The future of long duration energy storage

Keeping the lights on in a carbon constrained world

CLEAN ENERGY COUNCIL

June 2024

Contents

Foreword

The concept of the energy trilemma – the need to deliver emissions reduction, while keeping the lights on and minimising price impacts – may be a well-worn one, but it remains accurate.

The only way to achieve a zero-carbon power system is if the lights stay on and customer bills are kept as low as possible. Failure to do so risks losing public support, delaying the transition at precisely the point it must accelerate.

Renewables backed with storage meets all three elements of the trilemma, and Australia's renewables transition is already well underway. However, we need to accelerate the growth of the sector if we are to create the zero-carbon economy of the future. Renewable generation, transmission and long duration energy storage must be ready well in advance of coal generation exit.

The exit of coal generation is unstoppable. There's a good chance it will happen faster than expected, as ageing coal units struggle to keep up with renewables. As these units go, they take with them energy reserves. We need to replace these energy reserves to maintain reliability of supply.

While some would have you believe it, nuclear and gas are not the solution. Nuclear is an uneconomic technology and is a poor fit for Australia. Gas will play a small role in the energy transition however it simply cannot provide enough energy while staying within carbon budgets.

Long duration energy storage offers a superior solution. It complements transmission and renewables, moving energy through time to when it's most needed. It reduces the total infrastructure we need to build, lowering costs and customer energy prices.

There are many forms of energy storage. The remarkable progress of lithium batteries shows the potential of this technology to support security, reliability and resilience of the power system. Along with pumped hydro as the backbone of our energy system, lithium battery energy storage has revolutionised the way we generate and transport electricity to maintain a reliable supply.

There is more to come. As demand for energy storage grows, new solutions are rapidly emerging. Compressed air, thermal energy and redox flow batteries are just some of the alternative forms of long duration energy storage available in Australia. These technologies bring remarkable energy carrying capabilities, helping to maintain reliability while minimising the cost of the transition.

This report introduces these 'alternative' long duration energy storage (ALDES) technologies, exploring how they complement lithium battery and pumped hydro energy storage, to replace fossil generation. Working with CEC members and experts, we have mapped some of the most promising ALDES solutions and explored how they might enable a faster, safer and lowest cost transition.

ALDES will complement lithium and pumped hydro to form a portfolio of storage solutions. This storage portfolio will be key to solving the trilemma. However, the need for these solutions is not far away - it is approaching rapidly and may well arrive sooner than expected.

We need to get started, right now, in building this portfolio of storage solutions. This is a key focus area of the CEC. We look forward to working with our members and our stakeholders nationally to accelerate the development of this critical technology, to deliver a low cost, reliable and zero carbon energy system for all Australians.

Kane Thornton
Chief Executive
Clean Energy Council

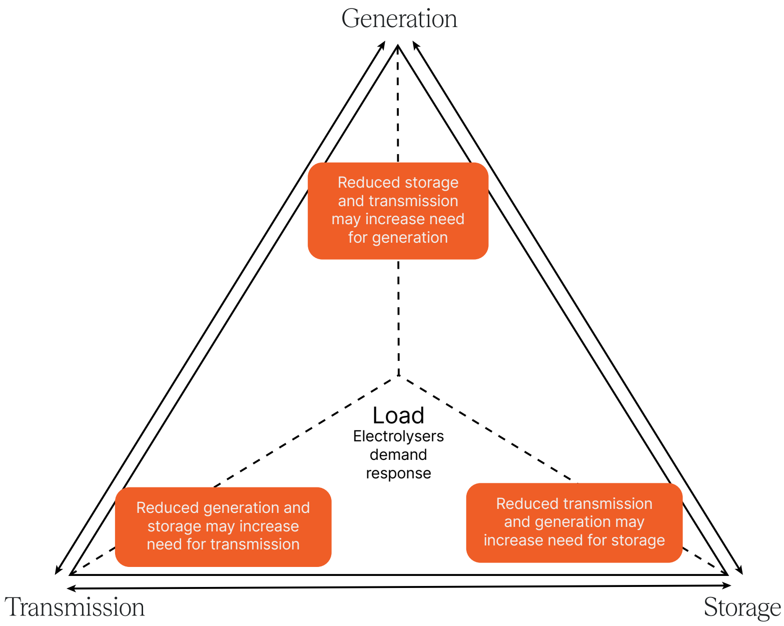
Executive summary

The future of long duration energy storage

Australia's power systems are going through a process of rapid decarbonisation. This is central to meeting our national emissions reduction commitments.

The pathway to power system decarbonisation has four foundations – generation, transmission, energy storage and customer load.

Figure 1: the foundations of power system decarbonisation



Each of these foundations complement and reinforce each other, that is if they are effectively coordinated. This coordination is key to maintaining a reliable supply of electricity at the lowest possible cost for consumers. Energy storage plays a key role in this coordination, helping reduce the need for both generation and transmission build, and driving marked reduction in overall system costs.

There are many different types of storage technologies, with lithium ion battery (LIB) and pumped hydro energy storage (PHES) currently predominant in Australia. PHES and LIB are effective, well understood technologies, and they will continue to play a major role in the energy transition.

Alternative Long Duration Energy Storage (ALDES) technologies are rapidly emerging as effective and complementary to reinforcing these established types of energy storage. Across a range of mechanical, electrochemical, and thermal technologies, ALDES exhibit particular characteristics that can be used to bring down the total cost of the transition while also reducing environmental and social impacts.

This report provides an introduction to ALDES, exploring the key ALDES technology families and the context in which they will operate. It explores the specific roles these technologies will play in delivering a secure and reliable supply of electricity. Finally, it explores the various policy reform areas that can be pursued to accelerate the market uptake of these promising technologies.

What is alternative long duration energy storage?

There are many energy storage technologies available. Mature energy storage technologies include LIB and PHES. LIB provide short to mid duration energy services and are predominantly non-synchronous. PHES provide medium to long duration services and are predominantly synchronous.[1]

This report explores how ALDES can complement and strengthen existing technologies and address the missing middle that lies between short and seasonal energy storage spectrum.

This report focuses on the ALDES categories of compressed air, redox flow and thermal energy storage technologies.

We have focussed these ALDES because of their applicability in the Australian power system. We have also focussed on technologies that have pilot projects underway, have commercial projects progressing towards or have already reached financial close.

These ALDES typically display characteristics that will be needed as the power system transition continues.

- **They typically have energy duration capabilities in the range of 12 hours and above and are able to carry stored energy through long periods of time.**
- **Most have the capability to repeatedly cycle, with low rates of degradation.**
- **They can provide key system stability services, including synchronous services.**

[1] Synchronous technologies are electromechanically coupled to the power system and inherently provide various critical system services such as inertia, system strength and frequency control. Non-synchronous technologies are coupled to the power system through power system electronic software and can provide some power system services through the rapidly developing area of grid forming inverter capability. As discussed later in the paper, these two characteristics are central to delivering a stable and reliable power system during the transition.

The role of ALDES in the Australian energy transition

This section explores the key challenges affecting the cost, security and reliability of energy supply in Australia and how long duration energy storage is well placed to meet these challenges.

ALDES are well positioned to help address the key physical challenges associated with the transition. They can help meet key system needs including:

- synchronous capability to maintain system security.
- cycling capability to meet an increasing diurnal demand spread.
- long duration energy supply capability, coupled with an ability to carry substantial volumes of stored energy across long periods of time, to support system reliability

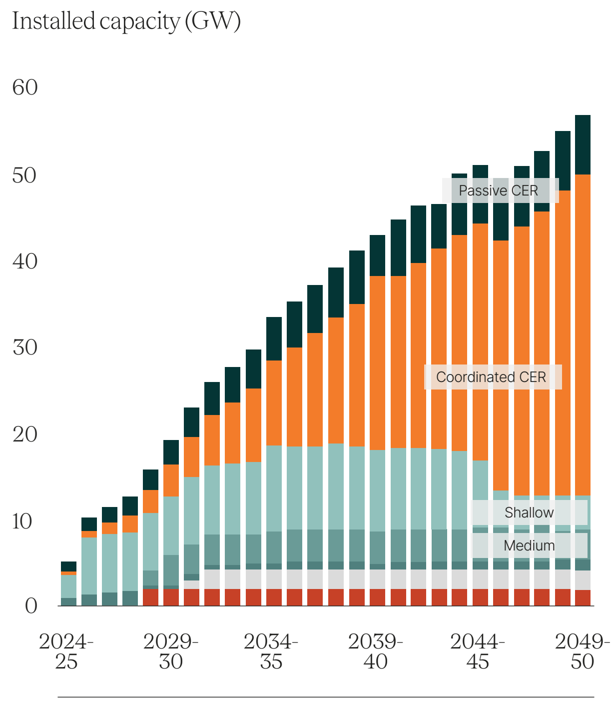
ALDES can address these issues directly but they also play a role in unlocking the full potential of wind and solar generation as well as supporting effective contract markets. Consumers are the ultimate beneficiary of these effects, as lower total system costs translate into lower energy prices.

Later in the report we will explore the specifics of these ALDES technologies and demonstrate how each is variously equipped to meet these needs of a transitioning power system.

The Integrated System Plan and projected storage volumes

The physical transition of the east coast National Electricity Market (NEM) power system is the key focus of the Australian Energy Market Operator (AEMO) in the 2024 Draft Integrated System Plan (ISP). The ISP is the central planning document prepared by AEMO that models total system development out to 2050.

AEMO projects approximately 12.7 gigawatt (GW) of utility-scale storage is forecast to be needed by 2030, with an optimal mix of 2.4 GW as deep, 3.6 GW as medium and 6.7 GW as shallow storage.[2]



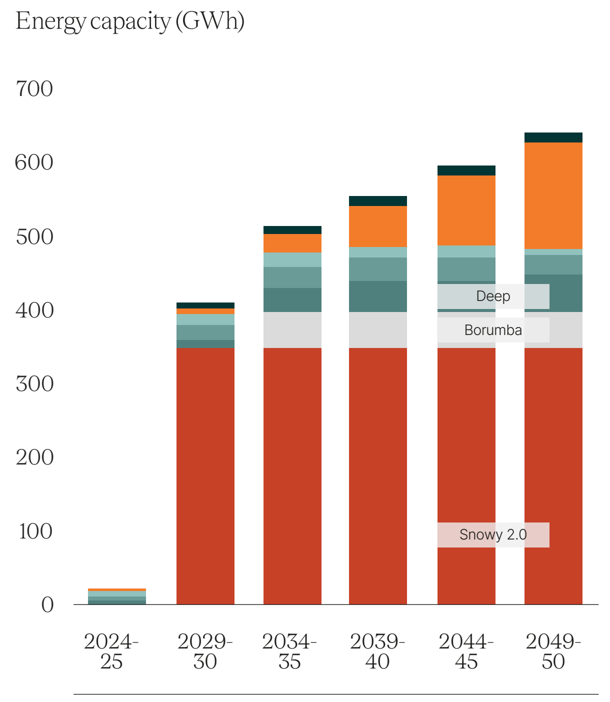


Figure 3: AEMO projections of new storage capacity required[3]

[2] AEMO defines shallow storage as grid connected storage that can provide energy up to 4 hours, medium storage from between 4 to 12 hours, and deep storage providing more than 12 hours of energy supply. AEMO, Draft 2024 Integrated System Plan, p.62. Available at draft-2024-isp.pdf (aemo.com.au).
[3] Ibid.

