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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.

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

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
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.

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 → 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
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 • Long cycle life • Fast response • Long discharge time • Quite mature and commercially available • Can be used for electric vehicles	• Expensive • Use hazardous material • Hard to construct • 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 $Na\text{-}NiCl_2$ 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 $Na\text{-}NiCl_2$ 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.

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