they be available and operate on peak demand days, or will thermal limits prevent operation?
- A move to 'net PV' tariffs for residential PV will lead to
    - metering in many PV systems needing to be rewired, at a cost to the consumer
    - loss of PV output data, which would otherwise inform network investment and management decisions.
- Some consumer connection arrangements require no export of energy, or impose ramp rate constraints. Management of intermittency (requiring control speeds of seconds) at a single

customer level is significantly more difficult (requiring more and a higher specification of energy storage) than at a network level, where the diversity of sources significantly reduces this variability.

- TOU arbitrage as a driver for energy storage deployments may result in
    - significant cycling of energy storage to reduce costs to the customer at times when there is no grid-side need for this. This reduces the lifespan of the storage system and increases energy usage and greenhouse gas emissions due to round-trip efficiencies
    - technologies being deployed that are better suited to daily cycling, rather than higher-power but infrequent operation, which would have been preferred for dealing with network power quality issues.

Ultimately, significantly more work is required to investigate the applicability of particular storage technologies to Australian conditions. We need to determine and implement the right regulations, standards and incentives to ensure safe, efficient storage deployment and benefit the broader electricity system.

# A. Appendix – Energy storage technology overview

Table 21 highlights key methods for storing energy in grid applications. These include mechanical, thermal, electrical/electrochemical and chemical methods. The following sections discuss these technologies in more detail.

**Table 21 Examples of different methods of energy storage**

| Mechanical energy storage | Thermal energy storage | Electrical/electrochemical energy storage | Chemical energy storage | Load coordination |
|---|---|---|---|---|
| • Pumped hydro Storage<br>• Compressed air energy storage<br>• Flywheel energy Storage | • Hot water storage<br>• Molten salt energy storage<br>• Phase-change material storage | • Supercapacitors<br>• Superconducting magnetic energy storage<br>• Batteries<br>• Fuel cells | • Hydrogen<br>• Synthetic natural gas<br>• Other chemical compounds e.g. ammonia, methanol | • Load shaping/ smart appliances (e.g. hot water, pool pumps) |

## A.1. Batteries

Batteries are energy storage devices that convert stored chemical energy into electrical energy. Batteries use chemical compounds that can either liberate or accept electrons or ions within an electrochemical cell during a redox reaction. During the redox reaction, the conversion of these chemical compounds into different chemical or ionic species or intercalation of ionic species into host matrixes either liberates or accepts electrons/ions. The movement of these liberated electrons/ions within the cell creates an electrical current flow out of the battery and allows the device to work.

All battery devices share a number of similarities in their construction. Each battery cell consists of two electrodes: a positive electrode (cathode) and a negative electrode (anode). In between these two electrodes is a layer of separator containing an electrolyte, which allows the movement of electrons or ions within the cells. Depending on the type of battery, the electrolyte can consist of a liquid, gel or solid material. Batteries also contain insulating separators to prevent the electrodes from physical contact and potential short-circuiting. Depending on the chemistry of the battery, additional safety features, such as pressure relief valves may also be incorporated; the type of feature is specific to the device. Multiple cells can be combined to create battery packs with performance characteristics required for the desired application.

The choice of chemical compounds determines the nature of the battery device, the redox reaction, cell voltages and energy storage and power capability. The different types of battery technologies based on the differing chemistries are discussed below.

### A.1.1. **Lead-acid battery**

The lead-acid battery has been in use for more than 50 years, and is one of the most well-known battery technologies. Lead-acid batteries can be commonly found in recreational vehicles, trucks and buses.

#### A.1.1.1 Basic chemistry

The lead-acid battery (as shown in Figure 10) is based on the reactions of lead compounds with sulfuric acid in an electrochemical cell. During discharge, the metallic lead at the anode oxidises and reacts with the dissociated sulfuric acid electrolyte, liberating the electrons needed for the external current. At the cathode, protons ($H^+$) from the electrolyte combine with the oxygen (from the lead dioxide, $PbO_2$, which is reduced), forming water and freeing the lead to combine with the sulfate ions. The four positive charges from the four protons are neutralised by the two negative charges of the sulfate ion and by two additional negative charges from electrons arriving at the cathode via the external load.

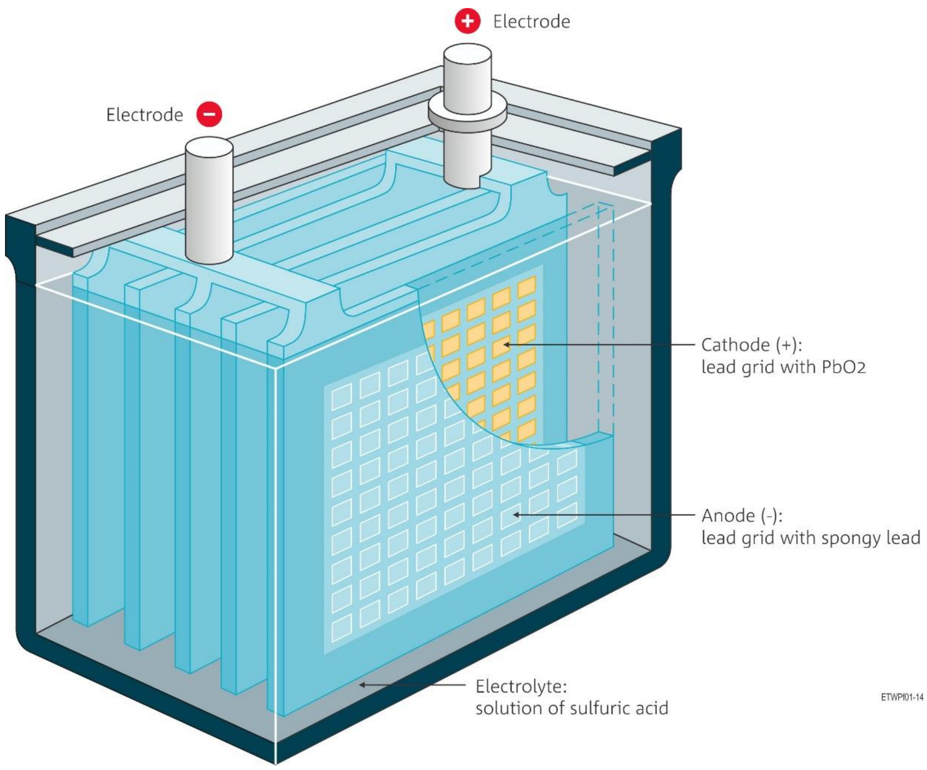



**Figure 10 Example of lead-acid battery construction**

There are two different types of lead-acid battery. The flooded type is the most cost effective, and tends to be used in automotive and industrial applications. The sealed type, also called the valve-regulated lead-acid battery, has been rapidly developed and is used in a wide range of applications, including hybrid and electric vehicles (EVs) and power supplies, such as uninterruptible power supply (UPS) and stand-alone remote area power supplies. The sealed/ valve-regulated type, either with absorptive glass mat separators or gelled electrolyte technology, has the advantage of low maintenance (due to acid restriction and oxygen recombination) and easy-fit configuration.

Both the power and energy capacities of lead-acid batteries are based on the size and geometry of the electrodes. The power capacity can be improved by increasing the surface area for each electrode, which means greater quantities of thinner electrode plates in the battery.

#### A.1.1.2 Existing technology development, maturity and applications

The oldest rechargeable battery technology, invented in 1859 by Gaston Planté, consisted of two lead plates separated by rubber, wound into a spiral and immersed into a sulfuric acid solution. The modern variant of the lead-acid battery is widely used in applications such as automotive, industrial, submarine and backup power. Advanced lead-acid batteries and lead-carbon based batteries are being investigated and demonstrated for use in newer applications, such as hybrid EVs and renewable energy storage solutions, including integration into electricity grids.

Since this technology is well established, a very large number of manufacturers can be found around the world. Some key manufacturers operating in Australia are Exide Technologies, Century Yuasa Batteries, Alco Batteries and Trojan Industrial Line Batteries, as well as many smaller retailers.

#### A.1.1.3 Technical advantages and disadvantages

Lead-acid batteries are a proven technology for energy storage, having been used in backup power and remote area power systems since the 1970s. The main advantages of the technology are its low cost, wide commercial availability, low self-discharge, rapid response and a large recycling rate with established processes. However, the technology has low energy density compared with competing technologies, needs to be kept in the charged state, has a marked decrease in lifetime at temperatures above 30 °C, and uses toxic heavy metals and highly corrosive acids.

#### A.1.1.4 Most common applications/desired outcomes

The lead-acid battery is suited for applications that require both power and energy. Therefore, applications such as backup power, off-grid/remote applications, time shifting, power quality and time shifting of renewables generation are suited to this technology.

#### A.1.1.5 Current Australian adoption

The technology has been proven for energy storage applications over a number of years and is well-known and trusted by industry. The drawbacks of low energy and power capabilities, in terms of energy storage for renewables, can be overcome by increasing the size of installation. The large number of worldwide suppliers means that the technology can be sourced at competitive rates.

### A.1.2. **Lithium-ion**

Originally proposed and investigated in 1912 by G. N. Lewis, it was not until the 1970s that lithium batteries were commercialised. The primary lithium metal disposable systems (using a variety of cathode materials, e.g. FeS, CuS, chromates, CFx or $V_2O_5$) were commercialised during this period. The Li-ion rechargeable technology became feasible in 1980 by the breakthrough results of

J. Goodenough and R. Yazami, who showed that Li cations could be reversibly inserted into cobalt oxide crystals and graphite layers, respectively. This led to the commercialisation of the Li-ion battery in 1991 by Sony. The higher operating voltage, capacity and power of the Li-ion technology, with a reduction in device weight and volume when compared with other technologies, has led the growth of uptake in electronic devices. Li-ion technologies are currently being investigated for a host of applications, including EVs and grid integration.

#### A.1.2.1 Basic chemistry

The Li-ion battery operates by the removal of lithium cations from the cathode crystals and subsequent insertion into the graphite layers on the anode during the charge reaction. Upon discharge, the lithium cations are removed from the graphite and inserted back into the cathode material. This was demonstrated earlier in Figure 3 for the $LiCoO_2$ battery system. The electrolytes for Li-ion batteries typically consist of a carbonate-based organic solvent with additives to improve cycling, or a Li-ion conducting polymer for solid-state devices. Since the advent of the $LiCoO_2$ system, a number of different materials have been found to act as the host crystals for the Li-ions, and relevant materials are shown in Table 22. In addition, anode materials such as lithium titanates or silicones are also being used in Li-ion batteries; however, at the time of writing, graphite was the most common anode material.

