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Review article

What energy storage technologies will Australia need as renewable energy penetration rises?

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ABSTRACT

The paper reviews energy storage technologies and their applicability to the Australian National Electricity Market (NEM). The increasing dynamic variability between maximum and minimum operational demand shall continue to increase as time-varying renewable generation penetration proceeds. During this ongoing transition, severe weather events driving the NEM ancillary services market for frequency and voltage control are becoming increasingly important as the mechanical system inertia of thermal power stations reduces with ongoing retirements. As a result, the NEM's demand for energy services is becoming diversified than ever before. To maintain grid stability, various storage technologies with different response times and endurances are needed to provide grid ancillary services such as the Frequency Control Ancillary Services (FCAS) and Network Services Control Ancillary Services (NSCAS). A review of existing storage technologies for short to medium-term storage (such as flywheels, batteries, and supercapacitors) reveal that hybrid systems with different power, energy density, and fast response capabilities will be part of the solution. Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage System (CAES), and green hydrogen (via fuel cells, and fast response hydrogen-fueled gas peaking turbines) will be options for medium to long-term storage. Batteries and SCs are assessed as a prudent option for the immediate net zero targets for 2030–2050. Current challenges as well as opportunities for future research are highlighted.

1. Introduction

The global supply of energy is increasingly transforming from fossil fuels to renewables, driven by the imperative to reduce CO_2 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 grid energy supply systems.

Australia's commitment to achieving net zero by 2050 and emission reduction of 43 % by 2030 [4] are evident from the 2022 energy mix with 32.5 % [5] renewables, up from 14.6 % in 2015 [6]. Further, fossil fuel-based generation contributed only about 59.1 % [5] of the total energy mix in 2022, down from 85.4 % in 2015 [6], illustrating the accelerated transition to renewables. In response to continuing fossil fuel thermal power generation retirements, 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 the dynamics in daily & seasonal demand-supply mix and the increasing wholesale daily energy price. Increasing Renewable Energy (RE) penetration [7] has driven an increase in daily wholesale energy price in the National Electricity Market (NEM) by 19 % from 2016 to 2022 [8] (N.B.: This excludes the 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 penetration of 69 % of total supply, and forecasts indicate resource adequacy to reach short or instantaneous RE penetration of 100 % by 2025 [9]. Consequently, power systems have an increasing deployment of renewable DGs and there will be a trend towards a drastic drop in rotating machine inertia, leading to potentially increasing system instability. Managing future power networks depends on augmenting system inertia resources to keep frequency and voltage within statutory limits. In conventional energy grid systems, frequency and voltage variations are steadied by synchronous generators with large

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dispatchable capacity or over-capacity ratings within a short response period. Synchronous generators use a classical proportional and integral frequency control feedback loop with a specified droop characteristic, and separate alternator excitation for the voltage control loop. External to this are also HV tap changers on transformers to ensure network voltage remains stable within the statutory requirements of the grid regulator. Increasing renewable DGs imposes a requirement for rapid deployment of significant energy storage systems (ESS) for controlled power absorption or release to support the network, as highlighted in the 2022 Integrated System Plan [9].

2. Driving factors for storage demand

2.1. Increasing gap in operational demand

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, 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 compared to a baseload coal fired thermal power station that can produce nominally 24 times its rating during a day. This indicates the enormous investment required in renewable energy capacity rating to replace baseload fossil fuel thermal generators' energy yields and does not take into account seasonal impacts of renewable energy generation yield.

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

i. Insufficient load at minimum operational demand to keep conventional synchronous generators online, possibly running 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 sufficient reactive power injection to manage excess system generation capacity.

ii. Difficulty in managing the peak renewable energy production now resulting in disconnection policy for domestic home PV systems during mid-day energy low demand, to then increasing load demand or excess energy absorption variability between minimum demand during the day, and variable evening peak loads, with sudden shoulder loads ramp-up requirement coupled with the unpredictability of weather and/or grid failure events.

