Review of Large-scale Energy Storage Technologies

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Abstract

The paper reviews energy storage technologies and their applicability to the Australian National Electricity Market (NEM). The increasing gap between maximum and minimum operational demand is likely to continue as time-varying renewable generation penetration proceeds. Recent severe weather events find the NEM ancillary services market for frequency and voltage control becoming increasingly important as the mechanical system inertia of thermal power stations reduces with the retirement of coal-fired power stations. To maintain grid stability through innovative technologies involving various storage technologies with different response times and endurances, a review of existing storage technologies for short to medium-term storage (such as flywheels, batteries, and supercapacitors) reveals that hybrid systems with different power, energy density, and fast response capabilities will be part of the solution. Pumped Hydro Energy Storage, Compressed Air Energy Storage System, hydrogen fuel cells, and fast response peaking hydrogen-fuelled gas turbines were reviewed for long-term storage. Batteries and Supercapacitors are assessed to be the solution for the immediate net zero targets for 2030-2050. While many varieties of batteries exist, metal ion batteries will continue to dominate with particular interest growing toward sodium ion batteries. Current challenges as well as opportunities for future research are highlighted.
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**Index Terms**—Energy storage, renewable energy, frequency control, voltage control, supercapacitors, batteries, hybrid energy storage.

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**I. INTRODUCTION**

The global supply of energy is increasingly transforming from fossil fuels to renewables, driven by the imperative to reduce CO₂ emissions to mitigate climate change and the threat of depletion of oil and gas reserves. Following the landmark Paris Agreement of 2015 on climate action, the efforts to reduce fossil fuel emissions have been growing globally by accelerating the integration of renewable distributed generators (DG’s) into power systems.

Australia’s commitment to achieving net zero by 2050 and emission reduction by 43% by 2030 [1] are evident from the 2022 energy mix with 32.5% [2] renewables up from 14.6% in 2015 [3]. Further, fossil fuel-based generation is contributing only about 59.1% [2] of the total energy mix in 2022 from 85.4% in 2015 [3] illustrating the accelerated transition to renewables. At this unprecedented withdrawal rate of fossil fuel-based generators (expected to be about 60% by 2030 [4]) coupled with the increase in intermittent renewables, there is a pressing need for dispatchable firm capacity from sources such as pumped hydro, flywheels, batteries, and other alternative energy storage systems to manage variations, dynamics in daily & seasonal demand-supply mix and the increasing wholesale daily energy price. An ongoing increase in Renewable Energy (RE) penetration and loss of low-cost base-load fossil fuel generation capacity [5] has driven an increase in daily wholesale energy price in the National Electricity Market (NEM) by about 19% from 2016 to 2022 [6] (calculated based on AEMO’s wholesale daily average data excluding data anomaly for 2020-2021 due to substantial reduction in demand during COVID-19 pandemic).

In the summer of 2022, the NEM recorded the highest instantaneous RE peak at 69% of total supply and forecasts indicate resource adequacy to reach the short or instantaneous bursts of RE penetration of 100% by 2025 [7]. A consequence of this future for power systems with increasing deployment of renewable distributed generators (DGs) will be a trend towards a drastic drop in rotating machine inertia, which is currently the primary driver for system stability. Managing such a power network depends on augmenting the available resources with advancing technologies to meet the market power demand in 5-minute intervals, while keeping grid frequency and voltage stable within statutory compliance, rather than adding renewable generation capacity in the grid. In the conventional power system, both frequency and voltage variations are intrinsically met by synchronous generators with large dispatchable capacity or over-capacity ratings within a short response period utilizing a classical proportional and integral
frequency control feedback loop with a specified droop characteristic, and a separate alternator excitation for the voltage control loop. External to this are also tap changers on transformers to ensure network voltage remains stable within the statutory requirements of the grid regulator. In recent times however, with the decrease in such synchronous generators and increasing intermittent renewables, there is a huge rise in supply and demand variability and therefore requires rapid deployment of significant energy storage systems (ESS) for absorption or release in specific ways to support the network, as highlighted in the 2022 Integrated System Plan [7].

II. STORAGE REQUIREMENT FOR AUSTRALIA

The linearly increasing trend in renewable power penetration in the NEM (noting this is quite different to energy yield to the system) from 40% in 2018 to 69% in 2022 (calculated from NEM data) and the converse trend for non-renewables is illustrated in Fig.1. Consequently, the divergence of maximum and minimum operational demand (demand supplied by scheduled, semi scheduled and significant non-scheduled generating units) is increasing as seen in Fig.2, resulting from increasing rooftop PV, renewable energy solar and wind farm installations. However, as renewable power generation rated capacity increases in the NEM, the actual energy yield per annum per MW of installed capacity is dropping due to the time-varying transient nature of renewable generation sources as represented by Fig.3. As a simple example, a rooftop solar PV system yields about 4.5 times energy in kWh of the rating of the solar panels during the average day e.g., a 5 kW solar panel array string in Southern Queensland on a clear summer low humidity day produces just over 25 kWh, while during a clear winter day, it will drop to just over 18 kWh), while an IC engine alternator running in typical base load mode provides nominally 19.2 times its rating in energy yield e.g., a 2.5 kW engine alternator will yield up to 48 kWh per day if operating at typical base load output of >85% of rating with 95% average daily availability.

This simple example indicates the enormous investment required in renewable energy capacity rating to replace continuous baseload fossil fuel thermal generators’ energy yields. It also illustrates the seasonal impacts of renewable energy, and as load demand on clear sunny winter days in Southern Queensland does not require the energy for air-conditioning, this often results in an excess of renewable energy availability, driving the local wholesale NEM price during solar maxima (late morning to mid-afternoon) into negative price territory with a rapidly rising wholesale price for the local evening shoulder and peak demand periods. As large capacity ESSs will be required to meet Australia’s 2050 net zero targets, while maintaining customer reliability and stability, turn-around-losses of such energy storage, plus potential increased transmission losses due to DG RE sources, will also have to be covered by further increases in renewable energy rated systems capacity.