In the ISP, AEMO projects different mixes of energy storage which are in turn dependent on cost and regulatory assumptions in the modelling. Changes in these assumptions may result in greater penetration of utility scale storage, including ALDES.[4]

The need to replace coal generation

The ISP has the bulk of coal fired generation exiting by the mid-2030s. While these dates may be affected by government intervention, the economic and environmental drivers are unequivocal – these assets will exit the system, likely sooner rather than later.

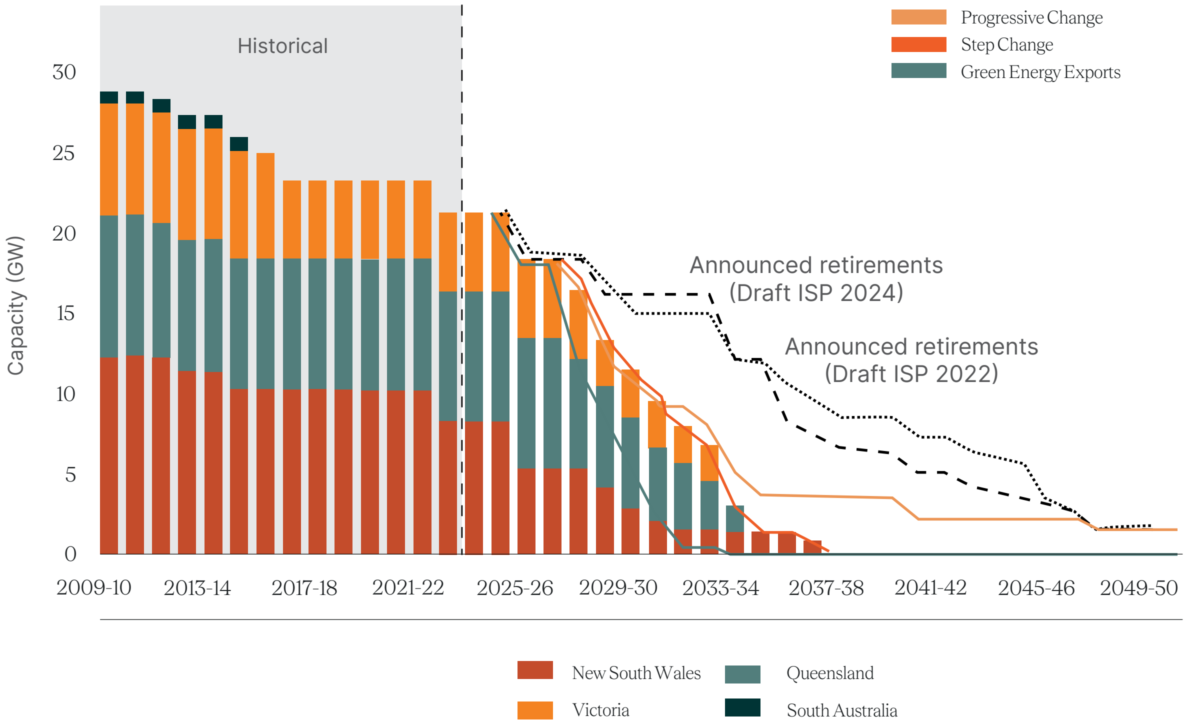


Figure 4: AEMO projections of thermal coal retirement [5]

Coal generators provide significant energy reserves and essential system services, such as system strength and inertia. From an operational perspective, AEMO is also currently reliant on these specific coal generation assets to maintain the operability and stability of the power system.

From a market perspective, the substantial energy reserves of coal generation have enabled the development of a diverse and liquid derivative contracts market. This market allows retailers to manage their exposure in the spot market and have supported the development of retail market competition. The retirement of these coal generator may reduce the supply of these contracts, with subsequent impacts on retail market competition.

Therefore, coal generation exit means new assets have to provide equivalent energy and system services to maintain reliability and security[6] as well as to support contract market liquidity.

Many forms of ALDES are well equipped to support these system needs, by providing bulk energy reserves as well as inertia and system strength. They are also well equipped to support reliability in a changing power system, by carrying significant volumes of stored energy over long periods of time. Finally, their substantial energy reserves complement and enable firming of renewables, which in turn will allow for the development of new contracts to manage retailer loads.

[4] For example, the forecast volumes of Coordinated CER storage – small scale storage behind the meter – are dependent on regulatory and commercial frameworks being in place to coordinate these assets. Similarly, cost inputs for utility scale storage are currently based around LIB costs. Any changes in these underlying assumptions will in turn change the rate at which different types of storage are adopted.

[5] AEMO, Draft 2024 Integrated System Plan, p.47. Note while this figure refers to the east coast NEM power system, similar coal retirement schedules are projected to occur in Western Australia.

[6] Reliability is about ensuring there is sufficient bulk generation and transmission available to meet total demand for energy. Security is about ensuring the power system stays with its technical limits.

Cycling capability to meet diurnal demand spreads

A key issue affecting the power system is the growing spread between maximum and minimum demand levels, which occur on a daily basis.

Known colloquially as the 'duck curve', this diurnal spread is driven by consumer demand patterns, exacerbated by changes in solar availability during the day. Issues arise when minimum demand gets too deep, where the afternoon demand ramp becomes too steep, or where the maximum demand level cannot be met with available generation.

Figure 5 below demonstrates how storage - in this case, small scale consumer energy resource (CER) storage - can assist in carrying energy through the day, to manage the spread. Utility scale storage such as ALDES can complement CER in this role.

These kinds of spreads occur every day, so storage assets must also be able to charge and discharge every day, without materially degrading. This ability to repeatedly charge and discharge is called cycling and is a core characteristic of many of the forms of ALDES that we will discuss in this report.

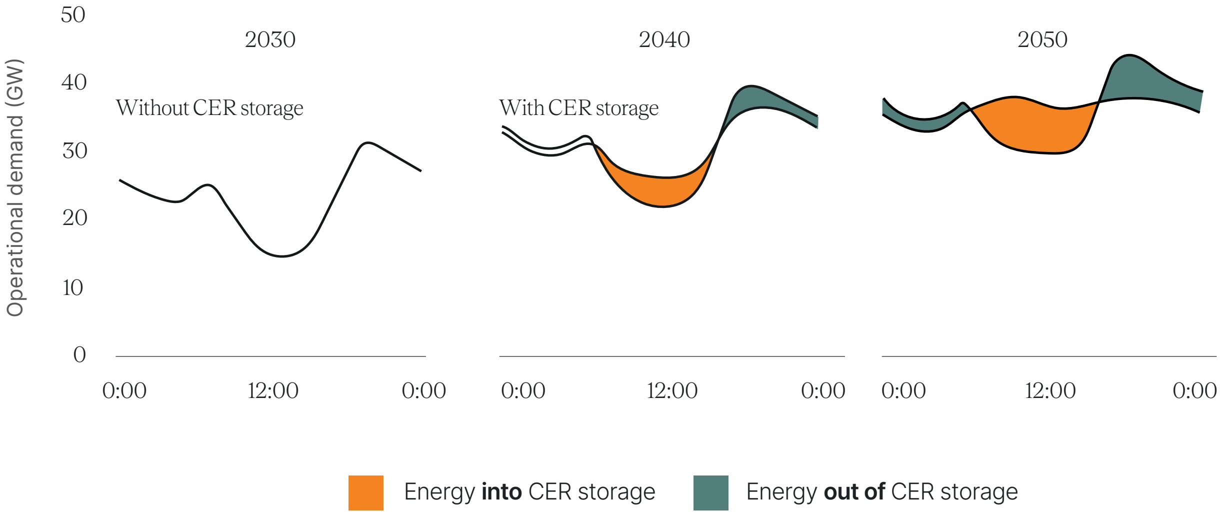


Figure 5: Average operational demand with and without storage

Long duration energy supply capability to support system reliability

The ISP demonstrates that energy storage will play a key role as patterns of energy demand change. There will be a particular requirement for energy storage to carry large volumes of energy through extended periods of time, to cover the kinds of supply shortfalls events that are increasingly likely to impact a renewables based power system.

This report refers to various supply side effects that will increasingly impact system reliability, as the power system transitions to higher levels of renewable energy penetration.

Seasonal supply shortfalls are caused by annual shifts in energy supply that can occur in a power system with higher levels of renewable energy. As opposed to a carbon intensive power system with lots of gas and coal, a low carbon renewable power system may have a relative surplus of energy in summer periods – due to the abundance of solar generation - but face potential shortfalls during winter periods – due to reductions in solar and wind availability.

These seasonal effects are somewhat predictable, however significant variance in their severity may occur year on year, caused by other weather events such as droughts, colder than average winters or La Nina / El Nino events. The predictability and severity of these weather events is likely to be affected by climate change. The impact of these seasonal shortfalls is also affected by other supply side variables, such as coincident coal generator outages, and underlying demand trends such as electrification of industry, transport and residential space heating.

These semi-regular seasonal supply shortfalls may be exacerbated by periodic *wind droughts*. A wind drought is a period of time – sometimes as long as several weeks - where there is a prolonged reduction in wind speeds across a wide area. This results in a sustained reduction in output from many wind farms.

The final term used throughout this report is *dunkelflaute*, a German origin word that is variously translated to 'dark lull' or 'dark doldrums'. This refers to a period of combined low solar and wind output, which tends to occur during the winter months.

By materially changing supply side availability, these various effects of seasonal shortfalls, wind droughts and dunkelflaute will increasingly affect overall power system reliability. Solutions such as ALDES are well suited to manage them.

However, the likely severity and system impact of these various effects is not yet known. For example, the Reliability Panel, the body responsible for forecasting long term reliability needs in the power system, considers that while reliability challenges will change into the future, particularly severe events are expected to occur very rarely.[7]

Of course, the final and possibly most impactful supply side effect is the decreasing reliability of coal generating units. Most recent supply shortfalls in the NEM have been related to issues with coal generation, including planned and unplanned outages occurring at the same time as decreased renewable output and, in some instances, elevated demand. This effect will become more pronounced as coal units continue to age and maintenance costs increase.

Long duration storage will play a key role in maintaining reliability of supply to manage these seasonal supply shortfalls. Figure 6 below demonstrates how deep, long duration storage – in this case PHES – can utilise particular physical characteristics to carry large volumes of stored energy over long periods of time.

This ***carrying capability*** allows them to 'charge' large volumes of energy in spring and early summer when water inflows are most abundant, then hold this energy for several months before dischargin when demand is highest, in autumn and early winter.

Further to this, PHES and other forms of ALDES exhibit relatively low levels of lost energy during this carrying period. This improves efficiency and reduces overall cost of the system.

These characteristics are central to maintaining reliability for customers in a high renewables power system. Many forms of ALDES explored in this report demonstrate very good carrying capability.

[7] AEMC, *Review of the reliability standard and administered price cap*, Draft Report, 18 April 2024.