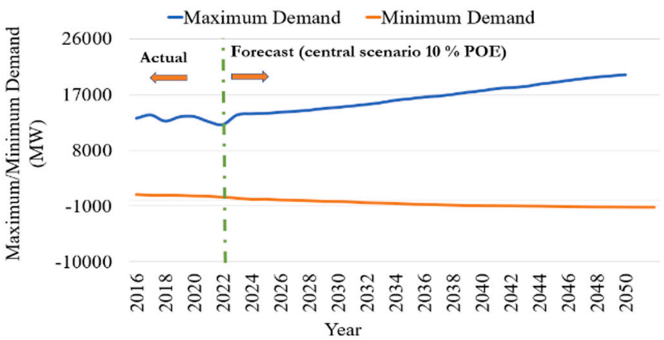

Fig. 2. Divergence in Maximum and Minimum Demand [1].

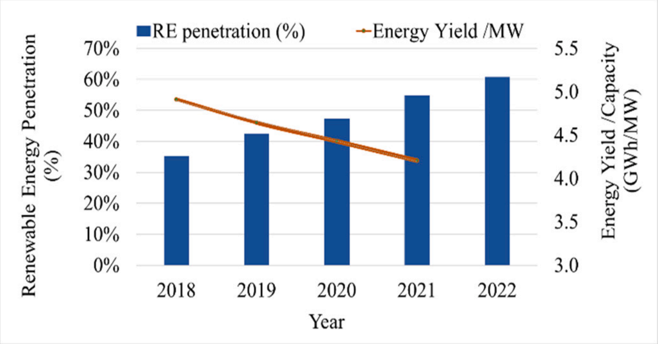

Fig. 3. Trend in RE penetration VS Energy yield per MW [2,3].

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) coupled with the loss of the high voltage interlink from spare generation capacity in the neighboring state of Victoria to meet the transition to orderly load-shedding without system catastrophic shutdown [10].

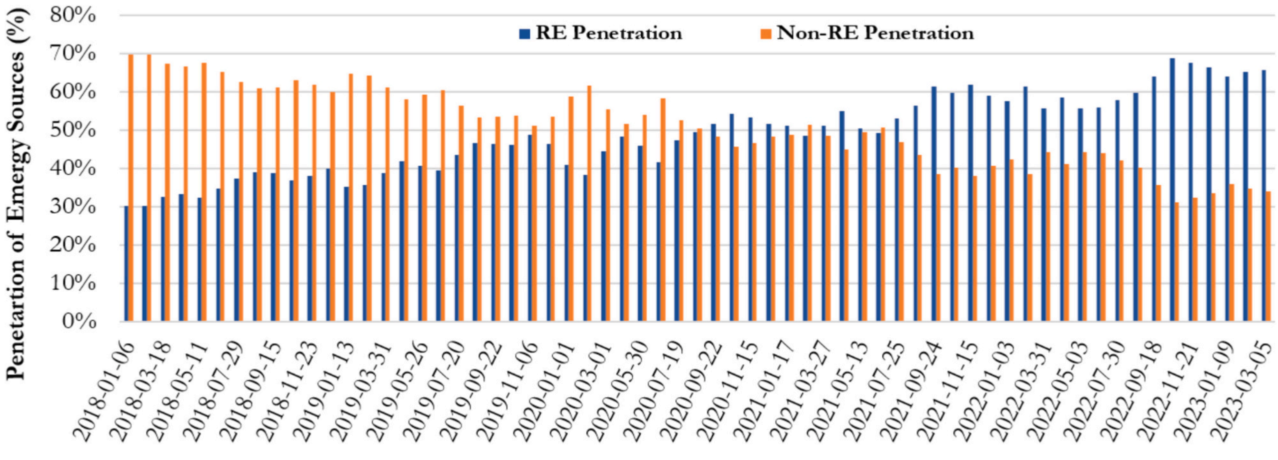

Fig. 1. Penetration of Generation Sources in NEM [8].

2.2. Regional autonomy requirement

The forecast maximum peak electricity demand of NEM in 2050 is 60 GW and annual consumption about 834 TWh [1] based on the central scenario at 10 % Probability of Exceedance (POE). Given the current energy mix dominated by coal-fired plants in the highest demand regions like New South Wales (NSW), Victoria (VIC), and Queensland (QLD), maximum peak demand ranges from ~15 to 20 GW on a daily autonomous reserve capacity to meet evening peak demand. For instance, Queensland with the highest consumption in the NEM region is forecast to consume about 271 TWh (i.e., 33 % of NEM total) energy by 2050 [1]. While some wind turbines are said to provide some grid inertia, i.e. about 5–10 % [11] 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. For example, a five days of autonomous storage emergency capacity period may be 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, because of loss of significant state-based wind generation capacity from high wind damage. Up to 750 GWh of ESS capacity in combination with alternative hydrogen gas peaking standby power plants would then be required. QLD currently has only a nominal 6.4 GWh pumped hydro storage currently available for emergency use if the upper pondage storages are fully refilled.