**Table 22 Typical characteristics of typical Li-ion cathode materials showing maximum discharge voltage and gravimetric capacities**

| Material components | Chemical formula | Discharge voltage | Theoretical gravimetric capacity (Ah/kg) |
|---|---|---|---|
| Lithium cobalt oxide | $LiCoO_2$ | 3.6 | 274 |
| Lithium manganese oxide | $Li_{1.07}Mn1.93O_4$ | 3.9 | 117 |
| Nickel cobalt aluminium | $LiNi0.8Co0.15Al0.05O_2$ | 3.6 | 265 |
| Nickel manganese cobalt | $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ | 4.4 | 170 |
| Lithium iron phosphate | $LiFePO_4$ | 3.4 | 170 |

#### A.1.2.2 Existing technology development, maturity and applications

Li-ion batteries have become the leading storage technology for portable and mobile applications (e.g. laptops, cell phones, electric bicycles and EVs). High cell voltage levels (up to 3.7 V) mean that the number of cells in series with the associated connections and electronics can be reduced to obtain the target voltage needed in many applications. For example, one Li-ion cell can replace three nickel-cadmium (Ni-Cd) or nickel metal hydride (Ni-MH) cells, which have a typical cell voltage of only 1.2 or 1.5 V, respectively. Another advantage of Li-ion batteries is their high gravimetric energy density, and the prospect of large cost reductions through mass production. Although Li-ion batteries have a share of more than 50% in the small portable devices market, there are still some challenges for developing larger-scale Li-ion batteries.

A number of overseas manufacturers make Li-ion batteries. For brevity, here we only consider the larger manufacturers. For lithium batteries in the polymer format (also called LiPo), Kokam in Korea manufactures for grid-scale storage using a range of chemistries, including lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate ($LiFePO_4$) and lithium titanate. The $LiFePO_4$ battery is also manufactured by BYD in China and A123 in the United States in a wet-cell format. The NMC battery is manufactured by Panasonic in Japan and the newly formed Tesla battery manufacturing business in the United States, while LG Chem in Korea also holds a large market share. The Tesla factory claims that they will be able to manufacture lithium nickel cobalt aluminium chemistry in the near future.

A number of demonstrator sites have been deployed for Li-ion batteries, the most recent being a 350-kW storage system using Kokam calls manufactured by Australian company, Magellan Power. This system has been deployed by Transgrid at their New South Wales site as an experimental test bed. In Victoria, United Energy is also deploying an experimental 1-MW system, though technical details are not in the public domain.

#### A.1.2.3 Technical advantages and disadvantages

Li-ion batteries generally have a very high efficiency, typically in the range of 95–98%. Nearly any discharge time (from seconds to weeks) can be realised, which makes them a very flexible storage technology. Standard cells with 5000 full cycles can be obtained on the market at short notice, but even higher cycle rates are potentially possible with further development, mainly depending on the materials used for the electrodes. Since Li-ion batteries are currently expensive, they can only compete with lead-acid batteries in applications requiring short discharge times (e.g. as primary control backup power supplies).

Safety is a serious issue in Li-ion battery technology. Most of the metal oxide electrodes are thermally unstable and can decompose at elevated temperatures, releasing oxygen, which can lead to thermal runaway. To minimise this risk, Li-ion batteries are equipped with a monitoring unit to avoid overcharging and over-discharging. A voltage balance circuit is also usually installed to monitor the voltage level of each individual cell and prevent voltage deviations among them. Li-ion battery technology is still developing, and there is considerable potential for further progress. Current research is focused on the development of advanced cathode materials.

#### A.1.2.4 Most common applications/desired outcomes

The high power and energy storage capabilities of lithium batteries mean that they may be suitable for applications such as power quality, network efficiency, off-grid/remote area power supply, backup power, time shifting, power quality and time shifting of renewables generation.

#### A.1.2.5 Current Australian adoption

A number of manufacturers are now producing lithium battery systems targeted at meeting the requirements of the renewable energy storage market. The inclusion of large players such as Panasonic, BYD and well-financed organisations such as Kokam and Tesla is beginning to drive the price of lithium batteries down. At the residential/industrial scale, a number of Australian engineering firms are negotiating directly with battery manufacturers to provide cells that will then be converted into energy storage systems for retail. These developments are growing a supply chain that will likely accelerate technology uptake.

### A.1.3. **Flow battery**

In conventional secondary batteries, the energy is charged and discharged in the active masses of the electrodes. A flow battery is also a rechargeable battery, but the energy is stored in one or more electroactive species, which are dissolved in liquid electrolytes. The electrolytes are stored externally in tanks and pumped through electrochemical cells, which convert chemical energy directly to electricity and vice versa. The power is defined by the size and design of the electrochemical cell, whereas the energy depends on the size of the tanks. With this characteristic, flow batteries can be fitted to a wide range of stationary applications.

Originally developed by NASA in the early 1970s as energy storage systems for long-term space flights, flow batteries are now receiving attention for storing energy for durations of hours or days with a power of up to several MW.

Flow batteries are classified into redox flow batteries and hybrid flow batteries.

### A.1.4. **Redox flow battery**

Redox flow batteries (RFBs) are a battery system in which the active chemicals are stored in liquid solutions that are pumped through a dry cell when the battery is required to operate. In a full redox flow battery, there are two solutions required for operation, while in a hybrid flow battery, one of the chemicals is kept permanently inside the cell and thus only one solution is required for pumping.

#### A.1.4.1 Basic chemistry

In RFBs, two liquid electrolytes containing dissolved metal ions as active masses are pumped to the opposite sides of the electrochemical cell. The electrolytes at the negative and positive electrodes are called the anolyte and catholyte, respectively. During charging and discharging, the metal ions stay dissolved in the fluid electrolyte as liquid; no phase change of these active masses takes place. The anolyte and catholyte flow through porous electrodes, which are separated by a membrane that allows protons to pass through it for the electron transfer process. During the exchange of charge, a current flows over the electrodes that can be used by a battery-powered device. During discharge, the electrodes are continually supplied with the dissolved active masses from the tanks. Once they are converted, the resulting product is removed to the tank.

#### A.1.4.2 Existing technology development, maturity and applications

Theoretically, an RFB can be ‘recharged’ within a few minutes by pumping out the discharged electrolyte and replacing it with recharged electrolyte. This is why RFBs are under discussion for mobile applications. However, until now, the energy density of the electrolytes has been too low for EVs.

Today, various redox couples have been investigated and tested in RFBs, such as iron titanium (Fe-Ti), iron chromium (Fe-Cr) and polyS-Br systems. The vanadium (V) redox flow battery (VRFB, Figure

11) has been developed the furthest; it has been piloted since around 2000 by companies such as Prudent Energy (China) and Cellstrom (Austria). The VRFB uses a $V^{2+}/V^{3+}$ redox couple as an oxidising agent and a $V^{5+}/V^{4+}$ redox couple in mild sulfuric acid solution as a reducing agent. The main advantage of this battery is the use of ions of the same metal on both sides. Although crossing of metal ions over the membrane cannot be prevented completely (as is the case for every redox flow battery), in VRFBs the only result is a loss in energy. In other RFBs, which use ions of different metals, the crossover causes an irreversible degradation of the electrolytes and a loss in capacity. The VRFB was pioneered at the University of New South Wales, Australia, in the early 1980s. A VRFB storage system of up to 500 kW and 10 hrs has been installed in Japan by SEI. SEI has also used a VRFB in power quality applications (e.g. 3 MW output over 1.5 sec).

The flow battery is currently being manufactured by GEC, based in China, using the vanadium chemistry. Additionally, the established ZBB in the United States is also manufacturing the vanadium chemistry-based flow battery.

A large-scale demonstrator (200 kW, 800 kWh) system has been previously deployed on King Island in the Bass Strait in 2003. However, containment leakage forced this system to be decommissioned.

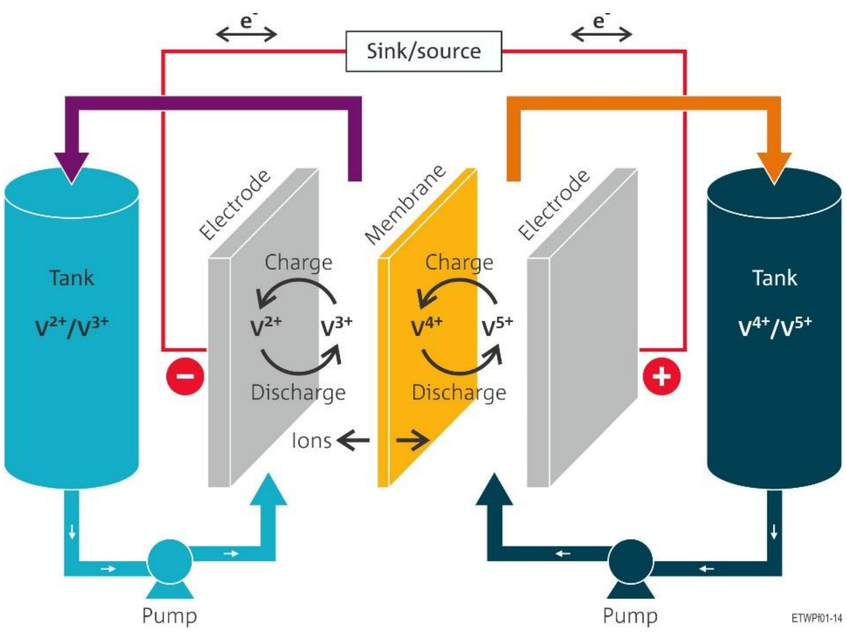



Figure 11 Schematic of the vanadium redox flow battery

### A.1.4.3 Technical advantages and disadvantages

Table 23 lists the operating parameters of vanadium redox flow batteries. The flow battery has a fast response time and is an easily scalable system. Early studies have indicated that it possesses a long lifetime in operation. Further, the individual mechanical parts can be individually replaced, meaning that the technology is easy to maintain. However, the technology is still in a developmental/demonstration stage. It is a complicated system with multiple components involving both chemicals as well as mechanical parts. Overall, the technology has low energy density compared with some competing technologies, possesses limited electrolyte stability and requires external power to start-up operation (operate the pumps).

**Table 23 Operating parameters of flow batteries**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Vanadium redox flow battery** | 10–20 ($13x10^3$) | NA/0.5–2 | 75/20–35 | s–10h | min | <1 ms | 0 to 40 | 0–10 | 0.7–0.8 |

#### A.1.4.4 Most common applications/desired outcomes

The properties of flow batteries mean that they are suitable for applications such as time shifting, network efficiency, off-grid/remote area power, time shifting and time shifting of renewables generation.

#### A.1.4.5 Current Australian adoption

There have been very few deployments of this technology in Australia, with the small number of demonstration systems that were in operation now removed from service.

### A.1.5. Hybrid flow battery

In a hybrid flow battery (HFB), one of the active masses is internally stored within the electrochemical cell, whereas the other remains in the liquid electrolyte and is stored externally in a tank. Therefore, HFB cells combine features of conventional secondary batteries and RFBs: the capacity of the battery depends on the size of the electrochemical cell. Typical examples of an HFB are the zinc cerium and, more commonly, the Zn-Br system. In both cases, the anolyte consists of an acid solution of $Zn^{2+}$ ions. During charging, Zn is deposited at the electrode, and at discharging, $Zn^{2+}$ goes back into solution.