Referring again to Fig.2, the increasing gap between the maximum and minimum operational demand poses the following challenges:

i. Insufficient load at minimum operational demand to keep conventional synchronous generators online, instead possibly having to run them as synchronous capacitors which is expensive. If there is no load demand strategy such as energy absorption and without sufficient rotating inertia in the system, there is a reduced reserve to meet voltage control via reactive power injection at sufficient rates to manage excess system generation capacity.

ii. Difficulty in managing the increasing load demand or excess energy absorption variability between minimum demand during the day, variable peak loads, and sudden shoulder loads ramp-up requirement at other times coupled with the unpredictability of weather and/or grid failure events.

As evidence of these issues, the state-wide blackout event of South Australia (SA) in 2016 faced the above challenges caused by frequency collapse due to insufficient system inertia (i.e., high penetration of wind and PV of about 50% with some major wind farm DGs with incorrect system ride through protection settings) and non-availability of conventional reserve synchronous generators due to the loss of the high voltage interlink from spare generation capacity in the neighbouring state of Victoria to meet the transition to orderly load-shedding to prevent system catastrophic shutdown [8].

![Fig. 1: Penetration of Generation Sources in NEM [8]](image-url)
The forecast maximum peak demand of NEM in 2050 is calculated to be about 60 GW and annual consumption about 834 TWh [9] based on the central scenario at 10% Probability of Exceedance (POE). Given the current energy mix dominated by coal-fired plants (trending towards withdrawal) in the highest demand regions like New South Wales (NSW), Victoria (VIC), and Queensland (QLD), maximum peak demands ranges from ~15 to 20 GW on a daily autonomous reserve capacity to meet evening peak demand in each of these regions [9] for which energy storage technologies to firm up the RE growth is inevitable. Queensland with the highest consumption in the NEM region is forecasted to consume about 271 TWh (i.e., 33% of NEM total) energy by 2050 [9]. While wind turbines are said to provide some grid inertia, i.e. about 5-10% [12] of their rated power capacity, their total energy contribution due to variability of available wind speeds in Queensland currently represents only a fraction (4%) of the current energy supply. Therefore, in the net zero target environment of 2050, the peak demand of ~15 GW must be met through other storage technologies to firm up the variable RE sources, which in turn requires more RE generation capacity to have sufficient spare energy for charge/recovery from energy storage systems. If five days of autonomous storage emergency capacity period were required to cover a cyclone event in Queensland’s net zero emissions 2050 electricity grid resulting from statewide cloud cover due to a resulting major rain depression, with possible loss of significant state-based wind generation capacity due to high wind damage, then up to 750 GWh of ESS capacity would be required. QLD has a nominal 6.4 GWh PHES storage currently available for emergency use if the upper pondage storages are fully filled.

Another challenge unique to Australia is the fact that the NEM is the longest radial transmission network of about 5000 km from QLD to SA. Unlike the mesh networks in USA and Europe, the NEM has a radial transmission network with sequential power transmission along five regions of the NEM. This imposes high voltage transmission losses, and inflexibility in catering to regional diversity in generation and demand. For instance, QLD's peak demand in 2022 was more than 3 times of SA [9] but its renewable generation was 11% lower [3]. In the absence of direct interconnection infrastructure between SA and QLD, and similarly, between other regions, there is no flexibility to capitalize on generation availability in one region to cater directly to the demand of another region. Also, the interconnection between QLD and NSW limits nominal transmission capability from NSW to QLD of a maximum of 600 MW via QNI AC interconnector and 107 MW DC via DirectLink [13]. Therefore, the energy required for the autonomy period discussed in the previous paragraph, will not be met even with import from NSW at the highest limits of HV interconnector.

This paper, therefore, reviews the current state of storage technologies, their applicability, and outlook concerning the above-highlighted issues and Australia’s ambitious RE targets to be met in 2030 and 2050.

### III. ENERGY STORAGE TECHNOLOGIES

To complement the changing needs of the power system and to bridge the gap between peak load and generation, storage technologies with varying storage types and capacities to manage the daily, weekly, and seasonal balance of energy availability and energy consumption are inevitable [14]. Different storage types as categorized by AEMO are summarised in TABLE I. Conforming to the description of storage types in TABLE I and from the review of the capability of different storage technologies, TABLE II fits different storage technologies into relevant categories.

#### TABLE I

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed</td>
<td>Non-aggregated</td>
</tr>
<tr>
<td>(DS)</td>
<td>Behind the meter battery installations</td>
</tr>
<tr>
<td>Coordinated</td>
<td>Coordinated via VPP arrangements</td>
</tr>
<tr>
<td>(CS)</td>
<td>Behind-the-meter battery installations</td>
</tr>
<tr>
<td>Shallow</td>
<td>Grid-connected energy storage</td>
</tr>
<tr>
<td>(SS)</td>
<td>(&lt; 4 hr storage capacity)</td>
</tr>
<tr>
<td></td>
<td>Valued for power capacity for FCAS</td>
</tr>
<tr>
<td>Medium</td>
<td>Grid-connected (4-12 hours storage)</td>
</tr>
<tr>
<td>(MS)</td>
<td>Valued for energy value with intra-day energy</td>
</tr>
<tr>
<td></td>
<td>shifting capabilities</td>
</tr>
<tr>
<td>Long</td>
<td>Grid-connected (&gt;12 hours storage)</td>
</tr>
<tr>
<td>Deep (LDS)</td>
<td>Valued for long-period storage (catering for RE</td>
</tr>
<tr>
<td></td>
<td>droughts and seasonal smoothing)</td>
</tr>
</tbody>
</table>

![Fig. 2. Divergence in Maximum and Minimum Demand][9]

[TABLE][9]

![Fig. 3: Trend in RE penetration VS Energy yield per MW][10, 11]
A. Pumped Hydro Energy Storage (PHES)

The world’s largest energy storage technology is from pumped hydro contributing to 96% of the total storage energy capacity [15]. PHES has obvious advantages from the scale of storage rating (i.e., a typical range of 10-4000 MW), technology maturity, and long life (40-60 years) but also at comparatively higher capital investment (2,000-4,300 $/kW). However, they have long lead times to commission, an average of 5 years [16], with some in more difficult or remote terrains being as long as 12 years. These remain some of the major barriers to address for PHESS as the widespread adoption of energy storage particularly to match the pressing storage need corresponding to the accelerated growth of intermittent renewables.