Another challenge unique to Australia is the NEM's longest radial transmission network of about 5000 km from QLD to SA. Unlike the mesh networks in USA and Europe, the radial transmission network with power transmission between five regions of the NEM 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 >3 times of SA [1] but its renewable generation was 11 % lower [6]. In absence of direct interconnection infrastructure between SA and QLD, there is no flexibility to capitalize on generation availability in one region and cater directly to the demand of another non-adjacent region except via the long state by state sequential interconnectors. 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 [12]. Therefore, the energy required for the autonomy period, will not be met even with import from NSW at the highest limits of HV interconnector.

2.3. Supply chain and workforce bottlenecks

The need for generation and firming capacity ahead of coal retirements necessitates adoption of energy storage technologies with minimum lead times. This also means, for the 2030–2050 energy target, aggressive infrastructural developments and/or replacement will be challenging due to supply chain and skilled workforce constraints in the energy sector. Economic recovery post pandemic and energy transition targets have further aggravated to the short-term demand for materials. Infrastructure for electricity is projected to increase the demand for both steel and concrete double by 2028. The workforce in renewable energy is forecast to double from 2022 to 2027 [9].

Therefore, while there are a range of energy storage technologies, a careful transitioning by adoption of relevant storage technologies in a timely manner is critical. The above major driver for different storage emphasises the following:

a) The increasing gap between maximum and minimum operation demand increases instability and requirements for ancillary services such as Frequency Control Ancillary Services (FCAS) and Voltage Control Ancillary Services (VCAS) for instantaneous generation and/or load absorption.
b) Radial transmission network and existing limitation of interconnectors between different regions, suggest the need for energy storage technology for regional autonomy in times of extreme weather events.
c) Challenges in expediting infrastructural replacement or new developments due to constraints in supply chain and workforce suggest the need to adopt energy storage technologies with minimum lead times and moderate infrastructural developments.

Considering the above three main criteria, the following sections presents a review of large-scale grid energy storage technologies and how they fit into different categories of Australia's requirement with potential challenges and prospective research areas highlighted.

3. Grid energy storage technologies

The Australian Energy Market Operator (AEMO) acquires different services across varying time scales to ensure system stability and therefore allows market participants to innovate technologies that can support the system through different ancillary services called the FCAS and NSCAS and System Restart Ancillary Services (SRAS). FCAS is utilized by AEMO to maintain grid frequency at any point in time close to 50 Hz, NSCAS to control the voltage and power flows at different points of the electrical network and SRAS reserved for contingency events to restart the network following a complete or partial blackout.

In order to cater to different energy needs for daily, weekly, and seasonal balance of energy availability and consumption [13], AEMO categorises storage technologies with varying storage types and capacities, an extracted version presented in Table I.

Using this categorization, subsequent headings provide review of different storage technologies.

3.1. 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 [14]. PHES has obvious advantages from the scale of storage generation rating (i.e., a typical range of 10–4000 MW), technology maturity, and long life (40–60 years). It requires comparatively higher capital investment (2000–4300 $/kW), with long lead times to commission, an average of 5 years [15], while in more difficult or remote terrains have lead times of 12 years.

Barbour, et al. [16] 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 viable combined cycle gas turbines led to a decrease in PHES installations. Abdellatif, et al. [17] in their investigation of the economic competitiveness of pumped hydro against simple cycle gas turbines (SCGT) in Egypt reported that for pumped hydro to be competitive, a double tariff structure should exist on international fuel imports for SCGT, and the cost of pumped hydro should not increase beyond 4180

Table I
Storage types [9].

Type	Duration	Services
Shallow (SS)	< 4 h	Valued for power capacity for FCAS and NSCAS
Medium (MS)	4–12 h	Valued for energy value with intra-day energy shifting capabilities and under bulk energy requirements such as SRAS
Long Deep (LDS)	>12 h	Valued for long-period storage (catering for RE droughts and seasonal smoothing)

$/kW at zero pumping cost. 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. Conversely, in Germany, some pumped storage was halted during the summer of 2014 as they could not operate profitably as a result of the reduction in wholesale electricity price caused by subsidized rates for solar and wind generation [16].