#### A.1.5.1 Basic chemistry

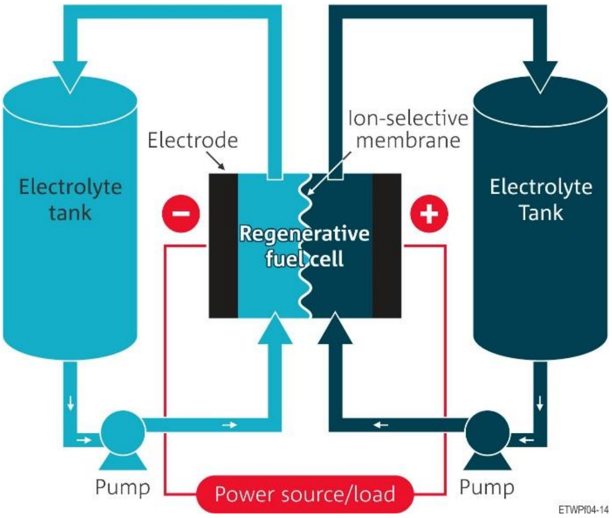
The two electrode chambers of each cell are divided by a membrane (typically a microporous or ion-exchange variety) as shown in Figure 12. This helps to prevent Br from reaching the positive electrode, where it would react with the Zn, causing the battery to self-discharge. To further reduce self-discharge and to reduce the vapour pressure of Br, complexing agents are added to the positive electrolyte. These react reversibly with the Br to form an aqueous solution and reduce the free $Br_2$ in the electrolyte. The working electrodes in a Zn-Br battery are based on carbon-plastic composites.

#### A.1.5.2 Existing technology development, maturity and applications

Various companies are working on the commercialisation of the Zn-Br HFB, which was developed by Exxon in the early 1970s. In the United States, ZBB Energy and Premium Power sell trailer-transportable Zn-Br systems with unit capacities of up to 1 MW/3 MWh for utility-scale applications. Some 5 kW/20 kWh systems for community energy storage are in development as well. In Australia, Redflow have developed a Zn-Br system for electrical energy storage applications. Zn-Br batteries can be 100% discharged every day without being damaged, and this can be repeated for more than 2000 cycles.

Flow batteries have been previously demonstrated in the Smart Grid Smart City trials in Newcastle and Scone in New South Wales, and also at the University of Queensland. The system sizes ranged from 5 kW (total of 200 kW in New South Wales) up to 90 kW in Queensland.

The major Australian manufacturer of hybrid flow batteries is Redflow Ltd in Brisbane. Redflow have been manufacturing the technology onshore but are now in the process of establishing operations in the United States and Europe. The other major supplier of this technology is ZBB, which is based in the United States (with Australian operations in Western Australia).




| Technical data for Redflow battery system | Per module |
|---|---|
| Maximum power | 5 kW |
| Energy | 8 kWh, 170 Ah |
| Maximum and minimum voltage | 58 V and 42 V |
| Operating ambient temperature | 5–45 °C |
| Net energy efficiency | 80% |
| Cycle life | 300–1500 cycles (15 years) |

**Figure 12 Schematic of a hybrid flow battery showing the anolyte and catholyte tanks and fuel cell components (left) and technical data for a sample battery system (right)**

### A.1.5.3 Technical advantages and disadvantages

Table 24 lists the operating parameters of hybrid flow batteries. The HFB, just like RFBs, has a fast response time and is an easily scalable system. Similarly, it potentially possesses a long lifetime in operation. Further, the individual mechanical parts can be individually replaced, meaning that the technology is easy to maintain. Overall, as with redox flow, the HFB has low energy density compared with some competing technologies, possesses limited electrolyte stability and requires external power to start-up operation (operate the pumps). The main difference between redox and hybrid is that one of the chemicals is kept permanently inside the cell in hybrid batteries, and thus only one solution is required for pumping.

**Table 24 Operating parameters of hybrid flow batteries**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Zinc bromide flow battery** | 5–10 (300-1500) | 50–150/1–25 | 60–80/20–35 | s–10h | 4 h | <1 ms | 10 to 45 | 0–1 | 0.17–0.3 |

#### A.1.5.4 Most common applications/desired outcomes

The properties of flow batteries mean that they are suitable for applications such as time shifting, network efficiency, off-grid/remote area power, and peak shifting of renewables generation.

#### A.1.5.5 Current Australian adoption

The Redflow system was demonstrated as part of the Ausgrid Smart Grids Smart Cities project. The broader technology still needs to be proven in large-scale deployments to entice utilities and consumers to purchase the product.

### A.1.6. **Sodium sulfur batteries**

Sodium sulfur (NaS) batteries are high-temperature batteries that require operating at above 300 °C to keep the electrolyte molten, thus enabling the battery chemistry to take place.

#### A.1.6.1 Basic chemistry

NaS batteries consist of liquid (molten) sulfur at the positive electrode and molten sodium at the negative electrode. The active materials are separated by a solid beta alumina ceramic electrolyte. The battery temperature is kept between 300 and 350 °C to keep the electrodes molten.

#### A.1.6.2 Existing technology development, maturity and applications

NaS batteries reach typical life cycles of around 4,500 cycles and have a discharge time of 6.0 to 7.2 hours. They are efficient (AC-based round-trip efficiency is about 75%) and have a fast response. The batteries can be economically used in combined power quality and time-shift applications with high energy density. The technology has been demonstrated at around 200 sites in Japan with a power output rating of more than 270 MW (used principally for peak shaving). Germany, France, the United States and United Arab Emirates also have NaS batteries in operation for applications such as capacity firming, time shifting, reliability and quality of supply.

Since around 1990, NaS batteries have been manufactured by one company, NAS NGK Insulators in Japan, with a minimum module size of 50 kW and typically 300–360 kWh. It is not practical at present to use only one isolated module. Since 20 modules are combined into one battery, the minimal commercial power and energy range is in the order of 1 MW, and 6–7.2 MWh.

To our knowledge, at the present time, there are no sites within Australia using NaS batteries or any sites planned for the future.

#### A.1.6.3 Technical advantages and disadvantages

Table 25 lists the operating parameters of NaS batteries and Table 26 lists their advantages and disadvantages. The main drawback is that to maintain the required operating temperatures, a heat source is required. This uses the battery's own stored energy, partially reducing the battery performance. In daily use, the temperature of the battery can almost be maintained by just its own reaction heat, with appropriately dimensioned insulation.

**Table 25 Operating parameters of sodium sulfur batteries**

| Parameter → / Technology ↓ | Typical life time Years (cycles) | Power density $Wkg^{-1}$ /$kWm^{-3}$ | Energy density $Whkg^{-1}$ /$kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature °C | Self-discharge %/day | Critical voltage/cell V |
|---|---|---|---|---|---|---|---|---|---|
| **Sodium sulfur battery** | 12–20 (>2000) | 90–230/120–160 | 150–240/<400 | s–h | 9 h | 1 ms | 300 | 20 | 1.75–1.9 |

**Table 26 Advantages and disadvantages of sodium sulfur batteries**

| Advantages | Disadvantages |
|---|---|
| • Can withstand high temperatures<br>• Long cycle life<br>• Fast response<br>• Long discharge time<br>• Quite mature and commercially available | • Expensive<br>• Use hazardous material<br>• Hard to construct<br>• High operating temperature (>300 °C) |

#### A.1.6.4 Most common applications/desired outcomes

These batteries are suitable for applications with daily cycling. As the response time is in the range of milliseconds and NaS batteries meet the requirements for grid stabilisation, this technology could be applicable for utilities and large consumers.

#### A.1.6.5 Current Australian adoption

At the time of writing, there are no present or planned sites for Na-S batteries in Australia.

### A.1.7. Metal–air battery

Metal–air batteries are a type of battery or fuel cell that uses the oxidation of a metal with oxygen from air to produce electricity. There are a number of common types: for example, zinc–air batteries (non-rechargeable) and zinc–air fuel cells (mechanically rechargeable) are metal–air batteries powered by oxidising zinc with oxygen from the air.

#### A.1.7.1 Basic chemistry

A metal–air electrochemical cell consists of an anode made from pure metal and a cathode connected to an inexhaustible supply of air. The anodes are usually metals with high energy density, such as zinc or aluminium, which liberate electrons when oxidised. The cathodes or air electrodes are often made using a porous carbon structure or a metal mesh covered with a catalyst layer. The electrolytes can be liquid or solid polymer membranes saturated with potassium hydroxide or other electrolytes, depending on the system configuration and electrode materials.

For the electrochemical reaction, only the oxygen in the air is used. Among the various metal–air battery chemical couples, the lithium–air battery is most attractive, since its theoretical specific energy excluding oxygen (oxygen is not stored in the battery) is 11.14 kWh/kg. This corresponds to about 100 times more than other battery types and even greater than petrol (10.15 kWh/kg).

However, the high reactivity of lithium with air and humidity can cause fire, which is a high safety risk. This technology is under intense research scrutiny for development at present.

#### A.1.7.2 Existing technology development, maturity and applications

Currently, only a zinc–air battery with a theoretical specific energy excluding oxygen of 1.35 kWh/kg is technically feasible. Zinc–air batteries have simular properties to that of fuel cells and conventional chemical batteries. That is, the zinc is the fuel, the reaction rate can be controlled by changing air flow, and oxidised zinc/electrolyte paste can be replaced with fresh paste. Some manufacturers of this technology can be found in Appendix C. As this technology is still under active R&D, there are presently no sites in Australia.

#### A.1.7.3 Technical advantages and disadvantages

Table 27 lists the advantages and disadvantages of metal–air batteries. Rechargeable zinc–air cells have a difficulty in design, since zinc precipitation from the water-based electrolyte must be closely controlled. A satisfactory, electrically rechargeable metal–air system potentially offers low materials cost and high specific energy, but no such system has reached the market.

**Table 27 Advantages and disadvantages of metal–air batteries**

| Advantages | Disadvantages |
|---|---|
| • High energy density<br>• Stable<br>• Non-hazardous materials<br>• Environmentally friendly | • Expensive<br>• Concerns regarding fire safety<br>• Has sophisticated air/oxygen electrode<br>• Not well developed yet, especially the electrically rechargeable battery |

#### A.1.7.4 Most common applications/desired outcomes

As this technology is presently under intense research and scrutiny, it is unclear which application the technology would be most suited for Australia.

#### A.1.7.5 Current Australian adoption

This is a relatively new technology and no significant deployments exist in Australia.

### A.1.8. Nickel-based batteries (nickel-cadmium and nickel metal hydride)

Nickel-based batteries have been quite well developed and are widely available for use in a variety of commercial products. Because of their light weight and rechargeability, they compete well with older batteries, such as common alkaline primary batteries.

### A.1.8.1 Basic chemistry

Most types of nickel-based batteries tend to contain the same cathodes, with nickel oxyhydroxide as the main material in the charged state. The anodes differ among various types, and include metals such as cadmium (Ni-Cd battery), zinc (Ni-Zn battery) or metal hydride (Ni-MH battery). During discharge, the nickel oxyhydroxide reacts with water and produces nickel hydroxide and a hydroxide ion. Upon recharge, the reaction process is reversed.

### A.1.8.2 Existing technology development, maturity and applications

Before the commercial introduction of Ni-MH batteries around 1995, Ni-Cd batteries had been in commercial use since approximately 1915. Ni-MH batteries were developed initially to replace Ni-Cd batteries. Large battery systems using vented Ni-Cd batteries operate on a scale similar to lead-acid batteries. In portable and mobile applications, sealed Ni-MH batteries have been extensively replaced by Li-ion batteries. On the other hand, hybrid vehicles available on today's market operate almost exclusively with sealed Ni-MH batteries, which are robust and far safer than Li-ion batteries. Ni-MH batteries currently have similar prices to Li-ion batteries.

Some nickel-based battery manufacturers can be found listed in Appendix C. At this time, we are unaware of any Australian deployment sites for nickel-based batteries, except for EVs.