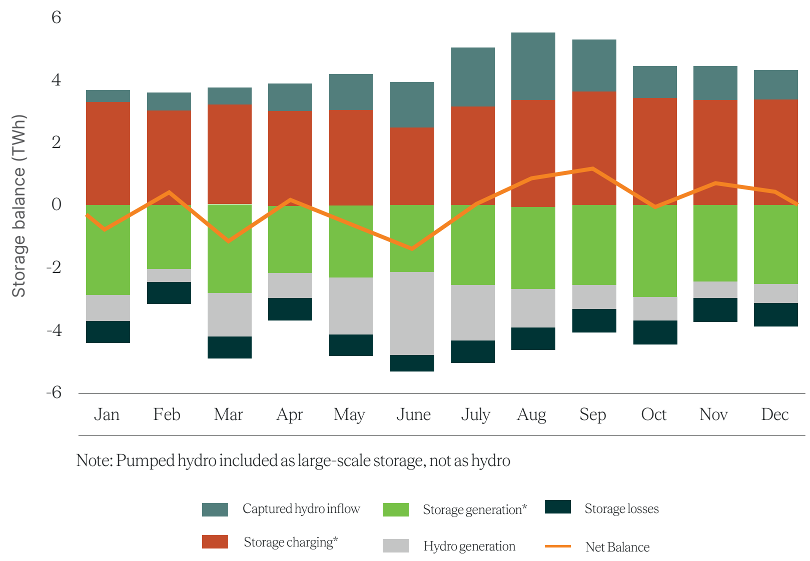


Figure 6: Seasonal patterns of energy use requires different kinds of storage[8]

Finally, energy storage is well placed to support the general reliability of networks. Generally speaking, network companies can meet their supply obligations in two ways, either by building more network infrastructure, or contracting with a third party to provide locally supplied power. As discussed below in regards to the Hydrostor Broken Hill project, ALDES are already being explored by networks as a key way to maintain network reliability at the edge of the grid.

As above, the long duration and energy carrying capabilities of many of the ALDES explored in this paper mean they are well placed to support network reliability.

The role of gas powered generation vs energy storage

While the Draft 2024 ISP has energy storage playing a central role in managing seasonal supply shortfalls, gas powered generation (GPG) was also identified as playing a role. Although GPG will likely play some role in the transition, it is likely that energy storage will make a much greater contribution to supporting reliability.

In the ISP, AEMO projects upwards of 16 GW of GPG will be needed, particularly in the 2040s onwards. AEMO suggests these assets will be operated primarily in a 'backup' function, to help meet demand during renewable energy droughts.

However, AEMO also highlights issues that indicate this reliance on GPG may be untenable.

Firstly, overall gas supply is expected to worsen under the central Step Change scenario, especially in the southern parts of the NEM. More broadly, commitments to achieve net zero by 2050 are inconsistent with the development of new gas fields. It's therefore unclear where additional gas for GPG will come from, particularly in 2040 as the economy moves towards net zero.

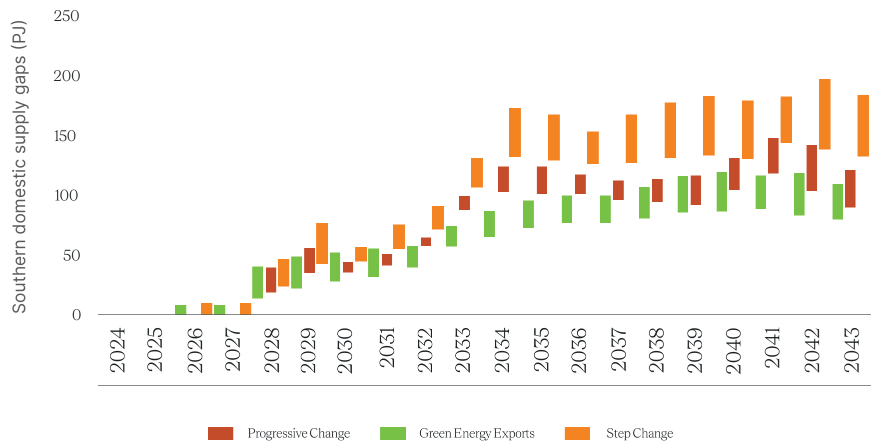


Figure 7: Projected gas supply shortfalls in NEM southern regions[9]

[8] AEMO Ibid., p.65
[9] AEMO, *2024 Gas Statement of Opportunities*, p.11. Available at www.aemo.com.au

This suggests that any future GPG will need to have onsite fuel storage. However, as AEMO identifies, very few existing GPG have onsite storage.[10] This is mainly down to the high associated costs. It follows that any future GPG will need to have expensive onsite gas or liquid fuel capacity, which will make these assets extremely expensive to run.

Furthermore, as the CEC[11], AEMO and others[12] have identified, the physical and commercial structures for gas pipeline capacity are not well aligned with the operation of GPG running in a seasonal basis. As shown below, AEMO forecasts that GPG offtake will become increasingly volatile. These kinds of volatile, highly variable offtake patterns are not well aligned to current pipeline physical and commercial designs, at least not without major augmentation works. However, given emissions reduction targets and high costs associated with pipeline augmentation, major improvements appear unlikely to occur.

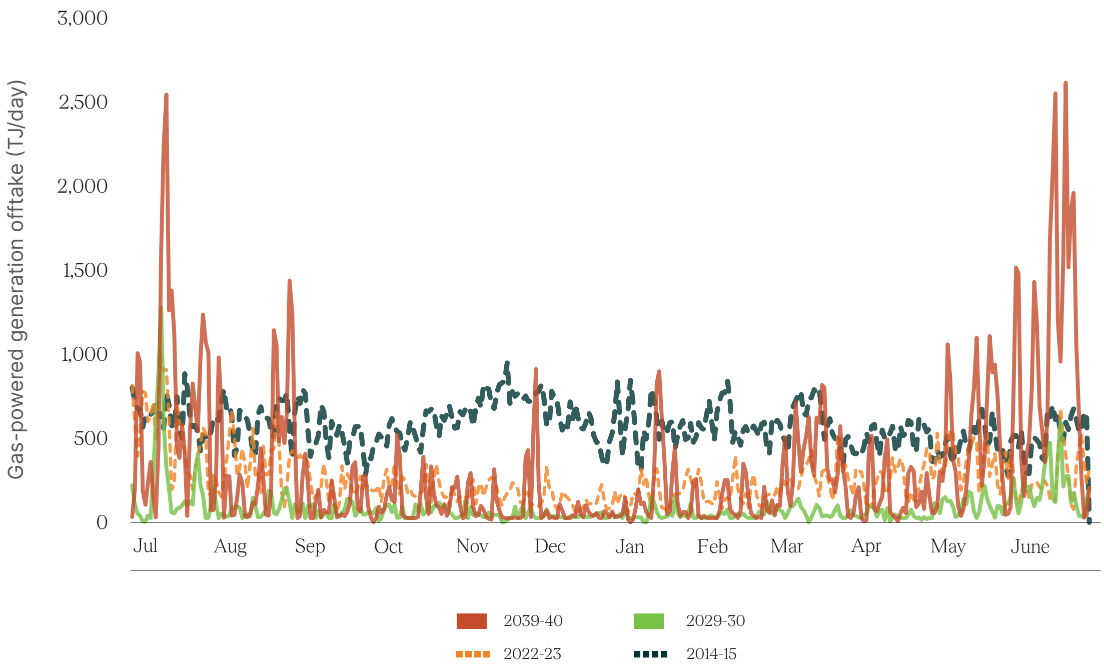


Figure 8: Gas powered generation offtake, NEM[13]

The CEC considers that over-reliance on GPG will create material reliability risks, particularly in the later stages of coal generation retirement in the 2030 and 2040s. While some form of fuel-based generation may be unavoidable to meet the last increments of demand, issues with underlying infrastructure constraints creates material risks associated with any particular reliance on GPG. These issues are likely to be particularly severe and problematic in the southern parts of the NEM, where declines in local gas supply and limited interconnection with Queensland.

Many of the forms of ALDES explored in this report are well equipped to supply energy to help meet these seasonal shortfalls and renewable droughts. As discussed later in the report, we find that ALDES can be used to effectively minimise reliance on GPG, helping to reduce total system costs while maintaining reliability for consumers.

We will return to these underlying system needs and how ALDES can meet them, later in this report. First however, we will explore the evolution of storage technologies in Australia and how developing ALDES fit into this evolution.

[10] Most gas generators rely on natural gas supplied continuously through the gas network as their primary fuel source and have no on-site gas storage capacity. A minority (13% by capacity) of gas generators have advised access to an average of 18 hours of gas storage, predominantly through access to local linepack that is within the control of the operator. Most gas generators do not have secondary fuel capabilities. Of the generators which have diesel as a secondary fuel source, the diesel storage is expected to be suitable for an average of 12 hours of operation. For those generators that use diesel only, on-site storage was advised to be suitable for an expected 24 hours of operation on average. AEMO, 2023 Electricity Statement of Opportunities, p.82.
[11] Clean Energy Council, *Submission to 2024 Draft Integrated system plan*, p.8.
[12] Gilmore, J. Simshauser, P. *Solving for 'yy': demand shocks from Australia's gas turbine fleet*.
[13] AEMO, *Draft 2024 Integrated System Plan*, p.66.

A brief history of energy storage

This section provides a short summary of the current status of energy storage technologies in Australia and how ALDES will complement these established technologies.

Energy storage has always been a critical part of modern electricity systems. Hydroelectric power and PHES have been used since the late 19th century and provide a large portion of grid-scale electricity storage around the world.[14]

PHES has played a key role in Australia for over 50 years, with the Tumut 3 PHES, part of the Snowy Hydro Scheme, commencing operation in 1973. There are a number of significant new PHES projects in Australia, including the Snowy 2.0, Pioneer Burdekin and Borumba projects, all of which will make a major contribution to the security and reliability of the transition.

Lithium ion battery (LIB) technologies have emerged as a key complement to energy storage developments in the last decade. The high energy density, modularity, and speed of build out, as well as the relative abundance of lithium as an input material have made this technology central to the transition of many modern power systems.

One of the first utility scale LIB in Australia was the 100 megawatt (MW)/129 megawatt hour (MWh) Hornsdale Power Reserve. This asset was famously constructed in under 100 days and energised in late 2017. Since then, the battery has been upgraded to provide 150MW of power as well as grid forming capability.

LIBs continue to be adopted at pace in Australia. Some 32 LIB projects have been commissioned in the NEM totalling 1.6 GW, since the Hornsdale battery was commissioned.

The CEC's Quarterly Investment Report for Q4 2023 found that over 9 GWh of energy storage totalling $4.9 billion of investment reached financial close in 2023.[15] This level of uptake is likely to continue, as LIB costs reduce through manufacturing scale economies and sharp learning rates.

LIB assets play a key role in maintaining power system security and reliability. They can provide intra-day energy support, while also providing voltage and frequency control, system strength and inertia. LIB assets such as the Hornsdale Power Reserve and the Victorian Big Battery have also been used to provide System Protection Integrity Schemes (SIPS), which increase the transfer capacity and overall resilience of the power system.

As the rollout of LIB technology has continued in Australia, we have seen a key trend towards increasing energy durations and maximum rated power capacity of existing and future LIB assets.[16]

As shown in Figure 9 below, while 2 hours remains the predominant duration of most LIBs, there is a growing trend toward 4 hour durations. This reflects the changing retail and commercial load, as well as management of physical and economic curtailment, neither of which typically require durations in excess of 4 hours.