A major part of the huge capital investment cost in PHES is in civil structures. A cost comparison of underground pumped storage with and without existing infrastructure for downstream reservoir showed cost increased by 81 % with new infrastructure [18]. Further, lack of other infrastructure such as roads and transmission lines is reported [19] as a highly cited techno-environmental barriers (i.e., lack of existing transmission lines was reported in 23 out of 47 studies). 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) [19] and therefore hurdles to rapid strategic deployment of PHES.

Queensland Hydro has embarked on a 5 GW Pioneer Burdekin and 2 GW Borumba since 2022 to accelerate decarbonization of Qld's energy targets by 2035. The estimated lead times of the projects vary between 7 and 10 years and estimated cost between $ 12–14 billion [20]. The individual project is designed to provide up to 24 h of storage. The Snowy 2 PHES original cost projection was $2 billion (AUD) and now is projected to be over $12 billion dollars [21] with levelized cost of electricity well over $60/MWh, based on purchase of renewable energy dropping to $20/MWh. However, current projections of greenfield renewable wind (including a price premium for firming) is approximately $70 – $80 MWh, while solar (with a price premium for firming) is approximately $77 – $99 per MWh [22].

Blakers, et al. [23] determined that Australia has adequate pumped hydro potential sites to support a 100 % renewable energy market. The assessment however 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 [24].

With response times ranging between seconds to minutes (from idle to full capacity) [25] and storage capability over days, PHES is an ideal option for medium and long term storage.

3.2. *Flywheel energy storage (FES)*

Another mature technology extensively investigated and continuously innovated through ongoing research is the FES. Its high power density, quick response time, and high energy efficiency have driven its popularity [26,27]. Nevertheless, due to its comparatively high capital cost, commercialization of FES has been a challenge [28,29]. Compared to electrochemical battery storage technologies, FES has moving parts that are susceptible to failure under the high operational speeds requiring specific design outcomes for specific applications [30]. 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 h storage [31]. Other existing FES are capable of storage duration of only about ~15–20 min [32] with multiple units working together to increase to the capacity such as the 20 MW installation in Pennsylvania, US comprised of 200 flywheels (each rated at 0.1 MW and 25 kWh) [32]. However, there has been only very limited FES adoption (32kWh) in Australia.

3.3. *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 generate energy (during peak demand). 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 such as the current 1.5GWh associated with Broken Hill mining (NSW Australia). CAES is not a widely used technology, with only eleven sites operational in the world [33]. Its current efficiency in operational plants between 45 and 55 % [32,34] needs to be improved for more commercial widespread development and adoption.

Various methodologies for efficiency improvements such as adoption of two level pressure systems and reconfiguration of compression chambers demonstrate efficiency improvements up to about 80 % [35] but these are not commercialized.

3.4. *Green hydrogen energy 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 [36], 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. However, the efficiency rate of electricity-hydrogen is 55–75 % depending on the transformation method [37]. Green hydrogen storage could function as a load demand when renewable peak energy generation exceeds normal grid load demand, instead of having to disconnect renewable energy sources to prevent grid protection events. Given the extensive natural gas (methane network) network of Australia [38] interconnected across all states from Northern Territory to Tasmania, and the isolated West Australian gas network, green hydrogen could be injected into the current gas pipelines. There is a feasibility to inject up to 10 % per volume in the current gas network without infrastructure change [35]. This has the potential for gas exports and domestic use to reduce GHG emissions without significant performance changes in fast-peaking gas turbine technology assets like those used in South Australia. The trial blending of a small volume (2 %) of hydrogen in the existing gas networks has been started in Western Australia and Jemena's Western Sydney Green Gas Project [39]. 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 [40]. But 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. Stored green hydrogen energy is recovered to the electrical grid by using fuel cells (using electrolytes such as proton exchange membrane (PEM), direct formic acid, direct-ethanol, alkaline, phosphoric acid, direct methanol), and regenerative fuel cells which can consume hydrogen for electricity production, or produce hydrogen directly from electrical current [14,41]. These are also an extensively explored area of hydrogen energy storage.