### A.1.8.3 Technical advantages and disadvantages

Table 28 lists the advantages and disadvantages of nickel-based batteries. Compared with lead-acid batteries, nickel-based batteries have a higher power density, a slightly greater energy density and the number of cycles is higher. Many sealed construction types are available. From a technical point of view, Ni-Cd batteries are a very successful battery product; in particular, they are the only batteries capable of performing well even at low temperatures from –20 to –40 °C. However, because of the toxicity of cadmium, these batteries are presently used only for stationary applications in Europe. Since 2006, they have been prohibited for consumer use.

Ni-MH batteries have all the positive properties of Ni-Cd batteries, with the exception of the maximal nominal capacity, which is still 10 times less than that of Ni-Cd and lead-acid batteries. Furthermore, Ni-MH batteries have much higher energy densities (weight for weight).

**Table 28 Advantages and disadvantages of nickel-based batteries**

| Advantages | Disadvantages |
|---|---|
| • Much longer cycle life than other batteries<br>• Quick response time | • Suffer from memory effect<br>• Higher self-discharge rate<br>• Environmental problems when disposing |

### A.1.8.4 Most common applications/desired outcomes

The most common application for Ni-MH technologies in Australia is in EVs. For example, the Toyota Prius uses Ni-MH batteries as part of its present hybrid vehicle drive chain. The technology could also be used within Australia's electricity network, where Li-ion or advanced lead-acid batteries may or are used. However, Ni-MH cycle life would be limited compared with the other two technologies.

#### A.1.8.5 Current Australian adoption

Use of the technology appears to be in decline, mainly due to the more advanced and cost-effective Li-ion technologies. However, the technology may remain used by Australia's vehicle industry, due to its inherent safety compared with Li-ion batteries.

### A.1.9. Sodium nickel chloride battery

Sodium nickel chloride (Na-Ni-$Cl_2$) batteries are high-temperature batteries that require operation at above 270 °C to keep the electrolyte molten, thus enabling the battery chemistry to take place.

#### A.1.9.1 Basic chemistry

During charging, chloride ions are released from sodium chloride and combined with nickel to form nickel chloride. The sodium ions then migrate from the cathode reservoir through a beta alumina separator into the anode reservoir. During discharge, the reverse chemical reaction occurs and sodium ions migrate from the anode reservoir through the beta alumina separator into the cathode reservoir. There is no self-discharge, because sodium ions can move easily across the beta alumina, while electrons cannot.

#### A.1.9.2 Existing technology development, maturity and applications

The $NaNiCl_2$ battery is better known as the ZEBRA (Zero Emission Battery Research) battery [47]. Like the NaS battery, it is a high-temperature battery, and has been commercially available since about 1995. Its operating temperature is around 270 °C, and it uses nickel chloride instead of sulfur for the positive electrode. $NaNiCl_2$ batteries can withstand limited overcharge and discharge, and have potentially better safety characteristics and a higher cell voltage than NaS batteries. They tend to develop low resistance when faults occur. This is why cell faults in serial connections only result in the loss of the voltage from one cell, instead of premature failure of the complete system.

The commercially available GE Durathon battery technology is based on the sodium and nickel chemistry. The GE Durathon battery has an operating temperature of 300 °C and is currently scaled in the 10–500 kWh range in a modular format, allowing for larger systems to be constructed.

$NaNiCl_2$ batteries are currently being manufactured by FIAMM in Italy and are represented by LC Engineering within Australia, while GE manufactures the technology in the United States. Both entities are targeting renewable energy storage and remote area power supply (including mining operations) within Australia. At this time, we are unaware of any Australian deployment sites.

#### A.1.9.3 Technical advantages and disadvantages

Table 29 lists the technical data of $NaNiCl_2$ batteries. The main advantages of this technology are that it can withstand extreme ambient temperatures, has a fast response time and long discharge time, and potentially has long cycle lifetimes in operation. However, the technology is expensive, uses some hazardous materials, is difficult to construct and requires a start-up time to raise the internal temperature to the desired operating temperature.

Table 29 Technical data of sodium nickel chloride batteries

| Technical data | |
|---|---|
| Maximum power | 1 MW |
| Maximum current | 2300 A |
| Maximum and minimum Voltage | 577 V and 432 V |
| Power delivery capacity | 6 h |
| Operating ambient temperature | –40 to 50 °C |
| Round-trip AC efficiency | 85 % |
| Cycle life | 4000–4500 cycles (15 years) |

### A.1.9.4 Most common applications/desired outcomes

Present research is in developing advanced versions of the ZEBRA battery with higher power densities for hybrid EVs, and also high-energy versions for storing renewable energy for load levelling and industrial applications.

### A.1.9.5 Current Australian adoption

At the time of writing, the technology has only recently been introduced to the Australian marketplace. The battery needs to be deployed and demonstrated onshore before consumers will be likely to purchase and use the technology.

## A.2. Flywheels

In flywheel energy storage, rotational energy is stored in an accelerated rotor, which is a massive rotating cylinder.

### A.2.1. Basic operation

The main components of a flywheel (Figure 13) are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings, and the transmission device (motor/generator mounted onto a stator).

The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored. To accelerate the flywheel, electricity is supplied by a transmission device. If the flywheel's rotational speed is reduced, electricity may be extracted from the system by the same transmission device.

Flywheels are capable of cycle efficiencies of more than 90%. The energy sizing of a flywheel system is dependent on the size and speed of the rotor, and the power rating is dependent on the motor-generator. Thus, power and energy can be sized independently. To increase efficiency, flywheel systems are often operated in a vacuum environment to reduce drag. Actual delivered energy depends on the speed range of the flywheel, because it cannot deliver its rated power at very low speeds.

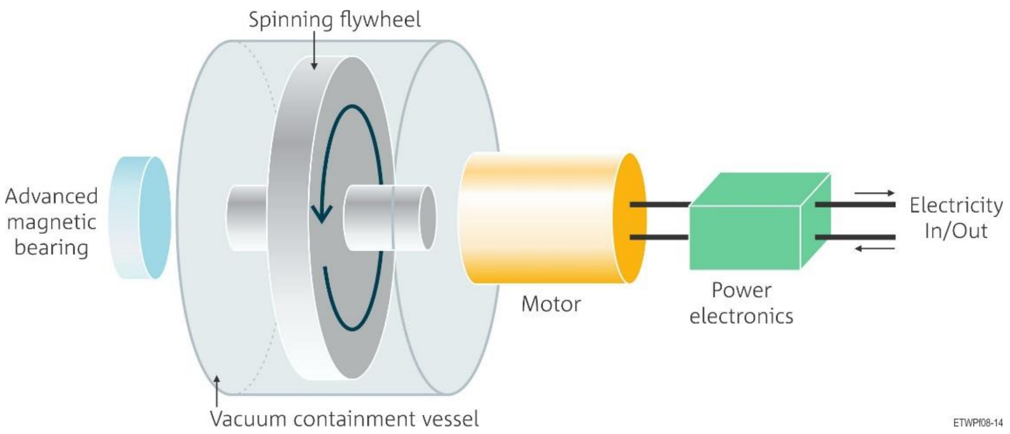



**Figure 13 Schematic of a flywheel showing the main components of the technology**

### A.2.2. **Existing technology development, maturity and applications**

Flywheels of the first generation, which have been available since about 1970, use a large steel rotating body on mechanical bearings. Advanced flywheel energy systems have rotors made of high-strength carbon filaments, suspended by magnetic bearings, which spin at speeds of 20,000 to more than 50,000 rpm in a vacuum enclosure. They are effective for rapid response applications, such as frequency regulation or renewable energy grid stabilisation. Appendix C lists some manufacturers of flywheels.

Current installations have rated power from 100 kW in the United States to more than 500 MW in Germany. In Western Australia, ABB installed PowerStore flywheels for a number of projects, including the Coral Bay, Marble Bar, Leinster Nickel Operation and Kalbarri Wind Farm projects. These installations range from 500 kW to 1 MW rated power and are mainly used for voltage support and frequency regulation. They help safeguard the conventional grid and ensure reliable integration of large amounts of renewable energy.

### A.2.3. **Technical advantages and disadvantages**

Table 30 describes the operating parameters of flywheel energy storage systems, while Table 31 lists their advantages and disadvantages. The main features of flywheels are their excellent cycle stability, long life, low maintenance requirements, high power density and the use of environmentally inert material. However, flywheels have a high level of self-discharge due to air resistance and bearing losses, and suffer from low current efficiency.

The disadvantages of flywheels include their relatively poor energy density and large standby losses. However, they are typically high-power storage systems used in applications such as UPS and EV applications.

**Table 30 Parameters of flywheel energy storage systems**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Flywheel** | > 20 ($10^7$) | 400–1600/5000 | 5–130/20–80 | 15 s–15 min | <15 min | < 4 ms–s | 20 to 40 | 20–100 | NA |

**Table 31 Advantages and disadvantages of flywheel energy storage systems**

| Advantages | Disadvantages |
|---|---|
| • High power capability<br>• Fast response<br>• High efficiency<br>• Non-hazardous material<br>• Excellent cycle stability<br>• Long life | • Low energy density<br>• Short discharge duration<br>• High cost<br>• Complicated device<br>• High self-discharge rate |

### A.2.4. **Most common applications/desired outcomes**

Flywheels are commercially deployed for power quality in industrial and UPS applications, mainly in a hybrid configuration. Efforts are being made to optimise flywheels for long-duration operation (up to several hours) as power storage devices for use in vehicles and power plants.

### A.2.5. **Current Australian adoption**

A number of deployments of flywheel technology exist in Australia. However, new deployments seem to have stalled, with battery technology appearing to be favoured most recently by system integrators.

## A.3. Electric double-layer capacitors and super/ultra capacitors

Double-layer capacitors (DLCs) are also known as supercapacitors or ultracapacitors. In DLC devices, energy storage occurs via adsorption and desorption of ions onto the electrode surfaces within an electric double layer (typically a few nanometres wide) that forms when voltage is applied to the electrode.

### A.3.1. **Basic chemistry**

Supercapacitor cells consist of two current collectors, two electrodes, a separator and an electrolyte (Figure 14). The electrolyte, which consists of a liquid organic or aqueous solvent, contains dissolved ions that migrate to and from the electrodes during charge and discharge, respectively. The electrodes are mechanically separated from each other by an ion-permeable membrane (separator) that prevents short circuits, and are connected via a metallic collector to the terminals. This sandwich-like mechanical cell of collector/electrode/separator/electrode/ collector is rolled into a cylinder or folded into a rectangular shape that is mounted into an aluminium can or a rectangular housing and impregnated with electrolyte. Given the electrode structure, the electrolyte defines the characteristics of the capacitor, the power or peak current capability, the operating voltage range and the allowable temperature range. The hermetically sealed housing ensures stable behaviour over the component's lifetime.