Another relevant trend is the increasing maximum power rating of LIB. From 2017 to 2022, maximum rated power capacity tended to be less than 200 MW. From 2022 onwards, these power ratings have begun to increase, with some projects sitting above 600MW and some new projects in development pushing as high as 1400 MW.

[14] International Hydropower Association, *The world's water battery*.
[15] Clean Energy Council, *Renewable Projects Quarterly Report Q4 2023*
[16] Duration describes the length of time the battery can export energy at its maximum rated power capacity – it is measured in MWh (or GWh for the largest batteries). Maximum rated power is a measure of the maximum possible instantaneous power output from the battery – it is measured in megawatts (MW). A battery can extend its duration by producing less than its maximum rated power capacity. For example, a 1000 MW battery might be able to operate for 2 hours at maximum rated capacity, producing 2 hours x 1000 MW = 2000 MWh. If it operates at half this max rated capacity, it can provide the same 2000 MWh over a 4 hour block, producing 4 hours x 500 MW = 2000 MWh.

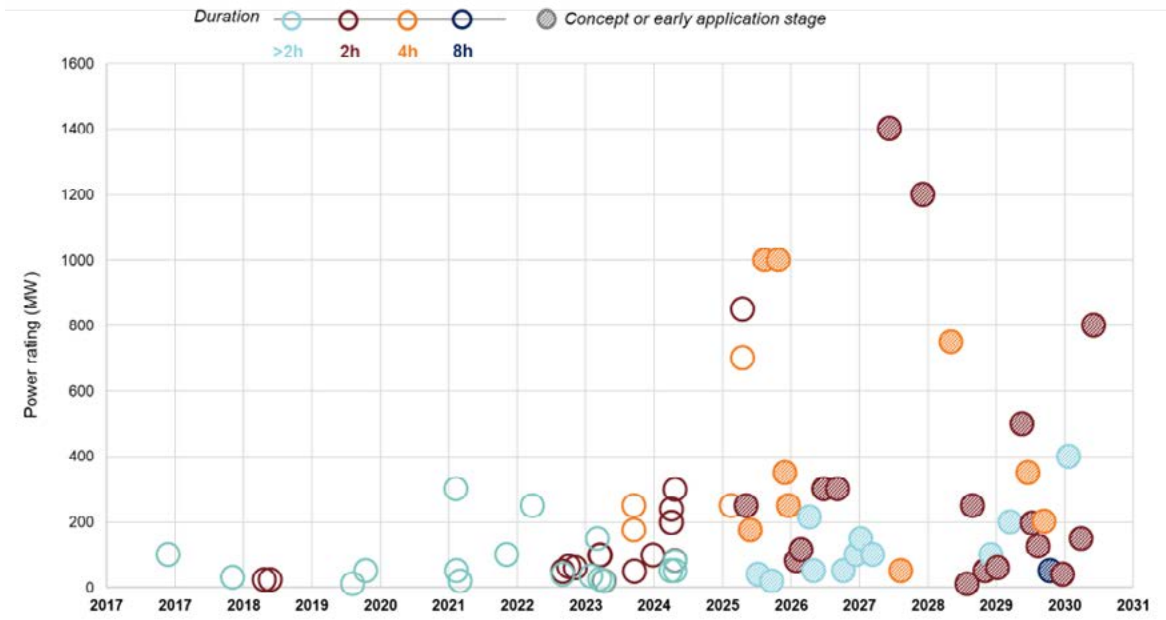


Figure 9: Duration and capacity of LIB assets

From 2025, multiple projects with high power ratings and longer durations have been announced or are in the early stages of development.

- The Lower Wanga Battery Storage project in Queensland, developed by SolarQ, which will combine a 350MW solar plant with 4,000 MWh battery energy storage.[17]
- The Collie Battery project in Western Australia, developed by Neoen. The project, which has development approval for a 1GW / 4GWh capability, will be build in 200 MW stages with the first stage expected to be completed in 2025.[18]
- The Limondale battery in NSW, developed by RWE, which will include a 50MW/400MWh battery. This project was the first to win a long duration storage LTESA in NSW.[19]

Beyond this, we expect to see continued growth in duration of LIB assets as cell costs decrease.

There is already evidence of this trend towards greater LIB durations, with Contemporary Amperex Technology Co. Limited (CATL) and Suncable announcing a potential LIB project of 16-hour duration[20]

LIB and PHES as part of a portfolio of storage solutions

LIB technology will play an essential role in the grid, as expressed in the Clean Energy Council's Batteries as the New Peaker report. As the electricity grid achieves higher variable renewable energy (VRE) penetration, LIB adoption will only continue to grow.

PHES will also play a central role in the future power system. As identified in the report, Hydropower: The backbone of a reliable renewable energy system, PHES can provide key system security and reliability services. PHES are also long lived assets that can support the grid for many decades at low cost of energy.

There are multiple examples of PHES projects being developed in the NEM, including the Snowy 2.0, Pioneer, Borumba, and Kidston. However, new PHES projects face challenges in project development. This reflects the specific risk profiles of these assets, including hydrologic and geologic risk, the cost of which needs to be accounted for in early stages of project development. As discussed in the final part of this paper, the CEC considers that urgent reform is needed to support investment in these critical long duration energy storage assets.

LIB technologies are currently the dominant short to mid duration storage technology.[21] The rapid uptake of LIB has been enabled by supply side factors, such as the development of mass manufacturing capability on the back of electric vehicle market development. This has supported wide scale deployment of the technology, with rapid learning rates and cost reductions.

On the demand side, market dynamics have converged towards 4 hour duration LIBs. Traditional peak demand periods, daily diurnal spreads, and ancillary service requirements are effectively met by 4 hour LIB assets. This is reflected in contract markets, where products

[17] Energy Storage News, *Giant 4,000MWh Li-ion battery storage facility proposed for 800MW PV farm in Queensland*
[18] More information available at www.colliebattery.com.au
[19] RWE, Limondale BESS
[20] RenewEconomy, *Quinbrook eyes 16-hour batteries for Sun Cable in massive storage deal with China's CATL*
[21] Denholm, Paul, Wesley Cole, and Nate Blair. 2023. *Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-85878.

around the 4 hour mark are being developed to manage evening peak requirements. These kinds of contracts are effectively backed by 4 hour LIB.

Put simply, there is currently little additional value to market participants from assets that can provide energy supply beyond the 4 hour mark.

As discussed earlier in this report, underlying system dynamics are rapidly changing and will create additional demand for longer energy duration. The deepening of diurnal demand spreads, coupled with the growing impact of seasonal shortfalls, will increase the requirement for additional energy supply, beyond the 4 hour duration mark. However, as discussed in Part 3 of this report, market signals are not yet present to reflect this developing system need.

It's not yet clear what combination of storage technologies will meet this increasing demand for energy at lowest overall cost. There are many relevant variables, but key amongst these are capital and input costs, asset lifespan, technological maturity and construction / siting concerns.

Figure 10 conceptually describes how these variables influence the 'energy capex' of a storage asset. Energy capex is the incremental capital cost associated with providing an additional unit of energy storage, in this case measured by hours of output.

The key point to note is that for longer energy duration requirements, the various forms of LDES are typically the lowest cost solution. This reflects the scale economies exhibited by many of these technologies. This suggests that at a certain energy duration point, LDES technologies will tend to become more cost competitive that LIB technologies.

However, there are multiple factors that influence where 'switchover point' between LIB and LDES occurs, which are reflected in Figure 10:

- The flatter cost curves associated with additional energy from LDES technologies reflect their strong scale efficiencies. These enable a lower incremental capital cost associated with additional energy storage. This is enabled by the relatively lower cost of increasing energy storage – such as installing bigger tanks for redox flow batteries, larger caverns for compressed air or more thermal storage medium for thermal energy storage.
- The point of intersection with the Y-axis reflects the relative capital costs of the two asset classes. Due to technological maturity and reductions in input costs, LIB assets tend to have lower upfront capital costs. LDES may also face higher siting and construction costs, which tend to increase capital costs.
- The steepness and relative position of both curves can vary, depending on the multiple factors mentioned above. For example, decreases in the cost of critical input materials such as lithium carbonate / hydroxide for LIB, or vanadium pentoxide for RFB, will tend to lower and flatten the respective curves.
- Finally, the point of intersection of the two curves occurs across a range. Currently, reflecting decreases in LIB input costs and relative maturity, the point of intersection is likely somewhere around the 8 hour mark. However, changes across the multiple variables discussed above, such as input costs and learning rates, will tend to move these points of intersection over time.

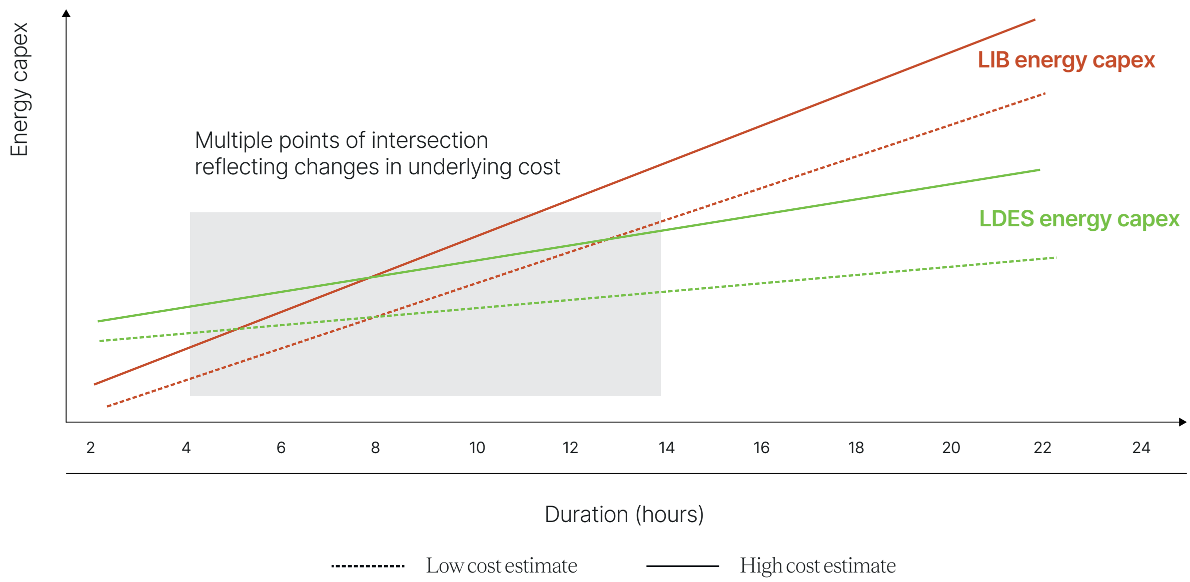


Figure 10: Energy capex for LIB and LDES over different durations.[22]

[22] Source: Long Duration Energy Storage

None of the above should be read as a forecast as to which technology class will tend to predominate. The multiple variables that influence these cost curves will change over time, as will system and market demands.

However, it appears likely that, as system demand for longer duration energy supply increases, under most scenarios LDES will have a complementary role to play with LIB.