The 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 [41]. 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 [42] for potential use in grid based energy storage. 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 [43] 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 SOFC could be a useful baseload generation source replacement, but its slow start-up time limits its applications in high-load fluctuation applications [14,43]. 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 [41,44] with high inrush current for which hybrid with supercapacitor is reported to enhance power capacity by 50 % [45].

3.5. *Batteries*

Batteries are widely used ESS technologies that store energy electrochemically. Construction of battery ESS takes a relatively brief period (1 year), has low capital expenditure, and is modular which can be located easily anywhere in the network. It can be moved quickly to account for seasonal different needs. For instance, following the blackout event of SA in 2016 as discussed earlier, the Hornsdale Power Reserve (HPR) rated 100 MW/129MWh was required to be completed within 100 days. In 2018, HPR prevented SA from load shedding during the QLD-NSW interconnector trip that caused load shedding in NSW and VIC but not in SA [46]. The frequency response of HPR is said to have contributed towards preventing load shedding in SA, illustrating the role of fast response ESS such as battery energy storage (BES).

Table II provides a comparison of various battery types and their high-risk safety aspects highlighted.

3.5.1. *Metal ion batteries*

The most commonly available metal ion battery is the lithium-ion battery (LiB). Metal-ion batteries have high power & energy density, long life (compared to other batteries) and high cycle efficiency as shown in Table II. Ongoing research focuses on increasing power and energy densities by exploring different electrode and electrolyte materials (e.g., the Lithium Iron Phosphate type) for scaling the storage capacity [47] while also minimizing issues such as thermal runaway, unstable solid electrolyte interface layer (SEI) formation, volume change, and preventing internal dendritic growth failures [48].

Owing to the similar electrochemistry of sodium and lithium, and significantly greater abundance of sodium, sodium-ion batteries (SiB) are being explored as a contender to LiB [49–51]. 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. Larger ionic radius and heavier atomic mass (Li 6.94 g/mol, Na 23 g/mol) provides lower theoretical capacity of SiB. Studies report [52] that issues of thermal runaway associated with SEI formations and volume changes in SiB are observed at higher rates than lithium equivalents [52]. On the contrary, Zhao, et al. [53] established that a SiB with a $NaFeO_2$ cathode is likely to have similar or better thermal stability to that of LiB with conventional $LiCoO_2$. The use of Aluminium as a current collector in SiB allows charge storage at 0 V which makes them safe for transport. However, safety research concerns of Na-ion remain inconclusive due to the unstable volumetric changes of the Na-ion [52]. Nevertheless, the prospect of the better commercial viability of SiB and sustainability drives research efforts in enhancing its storage capability to be equivalent to LiB [54,55]. The commercialization of SiB is mostly in the prototype development stage, being tested on electric bicycles and small-scale energy storage [56].

Table II
Comparison of battery types [15,31,43,48,57,61–65].

Characteristics	Metal Ion	LA	Nickel Based	Flow Batteries
Max. power density (W/kg)	2000	300	300	166
Max. energy density (Wh/kg)	300	75	100	80
Max. voltage (V)	4.2	2	1.65	2.37
Max. power rating (MW)	0.1	20	40	3
Operating temperature (°C)	−20 to 60	−20 to 50	−20 to 65	−20 to 50
Cycle life. (80 % DoD)	7000	3000	3000	20,000
Cycle Efficiency (%)	97	90	90	85
Daily self-discharge (%)	1	0.3	0.6	small
Capital cost ($/kWh)	3800	400	2400	1000
Metal Ion Battery Risks	Thermal cascade failure; heavy metals; Solid electrolyte combustion releases toxic fumes			
LA Battery Risks	Heavy metal risk to environment and human/animal health if not fully recycled.			
Nickel Battery Risks	Thermal decomposition /short circuit @ >85 °C operation, Nickel / cadmium heavy metal risks			
Flow Battery	Metal/halide effects on aquatic life and corrosion impacts on system components.			

When it comes to the recycling of metal ion batteries, the safest current commercial end-of-life recycling is pyrolysis [57]. Recovery of materials from metal ion batteries after pyrolysis follows normal mining metallurgical resource extraction practices and is currently quite expensive due to the inhomogeneity in battery chemistries and structures involving complex disassembly methods and safety issues for workers. Despite low cyclability, extensive research such as the study by Zhang and Azimi [58] indicates that metal components could be recovered using supercritical CO_2 with an extraction efficiency of 90 % and at 5–6 times shorter duration than conventional leaching process. Such research could potentially lead to further commercialization of metal-ion batteries.