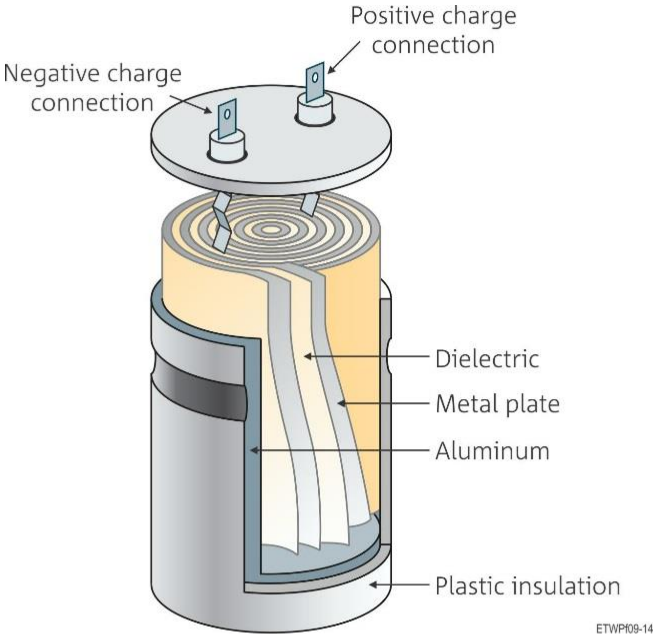



Figure 14 Double-layer capacitor showing the two-electrode configuration

### A.3.2. **Existing technology development, maturity and applications**

DLC technology has been known for 60 years. They fill the gap between classical capacitors used in electronics and batteries because of their nearly unlimited cycle stability, extremely high power capability, and energy storage capability many orders of magnitude higher than traditional capacitors. However, the energy storage capability of DLCs is inferior when compared with traditional batteries.

DLCs are suited especially to applications with a large number of short charge/discharge cycles where their high-performance characteristics can be used. DLCs are not suitable for the storage of energy over longer periods of time, because of their high self-discharge rate, low energy density and high investment costs. At present, DLC technology can be considered relatively mature when compared with some alternative competing technologies.

DLCs are already present in Australia in devices such as UPS and backup power. The technology is also deployed in systems for off-grid applications. New energy storage systems are also using combinations of batteries and DLCs to enable better power and energy capabilities.

Some manufacturers of DLCs are listed in Appendix C.

### A.3.3. **Technical advantages and disadvantages**

Table 32 describes the operating parameters of DLCs while Table 33 lists their advantages and disadvantages. The two main features are the extremely high capacitance values, in the order of many thousand farads, and the possibility of very fast charges and discharges due to extraordinarily low inner resistance. These features are unavailable in conventional batteries.

Other advantages are durability, high reliability, no maintenance requirements, long lifetime and operation over a wide temperature range and in diverse environments (hot, cold and moist). Their lifetime reaches one million cycles (or 10 years of operation) without any degradation, except for the solvent used in the capacitors (which deteriorates in 5–6 years, irrespective of the number of cycles). DLCs are environmentally friendly and easily recycled or neutralised. The efficiency is typically around 90%, with discharge times in the range of seconds to hours. They can reach a specific power density that is about 10 times higher than that of conventional batteries; only very high-power lithium batteries can reach nearly the same specific power density. However, their specific energy density is about 10 times lower than most conventional batteries.

Table 32 Operating parameters of double-layer capacitors

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Super/double-layer capacitors** | > 20 ($5x10^5$) | 0.1–10 /40000–120000 | 0.1–15/10–20 | ms–1h | s–min | 8 ms | –40 to 85 | 2–40 | 0.5 |

Table 33 Advantages and disadvantages of double-layer capacitors

| Advantages | Disadvantages |
|---|---|
| • High power capability<br>• Long cycle life<br>• Good durability and reliability<br>• Fast response/ramp rate | • High cost<br>• Low energy density<br>• High self-discharge rate |

### A.3.4. Most common applications/desired outcomes

DLC technology still exhibits a large development potential, which could lead to much greater capacitance and energy density than conventional capacitors, thus enabling compact designs.

### A.3.5. Current Australian adoption

The uptake of DLC technology continues to grow, especially in combination with batteries in energy storage systems. The technology is not a direct competitor to batteries, but rather a potential partner for the emerging applications for renewable energy generation.

## A.4. Compressed air energy storage

Compressed air (gas) energy storage (CAES) uses air as a storage medium. Typical underground storage options are caverns, aquifers or abandoned mines.

### A.4.1 Basic physics

Electricity is used to compress air and store it in either an underground structure or an above-ground system of vessels or pipes (Figure 15). When needed, the compressed air is mixed with natural gas, burned and expanded in a modified gas turbine. If the heat released during compression is dissipated by cooling and not stored, the air must be reheated prior to expansion in the turbine. This process is called diabatic CAES, and results in low round-trip efficiencies of less than 50%. Diabatic technology is well-proven; the plants have a high reliability and are capable of starting without extraneous power.

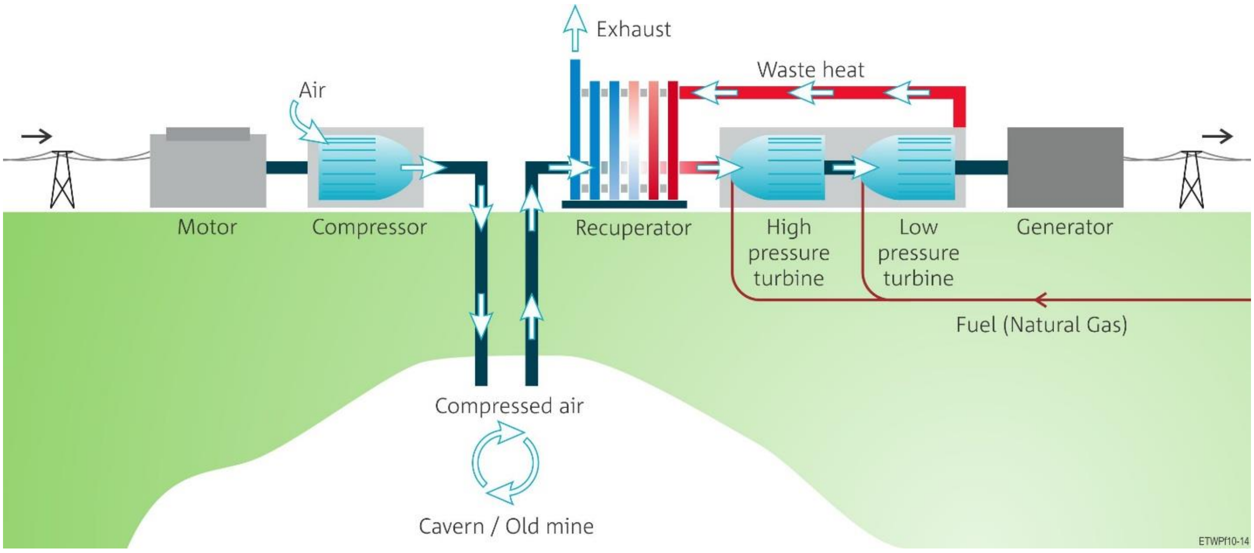



**Figure 15 Schematic of a compressed air energy storage installation**

### A.4.2 Existing technology development, maturity and applications

A number of compressed air energy storage systems have been constructed worldwide, ranging from 2–330 MW in size. A 40-MW (800-MWh storage capability) unit is being constructed in Cheshire, United Kingdom, for a projected commissioning in 2017. The main company engaged for this is Storelectric Ltd; if commissioned, it would be the largest storage system of this technology to date. In 2014, Storelectric had raised 125,000 of the anticipated 300 million pounds required for the project.

Only two diabatic CAES power plants are currently in operation worldwide. In 1978, the first diabatic CAES power plant was built in Huntorf, Germany. It has a round-trip efficiency of roughly 41%. It consists of a low-pressure and high-pressure compressor with intercooler, two salt caverns (2 x 155,000 $m^3$ usable volume, 46–72 bar pressure range), a motor-generator (60 MW charging, 321 MW discharging), a high-pressure turbine (inlet conditions: 41 bar, 490 °C) and low-pressure turbine (13 bar, 945 °C).

The second commercial CAES was a 110-MW unit built in McIntosh, Alabama in 1991. This unit comes on line within 14 minutes. There are no current CAES installations in Australia.

### A.4.3 Technical advantages and disadvantages

Table 34 gives the operating parameters of CAES while

Table 35 lists its advantages and disadvantages. The main advantage is its large capacity; disadvantages are low round-trip efficiency and geographic limitation of locations.

Table 34 Operating parameters of compressed air energy storage systems

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Compressed air (underground)** | 25–40 | NA/0.2–0.6 | 30–60/12 | h–days | min–h | 1–15 min | Ambient | 0 | NA |

Table 35 Advantages and disadvantages of compressed air energy storage systems

| Advantages | Disadvantages |
|---|---|
| • High storage capacity<br>• No hazardous waste<br>• Heat generated could also be used | • High cost<br>• Low efficiency<br>• Requires specific geologic characteristics<br>• Large footprint/underground storage<br>• Safety risks with high-pressure gases |

### A.4.4 Most common applications/desired outcomes

The CAES technology has uses for large-scale energy storage for suitable geographic sites. This technology has similar applications to pumped hydro energy storage, with the additional benefit of opening up a greater number of geographic locations such as coastal areas or abandoned mine sites.

### A.4.5 Current Australian adoption

There are no Australian deployments of this technology. A significant amount of work is required to deploy and demonstrate the technology in Australian conditions before a market can form.

## A.5. Superconducting magnetic energy storage systems

Superconducting magnetic energy storage (SMES) systems work according to an electrodynamic principle. The systems store energy in the magnetic field created by electric currents in superconductors, and operate at low temperatures.

### A.5.1. Basic physics

In an SMES system, the energy is stored in a magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature. The main component of this storage system is a coil made of superconducting material. Additional components include power conditioning equipment and a cryogenically cooled refrigeration system.

Much research and some luck have resulted in superconducting materials with critical temperatures much higher than the original 4 Kelvin (K) discovered about 100 years ago. Today materials are available that can function at around 100 K.

### A.5.2. Existing technology development, maturity and applications

There are several small SMES units available for commercial use and several larger prototyping projects around the world. Several 1-MWh units have been deployed for power quality control. These facilities have also been used to provide grid stability in distribution systems. SMES is also used in utility applications; for example, in northern Wisconsin, a string of distributed SMES units was deployed to improve the stability of a transmission loop.

Appendix C lists some manufacturers of SMES systems. To the best of our knowledge, no Australian deployments exist.

### A.5.3. Technical advantages and disadvantages

Table 36 gives the operating parameters of SMES systems while Table 37 lists their advantages and disadvantages. The main advantage of SMES is the very quick response time: power is available almost instantaneously. The system is also characterised by its high overall round-trip efficiency (85–90%) and the very high power output that can be provided for a short period of time. There are no moving parts in the main portion of SMES, but the overall reliability depends crucially on the refrigeration system. In principle, the energy can be stored indefinitely as long as the cooling system is operational, but the high energy requirements of refrigeration and high cost of superconducting wires makes present usage limited to short durations.

**Table 36 Operating parameters of superconducting magnetic energy storage systems**

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ $/kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ $/kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Superconducting magnetic energy storage** | 20 <br> ($10^4$–$10^5$) | 2.600 | 10–75 <br> /0.006 | ms–8 s | NA | < 100 ms | < –200 | 10–15 | NA |

**Table 37 Advantages and disadvantages of superconducting magnetic energy storage systems**

| Advantages | Disadvantages |
|---|---|
| • High power capability <br> • Long cycle life <br> • High efficiency <br> • Fast response/ramp rate | • High cost <br> • Low energy density <br> • Short discharge duration <br> • High self-discharge rate <br> • Difficult to maintain <br> • Strong magnetic field <br> • Cryogenic temperatures |

### A.5.4. Most common applications/desired outcomes

Power quality and grid stability are the main applications of this technology, assuming key technical challenges such as the need for cryogenic refrigeration (and subsequent costs of this) can be solved.