<table>
<thead>
<tr>
<th>Type</th>
<th>Duration</th>
<th>Response time</th>
<th>Storage Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHES</td>
<td>hrs-mon</td>
<td>Sec-min</td>
<td>DS, CS, SS</td>
</tr>
<tr>
<td>CAES</td>
<td>hrs-mon</td>
<td>Sec-min</td>
<td>DS, CS, SS, MS</td>
</tr>
<tr>
<td>FES</td>
<td>Sec-min</td>
<td>Sec</td>
<td>DS, CS, SS, MS</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>hrs-mon</td>
<td>Sec</td>
<td>DS, CS, SS, MS</td>
</tr>
<tr>
<td>BES</td>
<td>hrs-mon</td>
<td>milli-sec</td>
<td>DS, CS, SS, MS</td>
</tr>
<tr>
<td>SES</td>
<td>Sec-hrs</td>
<td>milli-sec</td>
<td>DS, CS, SS, MS</td>
</tr>
</tbody>
</table>


Barbour, et al. [17] points out that the historical development of PHES in Europe, Japan, and the USA coincided with the development of nuclear plants before 1990 and when oil and gas prices were high. A decrease in fuel prices thereafter coupled with more commercially combined cycle gas turbines led to a decrease in PHES installations. Abdellatif, et al. [18] in their investigation of the economic competitiveness of pumped hydro against simple cycle gas turbines (SCGT) in Egypt reported that for pumped hydro to have absolute competitiveness, a double tariff structure should exist on international fuel imports for SCGT, and the cost of pumped hydro should not increase beyond 4,180 $/kW at zero pumping cost.

A major part of the huge capital investment cost in PHES is accounted for by civil structures. For instance, an assessment study of underground pumped storage cost [19] with and without existing infrastructure for downstream reservoir showed that cost increased from 20.90 €/kWh to 38 €/kWh (an increase of 81%) for the construction of new infrastructure. Lack of other infrastructure such as roads and transmission lines is reported [20] as a highly cited techno-environmental barrier (i.e., lack of existing transmission lines was reported in 23 out of 47 studies) for pumped storage deployment. The capital cost due to delays in pre-project start together with a lengthening payback period leads to project financing challenges (investment, opposition to the project, institutional challenges, political, market, and sponsorships) [20] and therefore hurdles to rapid strategic deployment of PHES.

The increasing development of pumped storage in China in recent years is attributed to a lack of capacity to meet peak demand to support rapid economic development. The market mechanism in China is however comfortable in accommodating pumped storage as the energy tariff is determined on a cost plus or average price basis and not through free market competition. Therefore the market can operate under central government-controlled pricing mechanisms to justify such huge investment [17]. Conversely, in Germany, some pumped storage was halted during the summer of 2014 as they could not operate profitably for peak capacity as a result of the reduction in wholesale electricity price caused by subsidized rates for solar and wind generation [17].

Therefore, investment in pumped hydro storage needs to be justified by proper siting (near existing infrastructures) to bring down the capital cost and have a proper pricing mechanism to profitably compete in any open power exchange market. A review [21] determined that Australia has adequate pumped hydro potential sites to support a 100% renewable energy market. However, the assessment was not justified with regards to economic viability considering the additional infrastructures, climate change impacts on water availability, and ultimately its penetration in the market to justify the CAPEX cost as argued in [22].

With response times ranging between seconds to minutes (from idle to full capacity) [23] and storage capability over months, PHES seems like an ideal option for medium and deep storage given its economic and other environmental and social considerations justify that. However, modular types of storage systems that can be placed in any location in the power system quickly without involving large infrastructure developments are a more prudent and urgent requirement in the current accelerated energy system transformation between 2030-2050. Normal hydro generation can suffer from climate variable-induced droughts in various parts of the world, to which Australia is prone. Provided evaporation rates are not high, in the long term, strategically PHES does have the capacity to relieve part of this variable climate pressure on renewable energy generation.

B. Flywheel Energy Storage (FES)

Another mature technology extensively investigated and continuously innovated through ongoing research is the FES. FES stores energy based on the moment of inertia and the angular velocity of the flywheel. The flywheel system comprises of rotating mass (flywheel) accommodated in a vacuum container with bearings or magnetic levitation bearings used to support the flywheel and an inbuilt generator/motor to accelerate or decelerate the flywheel [15]. During times of low energy demand, the motor speeds up the flywheel system to store electrical energy as kinetic energy, while during the period...
of high demand, the motor functions as a generator to produce electrical energy [24].

Its high power density, quick response time, and high energy efficiency have driven its popularity [24, 25]. Nevertheless, due to its comparatively high capital cost, has made commercialization of FES a challenge [26, 27].

As opposed to electrochemical storage technologies like batteries, a flywheel system has moving parts that are susceptible to failure under the high operational speeds and therefore requires specific attention in designs for specific applications [28]. Investigations of various failure modes, scalability through arraying of multiple flywheel units, and operation under a different state of charge for application in utility-scale storage were achieved in Amber Kinetics M32 (32-kWh) with 4 hours storage [29]. Other existing FES are capable of storage duration of only about ~15-20 min [30] with multiple units working together to increase to the needed capacity such as the 20 MW installation in Pennsylvania, US that is comprised of 200 flywheels (each rated at 0.1 MW and 25 kWh) [30].