3.5.2. *Lead acid (LA)*

LA batteries for ESS today are Advanced Glass Matt (AGM) -regulated (VRLA) type, with longlife design having tubular positive plate construction. They use various lead doped with calcium/tin/cadmium/silver/antimony/ arsenic cast alloy grids “pasted” and pressed with active PbO_2 for the anode and lead sponge for the cathode with sulfuric acid as the electrolyte. These sealed AGM deep cyle batteries use immobilized electrolytes and are spillproof [14]. AGMs have fast charge/discharge capabilities due to low internal resistance and are therefore suitable for high-power applications.

LA battery has some environmental and health impacts of lead [59] during production and assembly. However, this battery is fully recyclable. The LA 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 m-Ohms. While its environmental impact is a major concern, LA batteries have achieved a 99 % recycling rate with stringent regulations in place for Pb emission, as compared to its counterparts like LiB, which have achieved only about 1 % [60] recyclability. Some battery manufacturers [61] even provide free recycling as it is profitable to recover all the component resources from LA batteries.

Low production cost of LA batteries is a major advantage but their lower energy density, depth of discharge and cycle life limits their competition in large-scale grid storage applications; though research efforts explore alternative materials such as carbon sponge half-capacitor electrodes on the cathode, to improve energy density [62] and cycle life.

3.5.3. *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 with deep discharge capability are more desirable of the above types in power system applications. The environmental toxicity of the Ni-Cd battery and high capital costs are the major barriers [62]. Some Ni-Cd battery types have a memory effect and their capacity is highly influenced by charging at partial discharge [47]. The Ni-Fe battery is only currently produced as a flooded alkaline battery and suffers from hydrogen generation during charging; requires auto-watering 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.

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 limited cycle life for deep cycle energy storage applications [47].

3.5.4. *Flow batteries*

Flow batteries have 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 with capacities ranging between 1 and 100 MW. However, the high production cost is still a major barrier to the commercialization of vanadium flow batteries [33]. Zinc bromine redox flow is another type being explored in similar ESS applications. They have relatively higher energy and power density than vanadium flow batteries but corrosion and dendritic formation are some of the challenges [47] that require modularisation of the assembly so that the separation membrane can be replaced regularly.

3.6. *Capacitors*

Conventional electrolytic capacitors use a dielectric insulator and electrolyte as 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 electrode interface enables energy storage via the electrical field due to charge separation between the electrodes and alignment of the electrolyte dipoles. Electrolytic capacitors commonly use Aluminium, Tantalum, and Niobium type [63] whose oxides act as interlayer electrical insulation with high 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 [63]. However, such capacitors face high leakage current, capacitance degradation under heating and are subject to failures [66 – 68] and especially so if they are incorrectly connected in polarity.

3.7. *Supercapacitors (SCs)*

Research efforts are continuing into increasing the storage capacity of conventional capacitors through the synthesis of new electrode and electrolyte materials. This has led to innovation of the new generation of supercapacitors. The SCs contain 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 storage at each electrode. [64,65]. Depending on their charge storage mechanism, SCs are broadly categorized as Electric Double Layer Capacitor (EDLC), Pseudo Capacitor (PC), and Hybrid Supercapacitor (HSC) [66].

Batteries generally have a high energy density, but low power density, and vice-versa for conventional capacitors. The SC on the other hand bridges the gap between the two for optimal power and energy density requirements. 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 [64]. In recent times advances in electrode materials using activated carbon, conducting polymers, metal oxides, and their composites with different electrolytes have achieved energy density of about 100 Wh/kg, power density of about 2 kW/kg, and lifetime more than a million cycles, provided the capacitors operate below 70 °C.

3.7.1. *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 [65] determined by the electrode material pore size, their 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 using various carbon electrode materials. Carbon as Graphene has a 2-D structure with a higher specific surface area than carbon nanotubes; but suffers from longer diffusion times for 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 [67]. Activated carbons have an even higher specific surface area (2000 m^2g^{-1}) [65]. 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 [67,68]. Pore structuring and heteroatom doping of carbon-based electrodes for further enhancement of storage capacity are the focus of research in recent times. EDLC's have high-rate capability and cyclic stability [68] but low energy density.