ALDES in the Australian energy transition

This report considers three of the main technology families of ALDES, with specific examples from each:[23]

Mechanical storage: focussing on **adiabatic compressed air energy storage**

Electrochemical storage: focusing on **redox flow** and **hybrid flow batteries**

Thermal storage: focusing on **concentrated solar power** and **miscibility gap alloy**

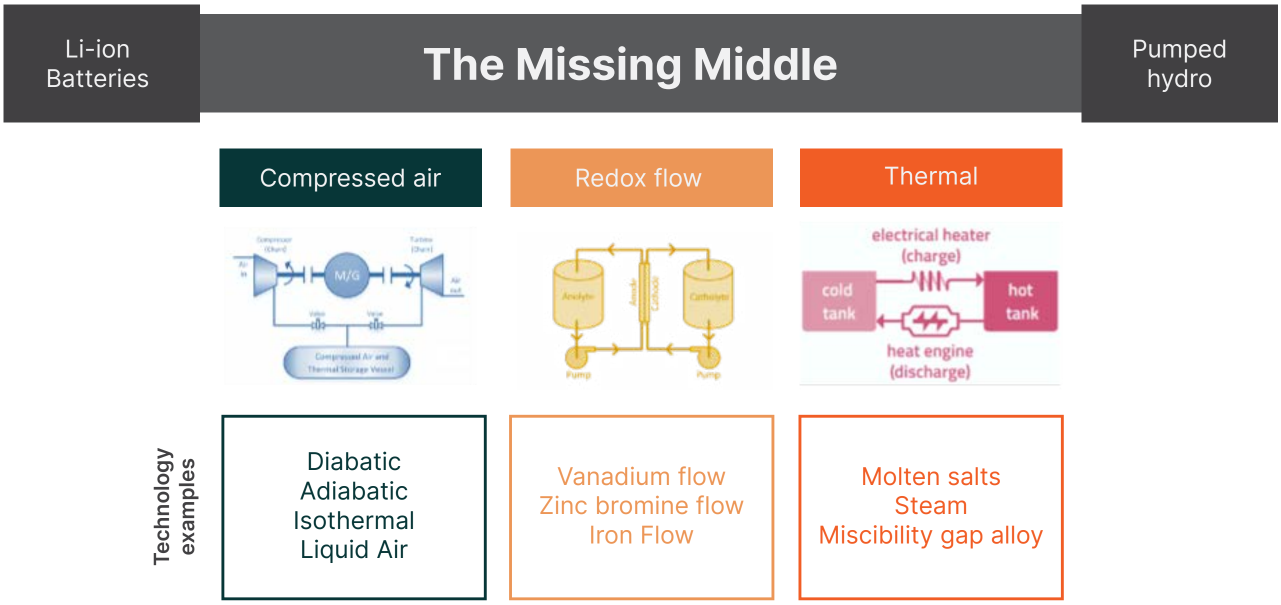


Figure 11: The missing middle

[23] The CEC acknowledges the detailed analysis already undertaken by the CSIRO in its Renewable Energy Storage Roadmap, which has informed this paper. See: CSIRO, Renewable Energy Storage Roadmap, 2023.

These ALDES types are briefly described below.

ALDES type	Description	Examples
Compressed air	• Utilises air under pressure to drive a traditional synchronous turbine generator. • Storage medium may include liquified air in tanks, or compressed air in underground caverns utilising water to maintain pressure • Heat capture and storage needed to ensure efficient operation.	Silver city, Broken Hill
Redox flow	• Flow batteries utilise a liquid that exists in two different charge states. Power is produced as electrons are exchanged between the two liquids. • A traditional flow battery generates power through electron exchange between ions of different charge states in a single liquid electrolyte medium.[24] Hybrid flow batteries may use different electrolytes and may involve a deposition reaction to create power. • Inverter connected, may utilise grid forming capability • Many different solutions exist, utilising a range of different chemical media.	Spencer Energy project
Thermal storage	• Utilises the ability of various substances to store heat, either in a liquid, a solid or in a substance that shifts between different phase states • Heat is used to drive a traditional synchronous turbine generator. May utilise steam, or other liquid to drive turbine. • May be integrated with industrial processes that make direct use of steam or heat in the asset.	Carwarp project

ALDES characteristics

Each ALDES energy storage technology demonstrates different characteristics, such as relative energy density, safety, durability, cyclability, cost, and other variables.

Modern power systems can utilise these different characteristics to meet different power system needs.

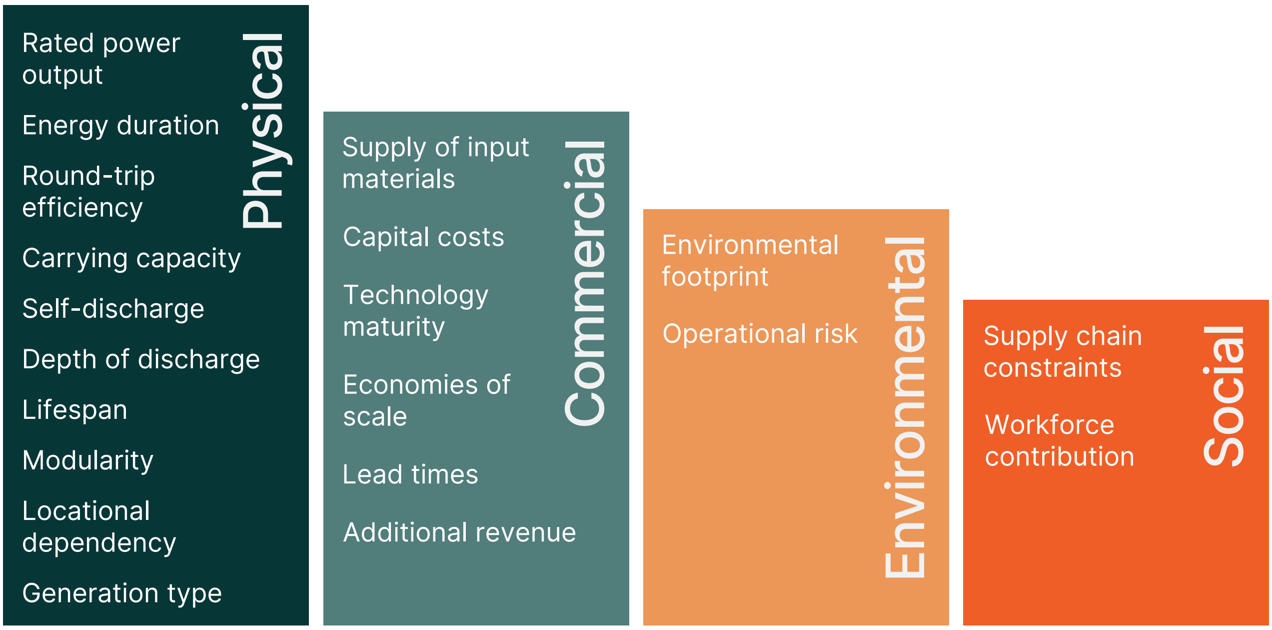


Figure 12: Physical, Commercial and Enviro/Social Characteristics of ALDES

[24] Traditional flow energy storage systems are only loosely termed batteries, as they generate current through direct, heterogenous electron transfer from a liquid to a solid state cathode. This is different to a more traditional battery, such as a LIB, which exploit the chemical characteristic of intercalation. More information can be found here: *Flow Battery - an overview* | ScienceDirect Topics

Table 1: Key characteristics of ALDES storage

Characteristic	Description	Physical implications for the power system
Physical functions		
Rated power output (MW)	The maximum instantaneous power out of the asset, measured in megawatts	A high power rating is useful to meet short, sharp requirements for active power, such as to manage the unexpected trip of a large generator or transmission line. Power ratings also contribute to providing a diurnal firming service such as needed to manage daily VRE spreads.
Energy duration (MWh)	The maximum amount of time an asset can discharge at its rated power output.	Longer energy durations lend themselves to maintaining reliability in a changing power system. In particular, the increasing likelihood of renewables droughts and seasonal shortfalls gives rise to the need for longer durations to meet demand when VRE output is lower than normal for a prolonged period.
Round-trip efficiency	The ratio of energy output to energy input	High RTE means a higher ratio of volumes of MW input in the asset, vs MW output. This is one of the key measures of asset efficiency / cost and is one of the reasons why LIB assets – which have a very high RTE – are currently the dominant storage technology.
Carrying capacity (h / d / m)	The nominal amount of time that material volumes of energy can be stored in an asset, without material decay in the volume of energy stored.	Carrying capacity will be increasingly helpful in maintaining reliability in the face of seasonal supply shortfalls. For example, some ALDES can carry significant volumes of energy for months at a time, allowing them to charge during in high VRE seasons, and discharge months late when VRE supply is lower. Carrying capacity also underpins the ability of an ALDES to provide a reliability network support service, as a permanent energy supply backup to cover the risk of a network outage.
Self-discharge	The rate at which energy is lost when held in the relevant storage medium, through either leakage - such as heat loss or leakage of compressed air - or through supply to auxiliary plant, such as cooling systems and pumps.	The rate of self discharge is key to the asset's carrying capacity.
Depth of discharge (%)	The ratio of the available energy to be discharged, to the total nameplate capacity (MW) of the system.	Close to 100% Depth of Discharge means an asset can provide more power and energy, increasing its overall value to the power system.
Cycling capability	The total number of charge-discharge cycles that an asset can deliver over its lifespan	ALDES assets with high cycling capability – ie, able to undertake many charge / discharge cycles without materially shortening their lifespan – will be particularly effective in managing diurnal demand spreads, by providing capability to manage daily ramps.
Lifespan	The expected total operational life of an asset, at minimum requirements for utility scale operation.	Assets with longer lifespans reduce total system capex and help to reduce waste otherwise associated with end of life asset replacement.
Modularity	The ability to incrementally expand the asset to increase rated power and/or energy duration	Modular systems can be relatively easily expanded and modified to meet changing system needs.

Locational dependency	The extent to which an asset has specific geographic requirements to enable operation, such as particular geological or hydrological requirements. The total footprint of the asset is also relevant here, as different land use limitations will apply in urban vs regional areas. Also affected by issues around thermal or chemical safety of input materials.	Locational requirements may limit technology choice in some situations. For example, ACAES or large LIB assets will probably not be appropriate for urban locations, while a redox flow asset may be appropriate. Conversely, the power and energy capabilities of larger ALDES, such as ACAES or thermal assets, make them more appropriate for location on the high voltage network outside of urban areas.
Generation type	How the asset produces electricity when in discharge mode. This is either through: • Electrochemical processes that generate a direct current which is then converted to alternating current through an inverter (non-synchronous generation), or • Mechanical or thermal processes that are used to operate a turbine to directly produce alternating current (synchronous generation)	These two generation types – synchronous and non-synchronous – each bring unique characteristics to the power system. This is relevant to their ability to provide specific services such as inertia, system strength, frequency control and voltage regulation.
Commercial functions		
Supply of input materials	The ease of accessing key input materials to build the energy storage facility. For example, access to lithium carbonate for LIB, or vanadium pentoxide for redox flow batteries.	Any supply chain limitations on input materials will impact cost, whether due to upfront costs or risks of future supply chain interruptions.
Capital cost ($/kWh)	The capital cost per unit of energy of the energy storage facility. This describes the entire capital cost of the asset, including the storage unit itself as well as the balance of plant needed to deliver energy. This is a simpler measure than measures such as levelized cost of energy, however as capital cost is the primary component of many ALDES it is the most relevant here.	Capital cost underpins investment in ALDES.
Technology maturity	The development of a technology along the commercial readiness index.	Technological maturity is a key factor in investment decision making. More 'mature technologies' – those with major utility scale projects or established pilots – are considered less risky and are more appealing to investors.
Economies of scale	The ability to add additional energy duration capability at a relatively lower marginal cost.	The specific application of scale economies here relates to the ability to expand energy duration capability at a relatively low incremental (marginal) cost. ALDES tend to display smaller marginal costs of additional energy duration capability, reflecting the scale economies associated with many of these forms of technologies.
Lead times	The time it takes to build the energy storage facility, including passing all planning, approval, construction and commissioning stages.	Technologies with shorter construction times can get to market faster and may therefore be advantaged over other technologies.