C. Compressed Air Energy Storage (CAES)

Large underground storage caverns or containers are required to store compressed air. Like PHES, this system uses a combination of a motor and a turbine to store (during the surplus energy generation period) and then generate energy (during peak demand). Using the surplus electricity during off-peak hours, the motor drives the compressor and stores energy and during peak demand hours, the compressed air is used to drive a turbine and generate electricity. Due to the low storage density, a large storage volume is required. The use of natural aquifers or old mines are options explored to bring down the cost of constructing storage caverns. However, CAES is not yet a widespread technology, with only eleven sites operational in the world [31]. Its high capital cost and low current efficiency in the range of 45-55% [30, 32] need to be improved for more commercial widespread development and adoption.

D. Green Hydrogen Storage

Hydrogen is the cleanest and most abundantly available fuel which drives its popularity. Its production using excess RE during off-peak periods using water electrolysis is called green hydrogen. According to Hydrogen Infrastructure Assessment Report [33], most of the hydrogen demand in Australia by 2050 is expected to be met by green hydrogen which has seasonal or even annual energy storage capability. Given the extensive natural gas (methane network) network of Australia [34] interconnected across all states from Northern Territory to Tasmania, except for the isolated WA gas network due to geographic and industry isolation, green hydrogen could be injected into the current gas pipeline. The feasibility to inject up to 10% per volume in the current gas network without infrastructure change has been assessed [35]. This has the potential to reduce gas exports and domestic use to reduce GHG emissions without significant performance changes in fast-peak gas turbine technology assets. The trial blending of a small volume (2 %) of hydrogen in the existing gas networks has started in Western Australia and Jemena’s Western Sydney Green Gas Project [35]. While gas turbine technology is capable of higher blends of hydrogen such as commercially available Siemens Energy’s gas turbines capable of running at up to 75% blends with a Dry Low Emission (DLE) burner [36], injection beyond 10% in the existing gas network of Australia will require additional infrastructural developments such as retrofitting of the existing gas networks and development of hydrogen pipelines or combination of both.

Therefore, investment in hydrogen storage and strategic integration of RE sources will underpin long-term autonomy storage requirements.

E. Hydrogen Fuel Cells

A fuel cell has a structure similar to a battery, with two electrodes and an electrolyte between them. The anode is fed hydrogen or hydrogen-rich fuels and the cathode is fed oxygen. Fuel cells are of different types depending on the type of fuel and electrolytes which includes proton exchange membrane, direct formic acid, direct-ethanol, alkaline, phosphoric acid, direct methanol, solid oxide, molten carbonate, and regenerative fuel cells [15, 37]. The proton exchange membrane (PEM) fuel cell which uses a polymer membrane as an electrolyte, is more commonly explored than others due to its high power density and low operating temperature [37]. However, its voltage response to significant step load increase shows that voltage regulation is not possible without a DC-DC boost/buck converter to maintain a steady voltage, which further reduces the cycle efficiency [38].

Solid Oxide Fuel Cells (SOFC) technology using zirconia stabilized with yttria oxide used as electrolyte. This type of fuel cell operates at very high temperatures of about 600-1000°C [39] and is available for distributed base-load power generation based on gas networks and provides industrial or domestic hot water resources using waste heat to further improve efficiency and ancillary usefulness. Currently, SOFCs run on hydrogen-rich hydrocarbon fuels, but in the future can run on mixed hydrocarbon/hydrogen mixes or pure hydrogen gas. The main drawback of SOFC is its slow start-up time limiting its applications in high-load fluctuation applications [15, 39].

Fuel cells are a promising technology for large-scale energy storage, extending their application largely in transportation and energy storage. However, challenges remain in their round-trip efficiency, cycle life, and cost [15, 27, 40]. Further limitations for grid-connected fuel cell systems include the requirement of a complex control strategy to enable voltage ride-through capability during voltage sags and grid faults [37, 41] when there is a high inrush current. In such high load step requirements, a hybrid system combining a high energy density fuel cell with a high power density supercapacitor can enhance the performance of the fuel cells as reported by Shin, et al. [42] where power capacity was increased by 50% at fuel reduction of 6.8%.

F. Batteries

Batteries are one of the widely used ESS technologies that store energy electrochemically. Construction of battery ESS takes a relatively brief period (1 year), have low capital
expenditure, and is modular which means they can be located easily anywhere in the network depending on the requirements or even moved quickly to account for seasonal different needs. Such advantages have driven their popularity, however, depending on the types and their characteristics to suit diverse needs, some batteries are more widespread than others. TABLE IV provides a comparison of various battery types, and TABLE V highlights the safety aspects of batteries (noting that only high-risk issues are highlighted).

i. Metal Ion Batteries

The most commonly available metal ion battery is the lithium-ion battery (LiB). Due to the small ionic radius and low atomic mass of lithium, it has high energy density (energy per unit mass). The common cathode materials used in lithium-ion batteries are metal oxides such as lithium cobalt, manganese, and nickel. The common anode materials are carbon materials such as graphite and the most common electrolytes are lithium salts. Metal-ion batteries have high power & energy density, long life (compared to other batteries) and high cycle efficiency as shown in TABLE IV. Ongoing research is focusing on increasing power and energy densities further by exploring different electrode and electrolyte materials for scaling the storage capacity [43] while also minimizing issues such as thermal runaway, unstable solid electrolyte interface layer (SEI) formation, volume change, and preventing internal dendritic growth internal failures [44].