3.7.2. *Pseudo capacitors (PCs)*

In PCs, double-layer charge accumulation is based on redox reaction at the electrode-electrolyte interface [65] by using transition metal oxides, conducting polymers, and composites. Due to electrochemical reactions, the capacitance and energy density is higher than EDLC [68] but lower power density due to low electrical conductivity and high mechanical degradation during cycling [65]. Carbon nanotubes, graphene, and activated carbons in PCs with doped metal oxides or conducting polymers are employed to increase the power density.

3.7.3. *Hybrid supercapacitors (HSC)*

The 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, 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 [64] per capacitor and can operate up to a maximum 85 °C.

TABLE III 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 LiB [14]) 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 [69]. However, efficiency loss due to internal resistance for high current

Table III
Characteristics of different capacitors [14,33,64].

Characteristics	Capacitor	Supercapacitors
Power density (W/kg)	~3000–10^7	500–10,000
Energy density (Wh/kg)	~ 0.05–5	0.05–15
Max voltage (V)	800	4.2
Max power rating (MW)	0.05	0.3
Cycle time	50,000	$> 10^5$
Cycle efficiency (%)	95 %	85–98
Operating temperature (deg C)	−20 to 100	−40 to 85
Charge time	10^{-3}-10^{-6} s	1–10 s
Capital cost ($/kWh)	500–1000	300–2000

or power pulsing reduces the efficiency to about 90 % (by a margin of about 8 %) [69].

4. Discussion

The review of various ESS has shown that the challenges faced by technologies vary and therefore does their respective advantages in different applications. Using AEMO's categorization from TABLE II and from the review ESS, TABLE IV provides a comprehensive summary of the six different storage technologies considering critical parameters for grid storage.

Table IV summarises parameters extracted from review papers on large scale energy storage technologies from 2020 onwards. Storage capacity and discharge duration are the focus here for grid ancillary services. From different papers, considering the minimum and maximum values, a range of their capacities, discharge time and response time were extracted. In case of similar technologies, for instance, all battery types were clubbed under the umbrella type BES to provide an overview.

Long-term storage like PHES has hurdles, with long-lead times, high investment cost and restrictive location conditions but also offers advantages such as long lifespan of over 50 years, extended storage duration (> 24 h) and high energy to power ratio. The constraints of FES include high capital cost, continuing challenges to determine failure modes and low storage capacity. The requirement of large storage volumes and the need for further improvement in efficiency impedes CAES.

Fast response, modular, medium scale ESS like BES have proven their feasibility and capability to cater to grid energy storage such as the HPR. In comparison to large scale PHES like Snowy Hydro 2, current contract costs for systems like the HPR range from $77–92/MWh. In Victoria the projected contract costs to use 90 % of the output from the 190 MW Bulgana wind farm and 20 MW/34MWh Tesla battery designed to be with it will be between $55–65/MWh [77]. However, the major difference is Snowy 2's most optimistic energy storage capacity of 350 GWh energy storage available daily over up to 150 years (assuming no droughts). Meanwhile the HPR storage capacity of life capital renewal period calculated at maximum cycling would be from 80 to 120MWh per individual 100 % DOD cycle for 3000–4000 cycles for current LFP BES system. Provided sufficient mineral resources are available, utility scale BES are projected to achieve 28–67 % cost reductions by 2050 and lithium based batteries specifically are projected to continue to decline in price per MWh by 30–40 % by 2050 [78].

From above and referring to factors outlined in **Section II**, a 100 % renewable energy future likely requires a combination of fast-acting resources and long-duration storage solutions. However, given the pressing needs for immediate power stability management and with increasing RE penetration and decreasing baseload plants, modular (no special requirements on location) types of energy storage systems with quick distributed deployment in energy grid systems without involving large infrastructure developments are particularly critical during the transition period in the next decade for providing grid ancillary services. Beyond this, as larger PHES storage comes online, continuing development of ESS's as combinations of PHES and BES will depend on actual price point comparisons of these two energy storage types based on $/MWh/year of capex period and environmental impact assessment of each technology at that juncture of time.

Table IV
Comparison of storage types [29,70–76].