Additional revenue	Revenue from services other than energy arbitrage. This includes power system related revenue streams, such as frequency and voltage control, system strength / inertia and system integrity protection schemes (SIPS). Other non-power system sources of revenue include the provision of direct heat for industrial purposes.	Availability of additional revenue streams will reduce the overall investment cost of the asset.

Environmental and social factors

Supply chain considerations	Supply chain issues ranging from environmental impacts of key input material production, social and geopolitical issues (such as modern slavery risks or production in hostile nations) and workforce availability	Any of these listed issues can have material impacts on project risk and cost of capital. More generally, projects that are less exposed to environmental, social or geopolitical supply chain risks are in turn less exposed to risk of breaching ESG requirements. Technologies that are less dependent on critical minerals produced overseas are also less exposed to future interruptions in international supply chains, such as those associated with pandemic and war.
Environmental footprint	The use of land, water and chemicals as well as the ease of recycling at the end of a project's life	Use of land and general environmental impact of a project will impact on planning approvals for the project as well as choice of location. Consideration of end of life processes is also becoming increasingly more important as concepts such as the circular economy and preservation of mineral reserves become prevalent.
Operational risks	Different storage technologies utilise various processes and chemistries that have different associated risk profiles during operation.	Technologies with reduced operational risks may face reduced planning and locational issues, directly impacting investment costs.
Workforce contribution	The ability of energy storage projects to positively contribute to the local economy by employing tradespeople and other professionals	Projects that have a beneficial workforce contribution will gain wider support from policy makers regional / state government.

Other emerging ALDES technologies

In this report we have focussed on three candidate ALDES families. This is in part due to the specific applicability of those technologies given Australian power system needs, as well as their relative commercial and technological maturity.

However, there are many emerging ALDES technologies that may become predominant in future years. Here is a brief overview of some of these technologies, recognising that this is not an exhaustive list.

Sodium-ion batteries (SiBs)

SiBs are a promising technology with advantages related to high rated power, fire safety, sustainability, long lifecycle, cobalt-free cathode chemistry and cost-effectiveness. Input material abundance may be another positive element, with some estimates stating input costs of up to 30 times less than LIBs .

Several companies have invested in R&D, including the largest battery manufacturer, Contemporary Amperex Technology Co. Limited (CATL). A demonstration project by technology provider Great Power of 5MW / 10 MWh has begun in Qingdao, China and will be the first application for grid-connected energy storage.[25]

Metal-air batteries

Metal-air batteries provide energy through spontaneous oxidation of the metal that serves as a negative electrode, with the positive electrode taking oxygen from the air. Metal-air batteries are being investigated due to low material costs, high energy density, relatively simple cell designs and inherent battery safety. Typical metals studied include lithium-air, iron-air, zinc-air, and aluminium-air batteries.

One of the more advanced technologies are iron-air and zinc-air. Zinc-air batteries have faced some difficulties in reaching high specific energy; however, new generations are showing promise. Iron-air batteries have also been under development, and Form Energy have closed the largest deal, to provide Georgia Power with 15 MW / 1,500 MWh (100 hours) energy storage system.[26] Form energy is also building the first commercial scale battery manufacturing facility in West Virginia.

Gravity energy storage

Gravity energy storage utilises gravitational potential energy by lifting and lowering a heavy mass using a pump, crane, or motor.

An example of gravity energy storage is being pioneered by Energy Vault, with the first large-scale system being developed in China. The 100 MWh system is being built to augment and balance the national grid.[27] Some of the benefits of the system include long storage durations of up to 18 hours with a 80-90% RTE, durability through the materials used to fabricate the storage blocks, with an expected lifespan of between 35 – 50 years, utilising locally sourced materials.[28]

The technology can also repurpose mines by utilising deep shafts to suspend the weight. In Australia, Green Gravity has announced a project a project in collaboration with GHD and coal miner Yancoal to repurpose a mine shaft to construct the tower needed for gravity energy storage.[29]

[25] Energy Storage News, *'World First' grid scale sodium ion battery project launched in China.*
[26] Form Energy, *Form Energy, Georgia Power Continue Forward with 15 Megawatt Iron Air Battery.*
[27] Kennedy, R., PV Magazine, 2023, *Energy Vault completes 25 MW/100MWh gravity-based storage facility in China.*
[28] Roushenas, R., et.al., 2024, *"Improved marketing strategy of a hybrid renewable plant integrated with gravitational energy storage" Techno-economic analysis and multi-objective optimisation*, Journal of Energy Storage, Vol 78, pp 109991.
[29] Neiman, J., EE Power, 2024, *Gravity energy storage systems: transforming defunct mines into efficient energy producers.*

Liquid air energy storage (LAES)

LAES is a thermo-mechanical storage solution where electricity is stored as liquid air (or nitrogen) at extremely low temperatures. Operation of LAES produces hot (during charging) and cold (during discharging) streams that can be harnessed and reused within the process to improve energy efficiency.

Advantages include high energy density (50 – 200 Wh/L), sustained discharging for 2 to 12 hours, and location flexibility as all infrastructure is above ground level. LAES is capable of covering multiple electricity services: energy arbitrage, peak shaving, ancillary services, reactive power and voltage control, uninterrupted power, energy management, and waste heat / cold recovery.[30]

The technology is in early stages of development by British company Highview Power, deploying a 400 MWh facility in Vermont, USA, a 250 MWh facility in northern UK, and several 300 MWh facilities in Spain[31]. In Australia, Highview Power is targeting six projects in Northern Territory, with development planning on two projects underway[32], including a 90 MW / 1170 MWh on the Kathrine-Darwin grid and a 22 MW / 308 MWh at the Owen Springs Power Station outside Alice Springs.

Hydrogen energy storage

Hydrogen can be stored in three ways: as a gas under high pressure, in a liquid under extremely low temperatures, and on the surface of or within solid and liquid materials. The main advantage of hydrogen energy storage is the ability to provide seasonal energy storage, it does not degrade over time, and it offers versatility for industry, energy storage, and transport applications.

Hydrogen has the potential to be a game-changer in the global energy landscape with additional applications in heating and cooling, backup power, portable power, marine and aviation propulsion fuel, material processing, chemical processing, and food processing. However, currently producing and storing hydrogen is expensive, there is a lack of adequate infrastructure and overall energy density and RTE is low.[33]

The first large scale project using underground hydrogen energy storage has gone into operation in Austria, corresponding to 4.2 GWh that will shift energy from the summer months to the winter months. The demonstration plant will convert solar energy into green hydrogen by water electrolysis and store hydrogen in a porous underground reservoir and will also produce heat as a cogeneration facility.[34]

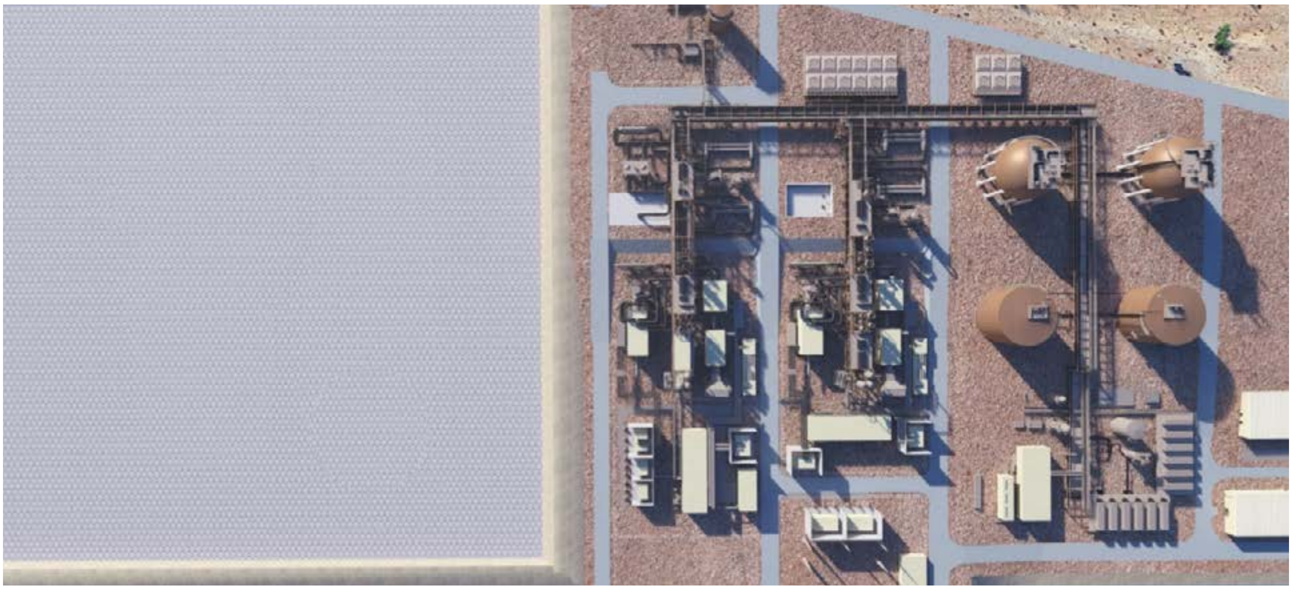
[30] Borri E., et. al., 2021, a review on liquid air energy storage, History, state of the art and recent developments, Renewable and Sustainable Energy Reviews, Vol 137, page 110572, https://doi.org/10.1016/j.rser.2020.110572
[31] Bellini, E., PV Magazine, 2021, A closer look at liquid air energy storage, www.pv-magazine.com
[32] Highview Power, International projects - Australia
[33] Hassan, Q., et.al., 2023, Hydrogen energy future, Advancements in storage technologies and implications for sustainability, Journal of Energy Storage, Vol 72, Part B, page 108404, https://doi.org/10.1016/j.est.2023.108404
[34] Matalucci, S., PV Magazine, 2023, The Hydrogen Steam: rising demand driving blue hydrogen plans, www.pv-magazine.com

Compressed Air Energy Storage

This section explores the first of our focus ALDES technologies, Compressed Air Energy Storage (CAES).

CAES is a relatively proven storage technology that can provide both high rated power output, sustained energy duration and multiple synchronous grid services. It is well placed to complement PHES as a key source of both system security and reliability services.

CAES uses electricity to compress air which is then stored in a reservoir (charging), before being released to run a turbine (discharging). Storage reservoirs include underground salt caverns, disused mines, expired oil and gas wells, new man-made caverns or above ground containers.