### A.5.5. Current Australian adoption

There are no Australian deployments of this technology. A significant amount of work is required to deploy and demonstrate the technology in Australian conditions before a market can form.

## A.6. Chemical energy storage

Chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers, since these could have a significant impact on the storage of electrical energy in large quantities. The main purpose of such a chemical energy storage system is to use 'excess' electricity to produce hydrogen via water electrolysis. Once hydrogen is produced, different methods are available for using it as an energy carrier, either as pure hydrogen or as SNG. Although the overall efficiency of hydrogen and SNG is low compared to technologies such as pumped hydro storage and Li-ion batteries, chemical energy storage is the only concept that allows storage of large amounts of energy, up to TWh, and for greater periods of time – such as seasonal storage over a period of days to months. Another advantage of hydrogen and SNG is that these universal energy carriers can be used in different sectors, such as transport, heating and the chemical industry.

### A.6.1. Basic chemistry

A typical hydrogen storage system consists of an electrolyser, a hydrogen storage tank and a fuel cell. An electrolyser is an electrochemical converter that splits water with the help of electricity into hydrogen and oxygen. It is an endothermic process (i.e. heat is required during the reaction). Hydrogen is stored under pressure in gas bottles or tanks, which can be done for a practically unlimited time. To generate electricity, hydrogen and oxygen flow into the fuel cell where an electrochemical reaction that is the reverse of water splitting takes place: hydrogen and oxygen react and produce water, heat is released and electricity is generated. For economic and practical reasons, oxygen is not stored, but is vented to the atmosphere on electrolysis, while oxygen from the air is taken for the power generation.

In addition to fuel cells, gas motors, gas turbines and combined cycles of gas and steam turbines are under discussion for power generation. Hydrogen systems with fuel cells (less than 1 MW) and gas motors (under 10 MW) can be adopted for combined heat and power generation in decentralised installations. Gas and steam turbines of up to several hundred MW could be used as peaking power plants. The overall AC–AC efficiency is around 40%.

Hydrogen can be stored in different ways: as a gas under high pressure, a liquid at very low temperature, adsorbed on metal hydrides or chemically bonded in complex hydrides. However, for stationary applications, gaseous storage under high pressure is the most popular choice. Smaller amounts of hydrogen can be stored in above-ground tanks or bottles under pressures up to 900 bar. For larger amounts of hydrogen, similar storage to compressed air energy storage systems (caverns, etc.) may be considered.

Synthesis of methane (also called SNG) is a second option to store electricity as chemical energy. In this case, a second step is required beyond the water-splitting process: a step in which hydrogen and carbon dioxide react to methane in a methanation reactor. As is the case for hydrogen, the SNG produced can be stored in pressure tanks, underground, or fed directly into the gas grid.

Several $CO_2$ sources are conceivable for the methanation process, such as fossil-fuelled power stations, industrial installations or biogas plants. To minimise losses in energy, transport of the $CO_2$ (from the $CO_2$ source) and $H_2$ (from the electrolysis plant) to the methanation plant should be limited. Indeed, the production of SNG is preferable at locations where $CO_2$ and excess electricity are both available. In particular, the use of $CO_2$ from biogas production processes is promising, given the relatively wide uptake of biogas technologies. Nevertheless, intermediate on-site storage of the gases is required, as the methanation is a constantly running process. This concept of 'power to methane' has recently been the subject of different R&D projects (e.g. in Germany, where a pilot-scale production plant is under construction).

The main advantage of using SNG gas to storage energy is the use of an already existing gas grid infrastructure. Moreover, methane has a higher energy density than hydrogen, and transport in pipelines requires less energy. The main disadvantage of SNG is the relatively low efficiency due to conversion losses during electrolysis, methanation, storage, transport and the subsequent power generation. The overall AC–AC efficiency is even lower than that of hydrogen.

### A.6.2. Existing technology development, maturity and applications

To date, no commercial hydrogen storage systems have been used for renewable energy. Various R&D projects over the last 25 years have successfully demonstrated the feasibility of hydrogen technology however, such as a project on the self-sufficient island of Utsira in Norway. Another example is a hybrid power plant being constructed by Enertrag in Germany. Wind energy is used to produce hydrogen via electrolysis if the power cannot be directly fed into the grid. On demand, the stored hydrogen is added to the biogas used to run a gas motor. The hydrogen produced will be used for a hydrogen refilling station at the international airport in Berlin. Water electrolysis plants on a large scale (up to 160 MW) are state-of-the-art for industrial applications; several were built in different locations (e.g. Norway, Egypt, Peru) in the late 1990s.

Hydrexia in Brisbane is an early stage company that has recently raised finances from Air Liquide Investissements d'Avenir, Southern Cross Renewable Energy Fund and Uniseed. To date, the company has demonstrated prototype units for energy storage.

### A.6.3. Technical advantages and disadvantages

As a storage medium, hydrogen can be easily scaled to hold large quantities of energy. The main disadvantages are the size of tanks required to store the gas, the high pressure required of the system, and discharge times of minutes–hours, meaning that applications needing fast discharge cannot be combined with hydrogen storage.

### A.6.4. Most common applications/desired outcomes

Hydrogen storage is suitable for large-scale storage systems connected to intermittent renewable generation. These systems can be used for load shifting of energy. At the residential/industrial scale, fuel cells can be combined with renewable generation for load supply (provided additional hydrogen gas is used as fuel) or for load shifting of renewables generation.

### A.6.5. Current Australian adoption

There are no Australian deployments of this technology. A significant amount of work is required to deploy and demonstrate the technology in Australian conditions before a market can form.

## A.7. Pumped hydro

Pumped hydro storage systems work through the principle of storing the gravitational potential energy of water by pumping it to high elevations from a lower elevation. Upon discharge, the energy is recovered by allowing the water to fall and release its stored energy.

### A.7.1. Basic physics

Conventional pumped hydro storage systems (Figure 16) use two water reservoirs at different elevations to pump water during low cost or off-peak hours from the lower to the upper reservoir (charging). When required, such as during periods of high electricity demand, the water is released to the lower reservoir to turn turbines with a generator to produce electricity (discharging): similar to the way in which conventional hydropower plants generate electricity. There are different options for the upper and lower reservoirs: for example, high dams may be used as pumped hydro storage plants, while the lower reservoir may capitalise upon flooded mine shafts, other underground cavities and the open sea.

### A.7.2. Existing technology development, maturity and applications

Pumped hydro storage is the largest and most widespread energy storage technology in the world. It is the only technology that is capable of storing energy up to multiple GWh scale. With more than 127 GW worldwide, pumped hydro storage power plants represent nearly 99% of worldwide installed electrical storage capacity, which is about 3% of global generation capacity.

Many existing pumped hydro storage plants store at least 6 hours or more of energy, making them useful for bulk power management, load levelling and providing firm capacity. Pumped hydro storage can also ramp rapidly while generating, making it useful for load following or levelling, and providing ancillary services such as contingency spinning reserve and frequency regulation.

The Tumut Hydroelectric Power Station 3 in New South Wales is an open-loop pumped hydro system that was the first pumped storage hydroelectric power station built in Australia. It can generate 1500 MW of electricity through six Toshiba turbines. Additional systems at Shoalhaven (240 MW) and Kangaroo Valley (160 MW) in New South Wales, and Wivenhoe (500 MW) in Queensland also are in operation.

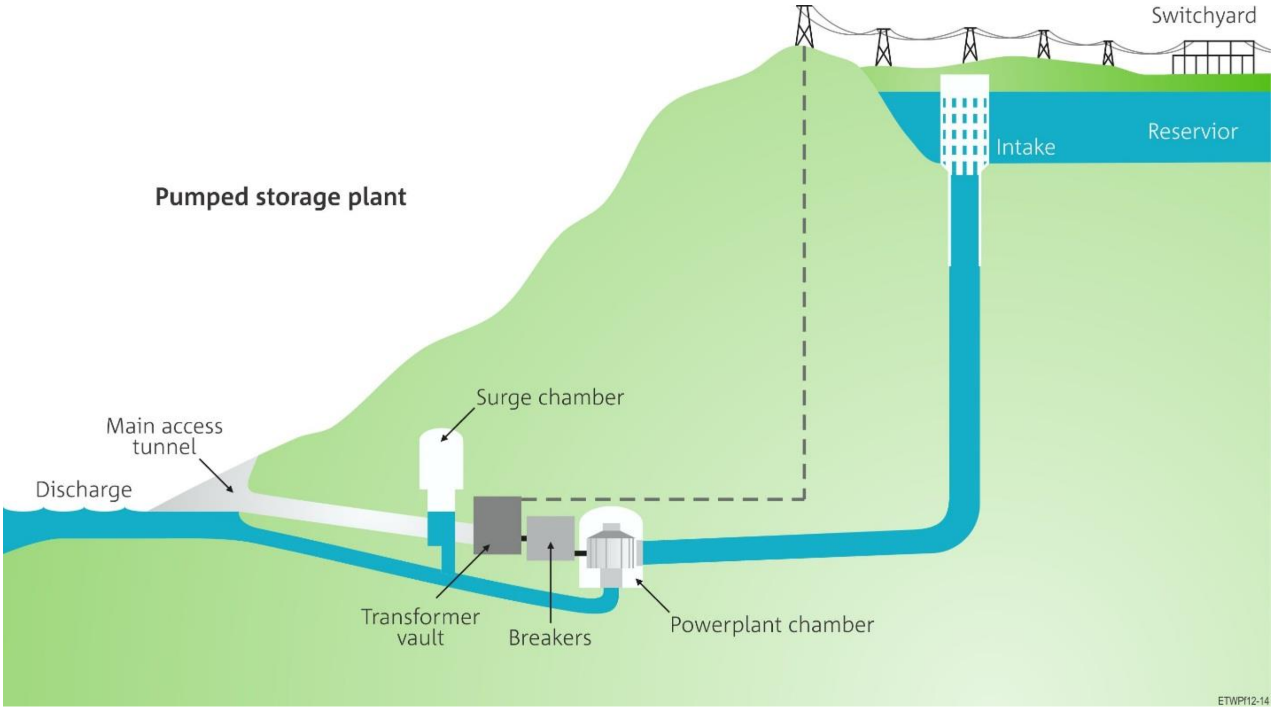


Figure 16 Schematic of a pumped hydro energy storage installation

### A.7.3. Technical advantages and disadvantages

Table 38 describes the operating parameters of pumped hydro energy storage, while Table 39 lists its advantages and disadvantages. The main advantages are the very long lifetime and practically unlimited cycle stability of the installation. The main drawbacks are the dependence on topographical conditions, large land use, and challenges/costs of getting access to the land.