Storage	Capacity range (MW)	Energy range (MWh)	Discharge time[2]	Response time[2]
PHES	10–5000	180–8000	h-days	sec-min
FES	0–387	0.005–10	sec-mins	ms-min
CAES	5–3000	0.008–5000	h.-days	sec-mins
HES	0–58.5	0–100	sec-days	ms-min
BES	0–300	0–450	min-24 h.	sec-mins
SCES	0–1	0–0.1	sec-1.2 h.	<5 ms

[2] h: hours; *sec*: seconds; min: minutes; ms:milliseconds.

Currently, for FCAS, battery energy storage systems [11,79] are being used to maintain the frequency of the grid within a nominal range. *Siti,* et al. [80] employed adaptive control strategies for frequency control using ESS and illustrated the critical role of fast response ESS in an interconnected system. Metal Ion batteries such as LiBs have high specific power, energy density, high operating voltage, up to 3000 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. Metal ion battery research will continue to explore this area, particularly with sustainable and environmentally friendly materials such as activated carbon and its composites.

For NSCAS, synchronous condensers and generators have been conventionally utilized to maintain the grid's voltage within the nominal range [81–83]. 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 [84–88].

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 [89,90]. Such hybrid systems would underpin the future of energy management widely termed "virtual power plants" (VPP) [91]. Very little is known however with regards to peformance of the hybrid system particulary the fatigue aspects of these hybrid systems require more investigation to increase reliability [92,93].

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 [94]. Countries in Europe have an interconnected systems 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. However, further assessments are still required covering any negative impacts to end users' downstream installations [95].

5. Conclusion

Recent events in the NEM suggests the need for storage technologies that can support the grid in different time scales. Many in the energy market see the different storage technologies as competing, when in fact they are complimentary in their characteristics as seen earlier in TABLE IV. As the future of energy is increasingly trending towards distributed systems and for the urgent transition to 50 % and onwards then to 100 % RE, fast response and modular type of storage such as hybrid of batteries and supercapacitors are deemed to be prudent solution particularly for providing grid ancillary service whilst large storage like PHES and Hydrogen are also part of the solution for long-term storage.

Also due to the disparity of typical cost of electricity, and capital replacement periods of different ESS as shown in TABLE V, it is misleading to consider cost comparisons on same scale amongst different storage technologies. This paper emphasises the different roles each technology can provide in support for a stable grid in future as renewable energy penetration increases.

Table V
Comparison of storage types based on operation performance [29,70–76,96,97].

Storage	Nominal Capex Renewal Periods (yrs.)	Typical LCOE (AUD*/ kWh)	Typical AEMO purpose
PHES	40–60	0.09–3.24	Peak generation periods, Ride-through fault conditions, voltage support by acting as sink for excess renewable energy; black start ancillary services, STATVAR rotating system inertia
FES	15–25	0.16–0.38	FCAS and major load step voltage support
CAES**	20–50	0.09–7.5	Peak load lopping, energy sink for voltage control when excess renewable energy generation
HES	15–20	0.18–0.75	Peak power generation, black start ancillary services, STATVAR rotating system inertia
BES	5–20 (depends on duty cycle)	0.06–5.4	FCAS, initial fast energy sink when excess energy from renewables, black start ancillary services
SCES	8–20 (depends on duty cycle)	> 0.3	Potential use in hybrid BES systems to lengthen life of battery technology

* USD to AUD conversion of 1.50.
** Not currently in use by AEMO.

Battery energy storage technology has proven its capability in maintaining system integrity during contingency events. However, there is yet to explore the long-term performance of such plants, particularly in regards to their performance and life cycle dependency on ambient temperature. Similarly, the scalability of supercapacitors arrays comes at some considerable cost to achieve power at 660 V operation voltage (using the current maximum individual supercapacitor voltage rating of 4.2 V).

The literature has indicated scope in hybrid battery-supercacitor in order to balance between energy-power density and also extend battery life. However, the technology is not matured and has further scope for investigation regarding performance and life cycle dependency on ambient temperature.

For long-term storage to cater for seasonal storage or RE droughts, there is a growing momentum for Green Hydrogen based fast-peaking gas turbine technology, or potential for baseload generation using SOFC arrays at constant load. In addition, where potential HV connections and geography is appropriate, the development of large scale PHES systems should continue for longer term grid stability.

CRediT authorship contribution statement

Wangmo: Methodology, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Andreas Helwig:** Validation, Supervision, Writing – review & editing. **John Bell:** Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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