Source: Hydrostor

At a glance: Compressed Air Energy Storage key characteristics

Characteristic	Capability of technology type
Rated power output (MW)	200MW to 500MW. Based on current projects in development.
Energy Duration	8 to 12 hours. Based on current projects, easily scalable well beyond 12+ hours.
Round trip efficiency (%)	40% to 80%. This is affected by efficiency of turbine, as well as effectiveness of heat capture and reuse equipment.[35]
Carrying capability + self discharge	Capable of carrying large volumes of energy for many months with minimal to no self-discharge.
Cycling capability	High, with very little degradation to plant from repeat cycling.[36]
Lifespan	Long lived assets, up to 60 years or longer.[37]
Locational dependency	Moderate. Can be based on existing mine sites so dependent on availability of sites. Alternatively may require new caverns to be bored, so dependent on geology and social license issues.
Generation type	Synchronous. Able to provide all synchronous services when generating, with option to fit clutch to turbine to allow for operation in synchronous condenser mode when not discharging.

[35] Dooner, M. and Wang, J., 2020, Compressed-air energy storage, in Future Energy (Third Edition), page 281, Table 14.1, https://doi.org/10.1016/B978-0-08-102886-5.00014-1
[36] Ibid.
[37] Ibid.

Supply of input materials	Zero to low risk. The only supply dependency is in construction based around sourcing turbines, pumps and heat exchangers, all of which are standard and easily accessible equipment.
Capital cost	US$120 - $280/kWh, reducing with larger sized assets and effective heat capture and storage.
Construction lead times	Construction involves typical earth works, most of the time is designated to creating the underground cavern. Estimated at 2-3 years.[38]
Environmental, social and geopolitical considerations	Minor to Moderate. Asset has a relatively small above ground footprint and also requires some water in a closed loop system. No significant social or environmental issues identified with supply chain.
Commercial maturity	Multiple projects across the world of different size, totalling 15 projects.[39] Among them Zhongyan Jintan, China, 60MW/300MWh[40] Goderich, Ontario Canada, 2.2MW/10MWh[41], ADELE, Germany, 200MW/1GWh[42]

Technology summary

CAES is well placed to help manage system reliability:

CAES has the capability to provide both significant max rated power as well as long energy duration. With the capability to harness material scale economies, CAES is particularly well positioned to address current and emerging reliability challenges.

The rated power capability of CAES is determined by the size of turbine installed. Utilising standardised open cycle turbines, CAES projects can deliver significant volumes of instantaneous power, equivalent to that provided by traditional open cycle gas turbines. This means they can provide equivalent peaking and ramping services to traditional gas turbines. It also means there may be some start up time limitations associated with CAES, in a similar vein to gas turbines.

The energy duration capability of a CAES asset is determined by the size of this reservoir. CAES projects that are based on new man-made caverns bored into porous rock can expand the size of these caverns at a relatively low additional capital cost. These projects can therefore deliver marked increases in energy duration capability at a low additional marginal cost.

CAES projects also demonstrate good energy carrying capabilities. Once air is compressed and stored in a reservoir, there is little in the way of self discharge, whether through leakage or powering auxiliary loads. This means that CAES facilities are well placed to carry large volumes of energy over long periods of time, with very little in the way of energy losses incurred in that time.

These key capabilities of duration and carrying capability means CAES is well positioned to manage emerging reliability risks, particularly seasonal energy shortfalls. These capabilities also mean CAES can provide reliability services as an alternative to building additional network, markedly reducing total system costs – this is discussed in more detail below.

CAES is also well placed to support system security and operability:

CAES typically utilise synchronous turbine generators when discharging. This enables it to provide synchronous services such as inertia, system strength and voltage regulation.

System strength itself consists of two key components: provision of fault current as well as management of inverter interactions. As a synchronous generator, CAES can provide both services. CAES also bring the added benefit of being able to provide energy, which other sources of system strength, such as a synchronous condenser, cannot.[43]

By providing system strength, CAES are well placed to support the overall 'hosting capacity' of the network. Hosting capacity is basically ensuring the maximum possible volumes of renewables can be connected and can operate stably on the power system. As a good source of system strength and power system stability, CAES can markedly increase this hosting capacity.

AEMO has also identified that it requires additional synchronous generation operationally, to assist in transitioning the power system away from reliance on existing sources of synchronous generation, particularly coal generators.[44] CAES can assist in this transition

[38] IRENA, 2020, Electricity storage valuation framework: Assessing system value and ensuring project viability, page 31, Figure 13, www.irena.org
[39] Latest information from Bloomberg New Energy Finance, Storage data hub – Storage Assets: data on commissioned compressed air energy storage projects with a total energy capacity of 6.8GWh. There are 9 commissioned projects over 30 MW. www.about.bnef.com
[40] Bellini, E., PV Magazine, 2022, China's first salt cavern for compressed air energy storage goes online, www.pv-magazine.com
[41] Hydrostor project operational since 2019, Goderich Energy Storage Centre - Hydrostor
[42] Zunft, S. et.al., 2017, Electricity storage with adiabatic compressed air energy storage: Results of the BMWi-project ADELE-ING, International ETG Congress 2017, Bonn, page 1-5, ADELE - ADIABATIC COMPRESSED-AIR ENERGY STORAGE FOR ELECTRICITY SUPPLY - RWE Power (readkong.com)
[43] Synchronous condensers are effectively large spinning loads on the system that provide inertia, system strength and, in some instances, voltage regulation. However, as loads, they do not provide power to the system.
[44] AEMC, Improving security frameworks for the energy transition, Rule determination, 28 March 2024, p.4.

process, by supplying some of the operational capabilities currently provided by coal generators.

Finally, the significant power and energy capability of CAES means it can provide black start capability. Black start capability enables the power system to be re-energised if there is a major blackout and is often sourced from gas or coal generation. CAES are ideal candidates to offer black start capability, as they are easy to energise from a 'cold start', have significant power and energy reserves and are capable of providing reactive power support to stabilise voltages during a restoration.

Capital cost, asset lifetime and locational complexities:

One of the key advantages of CAES is the lifetime of the asset. CAES assets have a very long lifespan, potentially in a range comparable to PHES. This means total costs are much lower than for those assets where significant asset replacements are required every 15 years or so.

However, this long timespan does require material upfront capital expenditure. The magnitude of this capital cost is dependent on two key factors.

Firstly, the reliance on underground storage reservoirs has capital cost implications. The use of existing sites – such as disused oil wells or salt cavers – can reduce costs however costs will increase if developers need to bore new reservoirs. This is also subject to some of the same geological risks as PHES – ie, the risk of hitting harder than expected rock when boring – although this is minimised by the smaller scale of boring for a greenfields CAES.

Secondly, capital costs and overall round trip efficiency (RTE) of CAES is affected by the required balance of plant. In particular, the compression and decompression cycles involved in the CAES process requires management of heat and cooling – cooling is needed to counter the heat from air compression and heating is needed to counter the cooling effect of decompression.

In traditional forms of CAES, this heating and cooling has been enabled by the combustion of methane gas, markedly increasing capital and operational costs. More modern forms of CAES – such as Adiabatic CAES (A-CAES) – utilise lower cost solutions to manage these issues.

ACAES comprises of four key sub-systems: compression, air storage, heat regeneration and turbine generation. The benefit of this process is that thermal energy from the compression cycle is stored and re-used during decompression. This helps to reduce capital and operational costs.

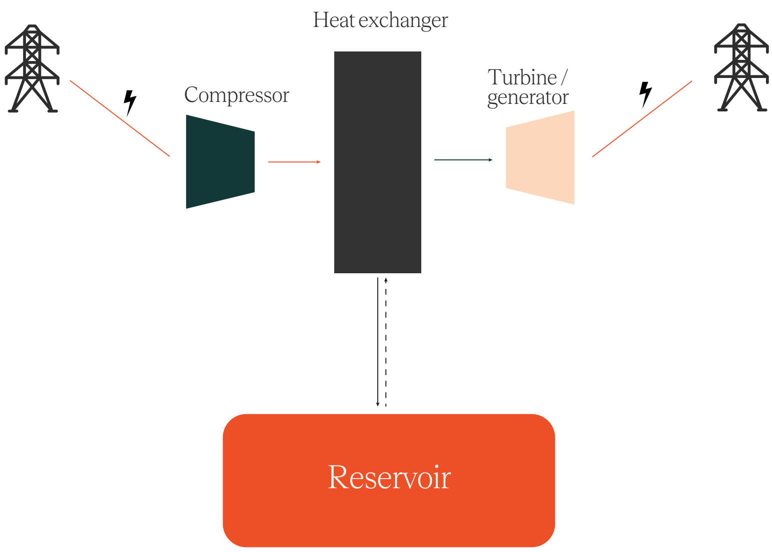


Figure 13: Adiabatic Compressed air heat exchanger

During charging / compression, heat generated is stored in a medium such as water. During discharge / expansion, this stored heat energy is used to raise the temperature of the decompressing air, increasing the efficiency of the overall system.

This process markedly increases the overall efficiency of A-CAES, relative to other forms of CAES. A-CAES have been known to reach round trip efficiencies of up to 70 per cent.

CAES is not affected by many of the social and environmental issues that affect other forms of ALDES. Building the asset does not require critical minerals and employs a simple engineering layout using technologies that are well understood (turbines, pumps, and heat transfer fluid). However, some models of CAES are dependent on water availability, where water is used as the heat transfer medium as well as to maintain air pressure on underground reservoirs.

CAES projects are also affected bound by locational factors. These are primarily related to the required underground storage reservoirs, which traditionally have been built in disused mines, salt caverns or oil wells. Similarly, required above ground assets, as well as construction processes, means CAES is more likely going to be built outside or urban areas.

Technology Feature: Hydrostor

Hydrostor is a Canadian company founded in 2010. Its proprietary A-CAES is a mature technology fit for utility-scale applications that provides LDES at a competitive cost of energy, while supporting the grid through synchronous energy generation.

Hydrostor has improved the conventional gas powered CAES resulting in higher RTE. The technology incorporates a thermal reservoir where heat is stored for later use to expand the air in the discharge cycle and a water reservoir to displace air in the cavern with a close water loop.

Land and water footprint are small. In the dry Australian environment context, water use is particularly important as most abundant renewable energy resources are in regional and dry parts of the country.

Hydrostor's A-CAES has siting flexibility as the air cavern can be build in hard rock, which are more prevalent than salt deposits. Disused mining sites can also be repurposed, with the advantage of utilising existing underground infrastructure.

The optimum markets for Hydrostor are those with a high penetration of renewable energy generation, gas replacement policies, and the need to deliver dispatchable and reliable bulk energy to the grid. The revenue stack comprises energy arbitrage, frequency control and reliability services, as well as back-up power.

Projects

Hydrostor has two large projects close to financial close: one in California, USA delivering a 500 MW / 4000 MWh and one in Australia.

The Australian project is a 200 MW / 1,600 MWh utility-scale A-CAES facility, the Silver City Energy Storage Centre, located in Broken Hill, New South Wales. Several elements make this project highly relevant in the context of the NEM:

- Broken Hill is located in a weak part of the grid and the project will provide 250 MWh back-up power in the event of a transmission outage
- Hydrostor and Transgrid have entered into a reliability contract that will replace existing end-of-life diesel-fired generators
- It is the first large-scale, LDES project in Australia to be selected as a preferred solution through a regulatory investment test for transmission (RIT-T)
- The project has also won a long duration long term energy service agreement (LTESA) from the NSW government, recognising its value and contribution to reliability

These regulatory arrangements highlight the key role of LDES in supporting efficient network build out and maintaining reliability of supply for customers.