Owing to the similar electrochemistry of sodium and lithium and the significantly greater abundance of sodium, sodium-ion batteries (SiB) are being explored as a contender to LiB [45-47]. However, the larger ionic radius of sodium (Na⁺ 1.02 Å vs Li⁺ 0.76 Å) affects the intercalation of Na ions on electrode materials. Owing to the larger ionic radius and heavier atomic mass, sodium-ion batteries have lower theoretical capacity as shown in TABLE III:

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Mass (g/mol)</th>
<th>Gravimetric Capacity (mAh/g)</th>
<th>Volumetric capacity (mAh/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>6.94</td>
<td>3860</td>
<td>2061</td>
</tr>
<tr>
<td>Na</td>
<td>23</td>
<td>1165</td>
<td>1129</td>
</tr>
</tbody>
</table>

It is reported [48] that issues of thermal runaway associated with SEI formations and volume changes in SiB are observed at higher rates than lithium equivalents [48]. On the contrary, Zhao, et al. [49] established that a SiB with a NaFeO₄ cathode is likely to have similar or better thermal stability than that of Li-ion batteries with conventional LiCoO₂. The use of Aluminium as a current collector in SiB allows charge storage at 0 volts which makes them safe for transport, unlike LiB. However, research on safety concerns of Na-ion is still inconclusive and requires deeper studies mainly due to the unstable volumetric changes of the Na-ion[48]. Nevertheless, the prospect of the better commercial viability of sodium-ion batteries and sustainability has driven tremendous research efforts into tackling such issues and enhancing the storage capability to be equivalent to LiB [50]. Various cathode materials under exploration are layered oxides, polyatomic compounds, and Prussian Blue Analogues with commonly explored hard carbon as an anode. The electrolyte used is sodium salts with different combinations of organic solvents. The commercialization of SiB is mostly in the prototype development stage being tested on small applications like electric bicycles and small-scale energy storage[51]. Tremendous ongoing research will unfold SiB’s competitiveness against LiB equivalents for large-scale commercialization [52].

When it comes to the recycling aspect of metal ion batteries, the safest current commercial manner for end-of-life recycling is pyrolysis using inert gas reprocessing [53] where water and CO₂ must be excluded or quickly removed in the inert gas stream. Recovery of materials from metal ion batteries after pyrolysis follows normal mining metallurgical resource extraction practices and is currently quite expensive. This is particularly due to the inhomogeneity in battery chemistries and structures involving complex disassembly methods and safety issues for workers. Neumann, et al. [54] highlighted that it is not easily possible to have a common robust recycling method that could make recycling profitable which in turn highlights the environmental impacts of such batteries. Despite low cyclability, currently about only 1 % [55], extensive research is ongoing, mainly in the recovery of valuable metal residues, such as the ongoing study by Zhang and Azimi [56] on the recovery of metal components (Ni, Co, Mg) from the end-of-life Lithium-ion batteries. This research indicates that metal components could be recovered using supercritical CO₂ with an extraction efficiency of 90 % and at 5-6 times shorter duration than conventional leaching process.

ii. Lead Acid

Lead acid batteries are of flooded and sealed or valve-regulated (VRLA) type. They use various lead doped with calcium/tin/cadmium/silver/antimony/arsenic cast alloy grids “pasted” and pressed with active PbO₂ for the anode and lead sponge for the cathode with sulfuric acid as the electrolyte. The flooded type requires upright mounting to avoid any leakage of electrolytes as the battery is not sealed. The sealed types are of advanced glass mat (AGM) or gel cell type which uses immobilized electrolytes and hence are spillproof [15]. Of the three types, AGMs have fast charge/discharge capabilities due to low internal resistance and are therefore suitable for high-power applications.

Lead Acid battery has some environmental and health impacts of lead [57] during production and assembly. However, this battery is fully recyclable. The lead acid battery does need short circuit protection, as its internal resistance of a fully charged battery is a few milli-Ohms, compared to a lithium-iron- phosphate battery of 100 milli-Ohms.

While the environmental impact of Lead acid batteries is a major concern, Lopes and Stamenkovic [58] argue that popular lithium batteries also have several health and environmental
impacts especially those using cobalt and nickel cathode materials. Further, limited recyclability coupled with increased production of lithium-ion batteries compared with lead-acid batteries is seen as a major concern. On the other hand, lead-acid batteries have achieved a 99% recycling rate and stringent regulations are in place for Pb emission while lithium-ion batteries have achieved only about 1% [55]. Some battery manufacturers [59] also provide free lead acid battery recycling as all the component resources are profitable to recover.

While the low production cost of lead acid batteries is a major advantage, their lower energy density and cycle life restrict their ability to compete in large-scale grid storage applications. Therefore, ongoing research efforts are concentrated on exploring alternative materials such as carbon sponge half-capacitor electrodes on the cathode, to improve energy density [60] and cycle life.

iii. Nickel Based

Nickel-based batteries such as nickel-cadmium (Ni-Cd), Nickel Iron (Ni-Fe Edison Battery), and nickel metal hydride (Ni-MH) are popular batteries in large-scale storage applications.

Ni-Cd and Ni-Fe batteries having deep discharge capability, are more desirable of the above types in power system applications but the environmental toxicity of the Ni-Cd battery and high capital costs are some of the major barriers [60]. Ni-Cd batteries also have a memory effect and therefore the capacity is highly influenced by charging at partial discharge [43]. The Ni-Fe battery is only currently produced as a flooded alkaline battery and suffers from hydrogen generation during charging, which requires auto-watering to maintain electrolyte levels, or recombinant technology to maintain electrolyte levels. The Ni-Fe battery does not have memory effect issues and does not grow metal dendrites on the anode, but has a higher self-discharge rate and higher internal resistance than the Ni-Cd battery. Both Ni-Cd and Ni-Fe batteries can be fully recovered and rebuilt instead of being recycled.