Table 38 Operating parameters of pumped hydro energy storage

| Parameter → <br> Technology ↓ | Typical life time <br> Years (cycles) | Power density <br> $Wkg^{-1}$ /$kWm^{-3}$ | Energy density <br> $Whkg^{-1}$ /$kWhm^{-3}$ | Typical discharge time | Recharge time | Response time | Operating temperature <br> °C | Self-discharge <br> %/day | Critical voltage/cell <br> V |
|---|---|---|---|---|---|---|---|---|---|
| **Pumped hydro** | 50–100 (>500) | NA/0.1–0.2 | 0.5–1.5/0.2–2 | h–days | 1 min–h | s–min | Ambient | 0 | NA |

Table 39 Advantages and disadvantages of pumped hydro energy storage

| Advantages | Disadvantages |
|---|---|
| • Long life<br>• Largest storage capacity<br>• No pollution or waste<br>• High cycle stability | • Expensive to build<br>• Requires specific geological topographic structures<br>• Long time to build<br>• Large footprint |

### A.7.4. Most common applications/desired outcomes

Pumped hydro energy storage is a mature technology. The first plants were used in Italy and Switzerland in the 1890s. By 1933, reversible pump-turbines with motor-generators were available. A seawater pumped hydro plant was first built in Japan in 1999.

Pumped hydro storage has historically been used by electric utilities to reduce total generation cost by time shifting and to control grid frequency. A conventional installation cannot function as a frequency controller while pumping, but an advanced, variable speed-control installation can do so by varying the rotational speed of the motor.

Typical discharge times of pumped hydro storage range from several hours to a few days. The efficiency of pumped hydro plants is in the range of 70–85%.

### A.7.5. Current Australian adoption

No new installations of pumped hydro have been instigated within Australia for the past 30 years. Further, the unique geographical and topological requirements of this technology mean that the number of locations within Australia where such technology could be deployed is limited.

## A.8. Thermal energy storage system

Thermal storage can be subdivided into different technologies: storage of sensible heat, storage of latent heat, and thermochemical sorption storage.

### A.8.1. Basic physics

The storage of heat is a well-known and widespread technology, with the domestic hot water tank as an example (as shown in Figure 17).

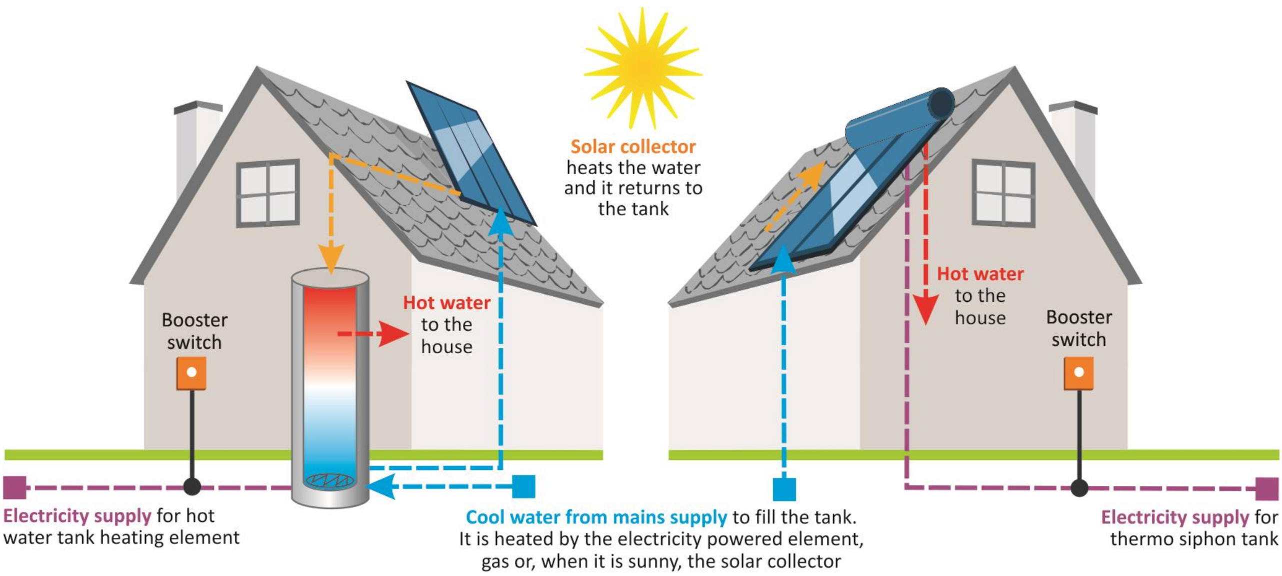



Figure 17 Schematic of a residential thermal energy storage solution

The heat storage medium may be a liquid (such as water or thermo-oil) or a solid (such as concrete or earth). Such systems are classified as sensible heat storage. Thermal energy is stored and used solely through a change of temperature of the storage medium. The capacity of a storage system is defined by the specific heat capacity and the mass of the storage medium used.

Latent heat is the energy exchanged during a phase change, such as the melting of ice. It is also called 'hidden' heat, because there is no change of temperature during energy transfer. Latent heat can be stored using phase-change materials as storage media; the best-known example is the ice cooler, which uses ice in an insulated box or room to keep food cool during hot days. Organic (paraffins) and inorganic (salt hydrates) phase-change materials are available for latent heat storage systems. Currently most phase-change materials use the solid–liquid phase change, such as molten salts as a thermal storage medium for concentrated solar power plants. The advantage of latent heat storage is its capacity to store large amounts of energy in a small volume and with a minimal temperature change, which allows efficient heat transfer.

Sorption (adsorption and absorption) storage systems work as thermochemical heat pumps under vacuum conditions and have a more complex – and therefore, more expensive – design. Heat from a high-temperature source heats up an adsorbent (e.g. silica gel or zeolite), and vapour (working fluid, e.g. water) is desorbed from this adsorbent and condensed in a condenser at low temperatures. The heat of condensation is then withdrawn from the system. The dried adsorbent and the separated working fluid can be stored as long as desired. As this process occurs, it charges up the system. During discharging, the working fluid takes up low-temperature heat in an evaporator. Subsequently, the vapour of the working fluid adsorbs onto the adsorbent, and the heat of adsorption is released at high temperatures. Depending on the adsorbent/working fluid pair, the temperature level of the released heat can be up to 200 °C, and the energy density up to three times higher than that of sensible heat storage with water.

### A.8.2. Existing technology development, maturity and applications

Thermal energy storage systems store available heat by different means in an insulated repository for later use in different industrial and residential applications, such as space heating or cooling, hot water production or electricity generation. Thermal storage systems are deployed to overcome the mismatch between demand and supply of thermal energy and thus they are important for the integration of renewable energy sources.

Latent heat storage manufacturers are being developed by German/Spanish consortium DLR and Endesa. Australian manufactures are Wizard power in South Australia and Lloyd Energy Systems and CCI (Valves) in New South Wales.

The two-tank indirect system is being deployed in 'Andasol 1-3' (three 50-MW parabolic trough plants in southern Spain), and is planned for Abengoa Solar's 280-MW Solana plant in Arizona. Apart from heat storage systems for concentrated solar power, latent heat storage is under development by a German/Spanish consortium – including DLR and Endesa – at Endesa's Litoral Power Plant in Carboneras, Spain. The storage system at the pilot facility is based on sodium nitrate, has a capacity of 700 kWh and works at a temperature of 305 °C.

A 2-MW superheated steam-molten salt energy system is being installed in Whyalla in South Australia by Wizard Power. The Whyalla Solar Storage plant is a pre-commercial demonstration of energy storage, with full integration, demonstration of start-up and shut down procedures, and the ability to handle intermittent solar input and deliver energy on demand. The project scope includes installation of a solar field with four Big Dish units, demonstration energy storage systems and a steam turbine and generator for power production. The Big Dish is a parabolic dish concentrator developed by the Solar Thermal Group at the Australian National University. The initial prototype was constructed on the Canberra campus of the Australian National University in 1994.

A 3.5-MW graphite block thermal storage system has been deployed in Lake Cargelligo in New South Wales. The system uses a water/steam storage system operating between 200 and 500 °C. It was installed by Lloyd Energy Systems using an AUD$5 million grant from the Australian Electricity Storage Technologies program.

### A.8.3. Technical advantages and disadvantages

Table 40 lists the advantages and disadvantages of thermal energy storage systems.

**Table 40 Advantages and disadvantages of thermal energy storage**

| Advantages | Disadvantages |
|---|---|
| • Low incremental cost of enabling functional energy storage<br>• Can fulfil applications that require energy storage to act as a controllable load (e.g. market participation) | • Cannot easily convert heat back into electricity<br>• Cannot fulfil applications that require storage to act as both a load and generator (e.g. raising frequency on the grid; business storage systems) |

### A.8.4. Most common applications/desired outcomes

In the context of energy storage, sensible/latent heat storage systems are used, not sorption methods. For example, concentrated solar power plants primarily produce heat, which can be stored easily before conversion to electricity and thus provide dispatchable electrical energy. State-of-the-art technology is a two-tank system for solar-tower plants, with molten salts as the heat transfer fluid and storage medium. The molten salt is heated by solar radiation and then transported to the hot salt storage tank. To produce electricity, the hot salt passes through a steam generator, which powers a steam turbine. Subsequently, the cold salt (still molten) is stored in a second tank before it is pumped back to the solar tower.

The main disadvantage of this technology is the risk of the liquid molten salt freezing at low temperatures, thereby blocking the pumping mechanism/piping. Additionally, the risk of chemical decomposition of the salts at higher temperatures reduces the lifetime of the system, which requires regular maintenance to replace and clean out decomposed materials. Typical salt mixtures, such as sodium nitrate-potassium nitrate eutectics, have freezing temperatures lower than 200 °C, requiring plant temperatures to be maintained at above this temperature during operation. In solar-trough plants, a dual-medium storage system with an intermediate oil/salt heat exchanger is preferred. Storage materials and containment also require a higher volume than storage systems for solar-tower plants.

### A.8.5. Current Australian adoption

Thermal storage in residential hot water systems is commonplace in Australia. Deployment outside residential hot water usage is limited, with few other applications of large-scale heat storage existing in Australia.

## A.9. Load coordination

Load coordination (or demand management) is where energy consumption is managed such that even though energy is not returned to the electricity system, a similar benefit is provided as could be achieved using energy storage. In this sense, load coordination can be considered as 'virtual' energy storage. One example (with no storage) is a pool-pump controller: as long as it runs sufficiently often, its operating times can be adjusted with no real impact on the end user. Another example (implicitly using thermal storage) is the pre-cooling of a residential home using an air-conditioner in anticipation of peak evening demand, which reduce loads at peak times.

### A.9.1. Basic physics

Load coordination provides an alternative to direct energy storage by exploiting flexibility in a service provided to an end user, thus allowing shaping of an energy profile. Where electricity is driving a mechanical, thermal, or chemical process, and the output is not required immediately, some direct or implicit storage of this converted energy can be used. The specific characteristics of different load coordination schemes vary substantially. However, they can be characterised most simply by:

- lead time required before an event
- power reduction profile during the event
- maximum sustained load reduction
- recovery time and profile
- load shift efficiency (was additional energy used?)
- allowed cycle frequency (how often an event can be called).

Through this type of broad characterisation, applied to a wide range of different load types, energy service providers can offer the market a firm aggregate response.

### A.9.2. Existing technology development, maturity and applications

Load coordination has been extensively deployed, and is of high technical and commercial maturity.