Nickel metal hydride has higher energy density, reduced memory effect, and is more environmentally friendly. However, it suffers from a high self-discharge rate and is therefore not as desirable longer term in deep cycle energy storage applications [43].

iv. Flow Batteries

Flow batteries have slightly different structural components with two electrolyte tanks separated by a porous membrane through which ion exchange takes place producing current.

Vanadium redox flow batteries have been adopted in large-scale storage for various applications such as peak shaving, load leveling, integration of wind power generation, etc with capacities ranging between 1-100 MW. However, the high production cost is still a major barrier to the commercialization of vanadium flow batteries [31].

Zinc bromine redox flow is another type being explored in similar applications in power systems. They have relatively higher energy and power density than vanadium flow batteries but corrosion and dendritic formation are some of the challenges in this battery type [43] that require modulisation of the assembly so that the separation membrane can be replaced regularly.

### TABLE IV

**COMPARISON OF BATTERY TYPES** [15, 31, 43, 61, 62]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Metal Ion</th>
<th>Lead Acid</th>
<th>Nickel Based</th>
<th>Flow Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. power density (W/kg)</td>
<td>2000</td>
<td>300</td>
<td>300</td>
<td>166</td>
</tr>
<tr>
<td>Max. energy density (Wh/kg)</td>
<td>300</td>
<td>75</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Max. voltage (V)</td>
<td>4.2</td>
<td>2</td>
<td>1.65</td>
<td>2.37</td>
</tr>
<tr>
<td>Max. power rating (MW)</td>
<td>0.1</td>
<td>20</td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>-20 to 60</td>
<td>-20 to 50</td>
<td>-20 to 65</td>
<td>-20 to 50</td>
</tr>
<tr>
<td>Cycle life (80 % DoD)</td>
<td>7000</td>
<td>3000</td>
<td>3000</td>
<td>20000</td>
</tr>
<tr>
<td>Cycle Efficiency (%)</td>
<td>97</td>
<td>90</td>
<td>90</td>
<td>85</td>
</tr>
<tr>
<td>Daily self-discharge (%)</td>
<td>1</td>
<td>0.3</td>
<td>0.6</td>
<td>small</td>
</tr>
<tr>
<td>Capital cost ($/kWh)</td>
<td>3800</td>
<td>400</td>
<td>2400</td>
<td>1000</td>
</tr>
</tbody>
</table>

### TABLE V

**RISK ASSESSMENT OF BATTERY TYPES USED FOR LARGE-SCALE STORAGE** [48, 57, 63-65]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Lithium Ion</th>
<th>Sodium Ion</th>
<th>Lead Acid</th>
<th>Nickel Cadmium</th>
<th>Redox flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire ignition risk</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Self-ignition risk</td>
<td>Internal thermal runaway due to mechanical and thermal abuse. Exothermic decomposition.</td>
<td>Inconclusive at this stage.</td>
<td>Low</td>
<td>Thermal decomposition and short circuit above 85°C</td>
<td>Low.</td>
</tr>
<tr>
<td>Environmental hazards</td>
<td>Heavy metals such as CO and Ni toxic to wildlife and human</td>
<td>Low</td>
<td>Sulfuric acid, lead, and arsenic cause aquatic toxicity.</td>
<td>ZnBr long term effects on aquatic life</td>
<td></td>
</tr>
</tbody>
</table>
G. Capacitors

Conventional capacitors have two electrodes (cathode and anode) and a dielectric material (insulator) in between such as ceramic and polymers [27]. When voltage is applied across it, dielectric material undergoes polarization (negative charges move towards the cathode, positive charges move towards the anode) thereby storing electrical energy.

Electrolytic capacitors are another type of conventional capacitor that has a dielectric insulator and electrolyte in a spacer material between the two conducting plates. The accumulation of electrons on one electrode, and positive holes (i.e. reduced electrons) at the other dielectric-electrode interface enables energy storage via the electrical field resulting from the charge separation between the electrodes and the alignment of the electrolyte dipoles. Common electrolytic capacitors are of Aluminium, Tantalum, and Niobium type [66] whose oxides act as interlayer electrical induction, and which have higher capacitance owing to a thin dielectric and high surface area whose capacitance is further enhanced by a polar gel electrolyte.

Their common application is in power supply filters due to their high voltage rating (over 600 V), power density, and high capacitance [66]. However, such capacitors face high leakage current, capacitance degradation under heating and are subject to failures [66-68], and especially so if their specified polarity is misconnected. In addition, the low energy density in such electrolytic capacitors has led to an exploration of new capacitors, called supercapacitors.

H. Supercapacitors (SCs)

Tremendous research efforts are continuing into increasing the storage capacity of conventional capacitors through the synthesis of new electrode and electrolyte materials which has led to the innovation of the new generation capacitors known as supercapacitors.

The SCs are composed of two conducting plates, an electrolyte, and a separating membrane enabling charge separation at each of the two electrode-electrolyte interfaces forming an electric double layer “half capacitor” storage at each electrode. [69, 70]. Depending on their charge storage mechanism SCs are broadly categorized as Electric Double Layer Capacitor (EDLC), Pseudo Capacitor (PC), and Hybrid Supercapacitor (HSC) [71].