At an industrial scale, on-call, large-scale demand management arrangements are well established (e.g. aluminium smelters). Within the commercial sector, heating, ventilation and air-conditioning typically accounts for around 60% of building energy use, and several energy service companies (e.g. EnerNOC and BuildingIQ) are now targeting demand response. This is a rapidly growing area. In the residential sector, off-peak 'controlled load' hot-water systems have been extensively deployed for more than 50 years. As an example, they are used to shift around 300 MW of demand within the Ausgrid network.

Recently – and at a lower maturity level – more sophisticated load coordination systems have become more common, through home automation and the development of load control standards such as AS/NZS4755. The standard is being developed to cover:

- air-conditioners
- swimming pool pumps
- water heaters

- EV charging
- energy storage systems.

Where an energy storage system connects to the electricity network through an inverter (as battery energy systems typically will), then both demand response and power quality functions are covered by AS/NZS4777.

Through the development of these Australian standards and other smart-appliance standards, there is an increasing ability for end-use equipment to be actively deployed for the management of peak electrical demand within constrained network areas. Examples of this are the PeakSmart air-conditioning schemes operated by Ergon and Energex in Queensland.

Within the commercial and industrial sectors, load coordination is typically used to manage peak electricity demand, both from a network and generation capacity (and augmentation deferral) perspective, but also to manage capacity, demand and energy costs within a specific site.

Residential applications of load coordination have targeted customer energy costs network and the deferral of network augmentation via peak demand reductions. They are also able to provide power quality management (specifically voltages within the low-voltage distribution network), especially in areas of high-penetration PV deployments.

### A.9.3. Technical advantages and disadvantages

Table 41 lists the advantages and disadvantages of load coordination technologies.

**Table 41 Advantages and disadvantages of load coordination**

| Advantages | Disadvantages |
|---|---|
| • Uses existing equipment<br>• Many mature deployment options<br>• Specific loads can be targeted based on locational and temporal requirements throughout the network | • Industrial loads may have long lead-times to provide a response<br>• Residential loads are usually small, so large numbers of devices need to be coordinated to provide a sufficiently large response<br>• Residential loads are often not reliably available at an individual level, so must be aggregated to provide a firmness of response |

### A.9.4. Most common applications/desired outcomes

The most widely deployed load coordination scheme is off-peak residential ‘controlled load’ hot water. Other emerging examples include ‘smart’ appliances such as pool pumps, washing machines and fridges, which turn on and off based on a range of network and tariff drivers.

There are a number of existing established industrial demand management arrangements, though these are more targeted towards support at the transmission and centralised generation level, where large industrial customers typically connect to the electricity network.

Commercial customers with significant building air-conditioning loads are well suited to target reductions in peak network demand, while also reducing their own costs through reduced demand, capacity and energy costs.

### A.9.5. Current Australian adoption

Uptake of demand management technology in Australia is increasing. There is a strong base in the existing industrial sector, plus residential hot-water control, new demand-response standards and initial uptake of demand-response-enabled air conditioning show an emerging residential market. There is also significant potential from additional appliance types and the charge management of EVs as they become more readily adopted.

# B. Appendix – Technology and manufacturing readiness levels

Table 42 provides a short description of technology readiness level (TRL) [13] and Table 43 addresses manufacturing readiness levels (MRL) [14]. For more information on TRLs and MRLs, please refer to relevant references above.

**Table 42 Description of technology readiness levels. Table has been adopted from reference [14]**

| Technology readiness level | Description |
|---|---|
| **TRL-1** | Scientific research begins translation to applied research and development. This is the lowest level of technology readiness. Examples might include basic paper studies of a technology's properties. |
| **TRL-2** | Creation and invention begins. Basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytical studies. |
| **TRL-3** | Active research and development is initiated. This includes analytical studies and laboratory studies to validate predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. |
| **TRL-4** | Basic technological components are integrated. Fundamental technological components are integrated to establish a system that works well work together. |
| **TRL-5** | Reliability of the technology improves significantly. The technological components are integrated with reasonable reliability so it can be tested in a simulated environment. Examples include 'high-fidelity' laboratory integration of the technologies' components. |
| **TRL-6** | Model and/or prototype system is tested in relevant or simulated application environment. Model or prototype, which is well beyond that of TRL-5, is tested in a relevant environment. This is a major step-up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment with a publication or technical report documenting the outcomes. |
| **TRL-7** | Prototype near or at planned operational system. This represents a major step from TRL-6, in that it requires demonstration of an 'actual' system in an operational 'field' environment. |
| **TRL-8** | Technology is proven to work. Technology completed and qualified through commission, testing and demonstration with minor technical issues. |
| **TRL-9** | Actual application of technology is in its final form e.g. mature technology. Technology has proven itself through numerous successful operations, and can be purchased commercially 'off-the-shelf'. |

**Table 43 Description of manufacturing readiness levels. Table has been adopted from reference [14]**

| Manufacturing readiness level | Description |
|---|---|
| **MRL-1** | Basic manufacturing implications identified. This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve manufacturing objectives. Basic research begins in the form of theoretical paper studies. |
| **MRL-2** | Manufacturing concepts identified. This level is characterised by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined technology needs. Typically this level of readiness in the science and technology environment includes identification, paper studies, and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging. |
| **MRL-3** | Manufacturing proof-of-concept developed. This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. Materials or processes, or both, have been characterised for manufacturability and availability but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality. |
| **MRL-4** | Capability to produce the technology in a laboratory environment. Technologies should have matured to at least TRL-4. This level indicates that the technologies are ready for development. Processes to ensure manufacturability, producibility and quality are in place, manufacturing risks have been identified, and target cost objectives have been established. Key design performance parameters have been identified as well as any special capability required. |
| **MRL-5** | Capability to produce prototype components in a production-relevant environment. Technologies should have matured to at least TRL-5. A manufacturing strategy has been refined and integrated with the risk-management plan. Prototype materials, tooling and test equipment, as well as personnel skills, have been demonstrated. Manufacturing technology development and producibility are ongoing. A cost model has been developed assess projected manufacturing costs. |
| **MRL-6** | Capability to produce a prototype system or subsystem in a production-relevant environment. Technologies should have matured to at least TRL-6. An initial manufacturing approach has been developed, manufacturing processes have been defined and characterised. Prototype materials, tooling and test equipment, as well as personnel skills, have been demonstrated. Projected manufacturing cost versus target objectives have been performed, long-lead and key supply chain elements have been identified. All subcontractors have been identified. |
| **MRL-7** | Capability to produce systems, subsystems or components in a production-representative environment. Technologies should be maturing to at least TRL-7. System detailed design activity is underway, material specifications have been approved and materials are available to meet the planned pilot run. Cost model has been updated with detailed designs, and supply chain and supplier quality assurance have been assessed. Production tooling, test equipment and development have been initiated. |
| **MRL-8** | Pilot line capability demonstrated; ready to begin low-rate initial production. Technologies should have matured to at least TRL-7. Detailed system design is essentially complete, and all materials are available to meet the planned low-rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot run. All known production risks |

| | |
|---|---|
| | pose no significant challenges. Engineering costs are driven by detailed design and have been validated with actual measured data. |
| **MRL-9** | Low-rate production demonstrated; capability in place to begin full-rate production. Technologies should have matured to at least TRL-9. This level of readiness is normally associated with readiness for full-rate production. Systems engineering should have been met, system design features are stable and have been proven in test and evaluation. Production risk monitoring is ongoing. Production cost targets have been met, with learning curves validated. |
| **MRL-10** | Full-rate production demonstrated, and lean production practices in place. This is the highest level of production readiness. Technologies should have matured to at least TRL-9. This level of manufacturing is normally associated with improving production life technology quality, and reducing technology costs. Lean production practices are well established and continuous process improvements are ongoing. |

# C. Appendix – Energy storage manufacturers and location

**Table 44 Key energy storage manufacturers and their location**

| Technology | Manufacturer | Location |
|---|---|---|
| **Lead-acid** | Century Yuasa (GS Yuasa Corporation) | China, Japan, United States, Australia, Indonesia, Thailand |
| **Lead-acid** | Exide | United States, Australia |
| **Advanced lead-acid** | Ecoult / East Penn Manufacturing | Australia, United States |
| **Advanced lead-acid** | Furukawa | Japan |
| **Nickel metal hydride** | GS Yuasa Company | China |
| **Nickel metal hydride** | Sanyo | Japan |
| **Lithium iron phosphate** | BYD | China |
| **Lithium iron phosphate** | Samsung SDI | Korea |
| **Lithium iron phosphate** | SMA | Germany (Korean battery supplier) |
| **Lithium iron phosphate** | Bosch | Germany (Japanese battery supplier) |
| **Lithium iron phosphate** | Magellan Power | Australia (Korean battery supplier) |
| **Lithium iron phosphate** | Sunverge | United States |
| **Lithium nickel manganese cobalt oxide (NMC)** | Panasonic | Japan |
| **Lithium NMC** | Tesla | United States (Japanese battery supplier) |
| **Sodium sulfur** | NAS NGK insulators | Japan, Australia |
| **Sodium nickel chloride (molten salt)** | General Electric | United States and worldwide |
| **Sodium nickel chloride (molten salt)** | FIAMM | Italy with Australian representatives |
| **Sodium nickel chloride (molten salt)** | Eagle Picher Technologies | United States |
| **Flow battery** | Redflow | Australia |
| **Redox flow battery (vanadium flow)** | GEC | Shanxi, China |
| **Hybrid flow battery (zinc bromine flow)** | Redflow | Brisbane, Australia |
| **Hybrid flow battery (zinc bromine flow)** | ZBB | Wisconsin, United States, Western Australia |
| **Metal–air (Zn–air) [grid applications]** | Eos Energy Systems | United States |
| **Metal–air (Zn–air)** | Panasonic | United States, Japan |
| **Metal–air (Zn–air) [military applications]** | Electric Fuel Corporation | United States |
| **Metal–air (Zn–air)** | Enove | Tunisia |

| | | |
|---|---|---|
| **Metal–air (Zn–air)** | GP Batteries | Singapore |
| **Metal–air (Zn–air)** | Renata | Switzerland |
| **Flywheel** | Beacon Power | United States |
| **Flywheel** | Calnetix | United States |
| **Flywheel** | Active Power Inc. | United States |
| **Flywheel** | Areees Power Solution | South Africa |
| **Flywheel** | Flywheel Energy Systems | Canada |
| **Flywheel** | Precise Power Corporation | United States |
| **Flywheel** | Urenco Power Technologies | United Kingdom |
| **Supercapacitor** | Maxwell Superconductivity and Magnets | United States |
| **Supercapacitor** | Ioxus | United States |
| **Supercapacitor** | Freqcon GmbH | Germany |
| **Supercapacitor** | Various | Various |
| **Superconducting magnetic energy storage (SMES)** | Superpower | United States |
| **SMES** | ABB | Switzerland |
| **SMES** | AML Superconductivity and Magnets | United States |
| **Pumped hydro** | Genex Power | Australia |
| **Pumped hydro** | Sulzer | Switzerland |
| **Pumped hydro** | Alstrom | France |
| **Compressed air energy storage** | SustainX | United States |
| **Compressed air energy storage** | LightSail Energy | United States |
| **Compressed air energy storage** | Dresser-Rand | United States, France |

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