Referring to Fig.4, batteries generally have a high energy density, but they generally have low power density, and vice-versa for conventional capacitors. The SC on the other hand bridges the gaps between the two for optimal power and energy density requirements. Therefore, SCs are also called electrochemical capacitors. The early commercialized SCs manufactured by Maxwell and Panasonic had an energy density of 2-3 Wh/kg and a power density of 1 kW/kg [69]. In recent times advances in electrode materials such as activated carbon, conducting polymers, metal oxides, and their composites along with different electrolytes have achieved energy density of

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Lithium Ion</th>
<th>Sodium Ion</th>
<th>Lead Acid</th>
<th>Nickel Cadmium</th>
<th>Redox flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human health hazards/risk</td>
<td>Hydrofluoric acid is highly toxic and corrosive</td>
<td>Low</td>
<td>Toxic to human health (eye damage, skin corrosion, respiratory, reproductive, and development)</td>
<td>Carcinogenic to human health (nickel and cadmium).</td>
<td>ZnBr is highly toxic and corrosive</td>
</tr>
</tbody>
</table>

Fig. 4 : Ragone plot -reproduced from [65]

about 100 Wh/kg, power density of about 2 kW/kg, and lifetime more than a million cycles, provided the capacitors remain below 70°C

i. Electric Double Layer Capacitor (EDLC)

Energy is stored based on electrostatic double-layer charge accumulation at the electrode-electrolyte interface which is a time-dependent function of ion diffusion [70] which in turn is dependent on the electrode material pore size and distribution and ion size of the electrolyte.

Various carbon materials such as carbon nanotubes, graphene, and activated carbon are used as electrodes with various types of electrolytes to enhance the storage capability. The following can be deduced regarding various carbon electrode materials:

- Carbon materials due to porous structures enable high capacitance, power, and energy density. Graphene having a 2-dimensional structure have a higher specific surface area than carbon nanotubes but suffers from longer diffusion of ions through graphene sheets. This led to graphene sheets with holes that shorten the diffusion pathway meanwhile retaining the electron transfer capability and therefore achieving a higher energy density of 35 Wh/kg [72].
- Activated carbons have an even higher specific surface area (2000 m²g⁻¹) [70]. The mesopore (2-50 nm) structures have been reported to exhibit high specific surface area and fast
ion transport pathway generating high power density while micropores are desirable for high energy density [72, 73].

- Pore structuring and heteroatom doping of carbon-based electrodes for further enhancement of storage capacity are the focus of research in recent times as supercapacitors still lack energy density compared to batteries.

EDLC has rate high-rate capability and cyclic stability [73] but has low energy density.

ii. Pseudo capacitors

In Pseudo capacitors (PCs), double-layer charge accumulation is based on redox reaction at the electrode-electrolyte interface [70] by using transition metal oxides, conducting polymers, and their composites. Due to electrochemical reactions, the capacitance and energy density is higher than EDLC [73] but have lower power density due to low electrical conductivity and high mechanical degradation during cycling [70].

Employing carbon nanotubes, graphene, and activated carbons in PCs with doped metal oxides or conducting polymers are techniques employed to increase the power density.

iii. Hybrid Supercapacitors

The Hybrid Supercapacitor (HSC) takes advantage of EDLC’s high-power performance and PC’s high-energy performance in an attempt to bridge the gap between the two separately. This is achieved using the composite of carbon materials with transitional metal oxides or conducting polymers.

Commercial HSCs, presumably the battery types are reported with a high energy density of about ~ 100 Wh/kg and power density of 2 kW/kg, cycle life of about a million cycles, and operating voltage of 4.2 V [69] per capacitor and can operate up to a maximum 85°C.

TABLE VI compares the characteristics of conventional capacitors vs SCs. In terms of specific power, rated voltage, and fast charging time, capacitors are comparatively better than SCs indicating their superiority in high-power burst applications. However, the high self-discharge rate (about 20% higher than the lithium-ion battery [15]) and low energy density limit its application in large-scale energy storage, which is where the supercapacitors, particularly PCs and HSCs are better suited. SCs have high efficiency, reportedly higher than 98% as in Maxwell’s ultracapacitor [74]. However, efficiency loss due to internal resistance for high current or power pulsing reduces the efficiency to about 90 % (by a margin of about 8 %) [74]. This impact - of the supercapacitor needs further investigation to determine its suitability for FCAS and NSCAS applications which require high current draws -using PWM inverters.

Extensive ongoing research and investigations show optimistic estimations on the capability of SCs for energy storage. However, there have been limited commercial developments and overestimation of power and energy densities in the literature (2-3 times higher than practically achievable in a commercial package) as highlighted by Burke and Zhao [69]. Critical evaluation and further research is important particularly concerning applications in large scale grid energy storage.

### TABLE VI

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Capacitor</th>
<th>Supercapacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density (W/kg)</td>
<td>~3000-10^7</td>
<td>500-10000</td>
</tr>
<tr>
<td>Energy density (Wh/kg)</td>
<td>~ 0.05-5</td>
<td>0.05-15</td>
</tr>
<tr>
<td>Maximum operating voltage (V)</td>
<td>800</td>
<td>4.2</td>
</tr>
<tr>
<td>Maximum power rating (MW)</td>
<td>0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>Cycle time</td>
<td>50,000</td>
<td>&gt; 10^3</td>
</tr>
<tr>
<td>Cycle efficiency (%)</td>
<td>95%</td>
<td>85-98</td>
</tr>
<tr>
<td>Operating temperature (deg C)</td>
<td>-20 to 100</td>
<td>-40 to 85</td>
</tr>
<tr>
<td>Charge time</td>
<td>10^3-10^4s</td>
<td>1-10 s</td>
</tr>
<tr>
<td>Daily self-discharge (%)</td>
<td>50 in 15 min</td>
<td>20-30</td>
</tr>
<tr>
<td>Capital cost ($/kWh)</td>
<td>500-1000</td>
<td>300-2000</td>
</tr>
</tbody>
</table>

### IV. ENERGY STORAGE OUTLOOK

AEMO acquires different services in varying time scales to ensure system stability and therefore allows market participants to innovate technologies that can support the system through ancillary services called the Frequency Control Ancillary Services (FCAS), Network Service Control Ancillary Services (NSCAS) and System Restart Ancillary Services (SRAS).

FCAS is utilized by the Australian AEMO to maintain grid frequency at any point in time close to 50Hz, NSCAS to control the voltage and power flows at different points of the electrical network and SRAS is reserved for contingency events to restart the network following a complete or partial blackout.

For frequency control, battery energy storage systems [12, 75] are being used to maintain the frequency of the grid within a nominal range. Metal Ion batteries such as LiBs have high specific power, energy density, high operating voltage, up to 3,000 cycle life, and efficiency as desired for such applications. However, the cost per energy is on the higher side which may be reduced through use of other metal ion batteries such as the sodium ion with similar electrochemistry and abundantly available raw materials. Meanwhile, lead acid, nickel-based, and flow batteries have low energy, power density, and operating voltage while efficiency and cycle life are comparable. The cost of production for AGM valve-regulated lead acid battery retains as the cheapest; and despite some environmental and health concerns remains a contender in the stationary energy storage systems. Metal ion battery research will continue to explore this area, particularly with sustainable and environmentally friendly materials such as activated carbon and its composites. However, their environmental footprint in terms of resource extraction for specific rare materials used also has raised concerns in the supply chain.

For grid voltage stability and frequency control, synchronous condensers and generators have been conventionally utilized to maintain the grid’s voltage within the...
nominal range [76, 77]. Recently due to improvements in power and energy capability along with the fast response of inverter energy storage systems using batteries and supercapacitors, investigations in both frequency and voltage management using batteries, supercapacitors, and hybrid systems are the focus of most researchers [78-82]. Studies have shown that the use of SCs as hybrid energy storage with batteries extends the potential cycle life of deep discharge batteries as it can easily absorb and inject high-frequency fluctuations which is the inherent drawback in batteries [83, 84]. Such hybrid systems along with power converters underpin the future of energy management widely termed “virtual power plants” (VPP) [85]. However, the fatigue lives of these hybrid power electronics require more investigation to increase reliability and reduced cost [86, 87]. For instance, power electronic inverter/converter failures account for the majority of failures causes in the wind and Solar PVs [88]. The impact of the short life of power electronics and their renewal period alongside other critical components of future RE-intensive grid impacts the end-of-life circular economy potential for valuable resource recovery.

The current focus of energy planning is highly inclined towards meeting short to medium-term energy storage. Simultaneous attention to long-term storage such as weekly and seasonal storage is also deemed pragmatic given the meteorologically dependent RE sources that will be dominant in the Australian future 2050 NEM electricity grid. As weather extremes are becoming more unpredictable, a predominantly RE-based grid could lead to energy droughts such as the "Dunkelflaute" event in Belgium in 2017 [89]. Countries in Europe at least have an interconnected system to enable importing from neighboring countries to manage such situation unlike in Australia which has network constraints even within the country. Australia is however in a strong position to potentially develop green hydrogen resources from excess renewable energy as well as dedicated remote non-grid connected PV solar farms. Green hydrogen resources and storage are crucial for long-term strategic and emergency energy storage and reserves in the current changing geopolitical situation already impacting the energy supply chain. Strong early strategic emphasis could be on the track for hydrogen energy integration with RE and blending hydrogen in the existing gas networks to help reach GHG Australian promised targets. The addition of hydrogen up to 10 % by volume in the existing gas network has no significant impact on the quality and safety aspects of its operation, however, further assessments are still required covering any negative impacts to end users’ downstream installations [90].

V. CONCLUSION

Unprecedented growth in renewable energy generation is seen over recent years worldwide. Specifically, the Australian NEM has seen RE transient peak generation penetration of about 69 % in 2022. As more intermittent and transient time-varying RE dominate the energy network, the future of the electricity grid is trending towards low inertia and increasing instability. Recent events in the NEM suggest the need for storage technologies that can support the grid in different time scales. Accordingly, AEMO shall increasingly require innovative FCAS and NSCAS services to maintain grid stability.

To provide such ancillary services, investment in energy storage technologies will not only require large-scale storage capability, but fast response capabilities. The following conclusions are drawn from the review of existing storage technologies:

- For the urgent need of the energy transformation system trending towards RE-based fuel mix, a hybrid of batteries and supercapacitors is envisaged to be more appropriate for distributed, coordinated, shallow to medium scale storage. However, the drawbacks of battery performance and life cycle dependency on ambient temperature is still an area that required to be properly assessed to scale battery modules adequately for grid storage. As more individual battery cells are stacked to build large battery modules, an increase in ambient temperature causes the generation of heat causing battery degradation and increased safety concerns. Similarly, the scalability of supercapacitors arrays comes at some considerable cost to achieve power voltages like 660V operation voltage (using the current maximum cell voltage rating of 4.2 V). Ongoing research and focus on metal ions, particularly sodium-ion batteries will play a critical role in the economics and sustainability aspects of batteries, besides equivalent performance with LiB.

- Both batteries and SCs are researched and investigated with different electrode and electrolyte materials to improve their performance, safety, and economics. However, literature on efficiency loss of SCs under high power or high current applications is limited presenting opportunities for further research.

- Also, areas that need further study are; coordination of charging and discharging cycles and depths in batteries/supercapacitors for timely provision of FCAS & NSCAS to also maximize its life cycle by assessing current limits during charging and discharging.

- Recycling and waste management requirements are another area of major concern and need to be aligned with the pace of technological innovation and production.

- For long-term storage to cater to seasonal storage or RE droughts, there is a growing momentum for Hydrogen based generation fast-peak gas turbine technology, or potentially for baseload generation using fuel cell arrays at constant load.

- The future of energy management however will require a hybrid system consisting of different scales of storage technologies with highly capable converters to emulate a conventional plant operated through VPP. Coordinated control schemes to optimally integrated different fuel mix and storage technologies to meet the dynamic load profiles and also with robust protection system will be required for which power electronics play a critical role. However,
some key unknowns for VPPs are reliability and cost aspects of the power electronics for such hybrid requirements.

REFERENCES


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