The facility will enable greater penetration and utilisation of renewables into the region, defer costly network infrastructure investment and provide a reliable source of system strength and inertia.

The project will unlock economic benefits to the region by leveraging existing local resources, creating sustained employment, and re-purposing redundant infrastructure. During the construction period, the project will create 780 full-time jobs and once completed 70 ongoing jobs. The project has setup community benefit schemes that will redirect funds back into the community, especially addressing the needs of the miners in the area.

Source: Hydrostor

Redox flow batteries

Redox Flow batteries (RFBs) utilise one or more liquids to store and generate power. Although not yet a widely established energy storage solution, the technology itself has been around for many years. Notably, the vanadium redox flow battery was actually invented in Australia in the 1980s by Dr Maria Skyllas-Kazacos, but is only today emerging as a key energy storage contender.[45]

The technology family of RFBs includes multiple subclasses of technology which utilise different electro-chemistries. The two main subclasses explored in this section include Vanadium and Zinc bromine batteries. We then discuss some of the emerging variants within this technology family.

Technology summary

RFBs generate a current by pumping two electrolytes through a set of cells, separated by a membrane – known as the stack - where ion / electron exchange occurs.[46]

[45] ATSE, The accidental engineer who invented the vanadium sustainable battery, Feb 2020. Available at www.atse.org.au
[46] While described as a 'battery', RFPs are not quite the same as a traditional LIB battery - energy is stored in the two electrolytes, instead of the electrode material as in the case of LIBs.

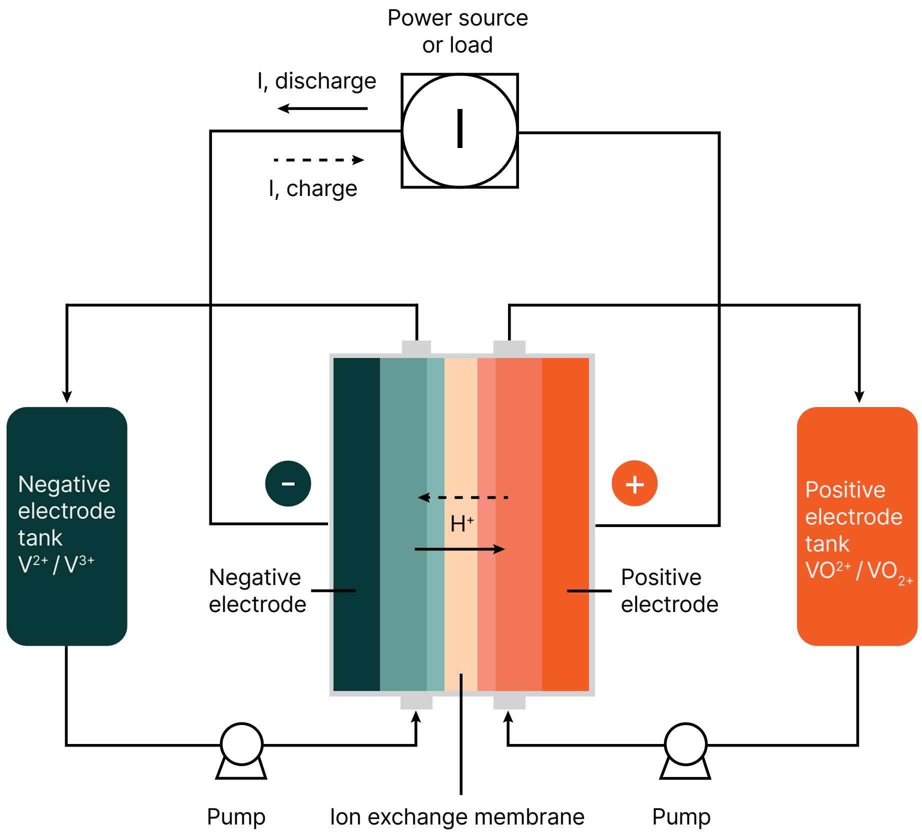


Figure 14: A typical 'pure' redox flow battery[47]

Source: Comsol.com

RFBs are based on the chemical process known as reduction / oxidation, or redox, which is the exchange of electrons between ions.[48] Discharging an RFB involves ions in the positive tank exchanging an electron with ions in the negative tank, to generate a current. Charging reverses this process, with an external current applied to 'pump' the electrons back to the liquid in the negative tank.

Rated power output of an RFP depends on the size of the stack, while energy duration capability depends on tank dimension, or the quantity of stored electrolyte. RFBs have relatively long asset lifespans and support a relatively large number of charge and discharge cycles.

RFBs are characterised by a clear separation of rated power output and energy duration capability. When coupled with other characteristics such as short response time, high cycling capabilities, low degradation rates and modular design, they show significant potential as part of the future NEM energy storage portfolio.[49]

Development of RFBs was prompted by concerns over availability of critical input minerals to build LIBs, on the basis that cobalt, lithium, manganese and nickel prices may be subject to volatility. Many redox couples utilised in RFBs use earth abundant metals or organic materials, reducing this dependency – although as noted below, this is not always the case.

There are many types of RFB, but they can broadly broken down into 'pure' and 'hybrid' types: [50]

Pure flow batteries are based on fluid electrolytes with no deposition of metal, utilising chemistries including vanadium, hydrogen-bromine and polymer-based materials,

Hybrid flow batteries often incorporate some solid metal deposition and utilise chemistries including zinc-bromine, all-iron, all-zinc, all-copper and metal air.

Vanadium redox flow batteries

Vanadium redox flow batteries (VRFBs) are probably the best known pure RFB technology. Having been developed in Australia, the chemistry and range of capability of this technology type makes it a unique fit to meet Australian power system needs.

[47] Fairclough C, Comsol Blog: Advancing Vanadium Redox Flow Batteries with Modeling, December 2017. Available at: www.comsol.com.
[48] An ion is an atom with an imbalance between its constituent protons and electrons – more electrons relative to protons creates a negative ion, fewer electrons to protons creates a positive ion.
[49] Sanchez-Díez, E., Ventosa, E., Guarnieri, M., Trovo, A., Flox, C., Marcilla, R., . . . Ferret, R. (2021). Redox flow batteries: Status and perspective towards sustainable stationary energy storage. Journal of Power Sources, 481, 228804. Retrieved from https://doi.org/10.1016/j.jpowsour.2020.228804
[50] Pure flow batteries store energy in the 2 liquid electrolytes, whereas a hybrid flow battery stores in a liquid electrolyte but with deposition of a metal solid – ie, Zinc cations are deposited as Zinc metal.

At a glance: Vanadium Redox Flow Batteries

Characteristic	Capability of technology
Rated power output	10 MW to 100 MW. Based on existing projects and projects in development.
Energy duration	8 to 12 hours, depending on tank size. Existing assets range from 60MWh to 400MWh.[51] VRFBs can scale easily to provide additional energy as this is largely dependent on increasing tank size / electrolyte volume.
Round trip efficiency	60% – 85%. Moderate to high RTE, dictated by the cell voltage of the chemistry, the pumping layout and shunt current.
Carrying capability + self discharge	High – weeks to months. Once pumps circulating electrolytes are turned off, there is minimal power degradation and minimal auxiliary load.
Cycling capability	15,000 – 20,000.[52] One of the strong features of the battery which allows it to be ramped up and down frequently. We understand that cyclability is not limited by a specific number in existing warranties.
Lifespan	25 + years. Lifespan of asset is largely determined by balance of plant equipment such as pumps.
Locational dependency	Low. Low toxicity of materials, zero fire risks and relatively small footprint means VRFBs are suitable for location in all areas, including urban locations. Standard chemical handling and storage industrial safety protocols apply
Generation type	Inverter connected, non-synchronous. Quick power injection capability enables provision of frequency and voltage control, however requires grid forming inverter to provide other services.
Supply of input materials	Potentially problematic. The price of vanadium pentoxide, the main input material for VRFBs, has been subject to marked volatility. However, developments of Australian supply chains may moderate this impact.
Capital cost	US$640 - US$ 1,100/kWh.[53] These costs reflect capex as well as quantity of electrolyte needed – ie, duration of the battery.
Construction lead times	1 year. Relatively quick installation for many types of modular VRFB, as modules come assembled and most of the construction involves installation of pipes / pumps. Larger, bespoke units may take longer.
Social and geopolitical considerations	The bulk of raw vanadium is currently produced in Russia, South Africa and China, while the majority of vanadium pentoxide is produced in India, the United States, Japan and China, somewhat ameliorating geopolitical supply chain risk.
Recyclability	Recyclability of vanadium pentoxide is relatively easy, reducing the final environmental impact of VRFBs.
Workforce contribution	Requires trained workforce in research and development, deployment, and project management. Once operational, several dozen on-going jobs will be needed. Hundreds more would be created through a local vanadium supply chain.[54]

[51] PV Magazine, China connects world's largest redox flow battery system to grid, September 2022. Available at: www.pv-magazine.com
[52] Sanchez-Díez, E., et.al., 2021, Redox flow batteries: Status and perspective towards sustainable stationary energy storage, Journal of Power Sources, Vol 481, 228804. Page 5, https://doi.org/10.1016/j.jpowsour.2020.228804; AND
Jiang, H.R., et.al., 2020, A high power density and long cycle life vanadium redox flow battery, Energy Strorage Materials, Vol 24, pages 529-540, https://doi.org/10.1016/j.ensm.2019.07.005
[53] Rahman, M.M, Oni, A.O, Gemechy, E & Kumar, A. (2020), Assessment of energy storage technologies: A review, Energy Conversion and Management, 223, pp113295, Table 6. Note that these are older measures from a 2020 paper. Estimates of capital costs provided by OEMs are markedly lower.
[54] The Queensland Government, *Ministerial Joint Statement: Copperspring budget boost to unlock vanadium industry*, Published Thursday, 22 June 2023
[54] 85% to 90% in theoretical testing and 57% to 75% in pilot systems, Guarnieri, M., Trovo, A., & Picano, F. (2020). Enhancing the efficiency of kW-class vanadium redox flow batteries by flow factor modulation: an experimental method. Applied Energy, 262, 114532-114542. Retrieved from https://doi.org/10.1016/j.apenergy.2020.114532

VRFBs are well placed to help manage system reliability:

A key characteristic of VRFBs is the relative physical ease of markedly expanding their energy duration capability. This duration is predominantly a product of the volume of electrolyte contained in the storage tanks. Relatively minor adjustments to tank volumes can therefore markedly increase the volumes stored in the tank, delivering significant increases in energy duration.

This duration capability is enabled by the inherent design of VRFBs, which allow for the effective separation of rated power capability from energy. These designs come in two broad forms.

In the first form, the electrolyte tanks and stack are housed in the same container. This modular design, used by Invinity and CellCube, provides a standard capacity per module. Increasing energy duration requires more modules be installed, to deliver the required energy storage volumes. This modular design reduces installation complexity and construction costs.

The other design is for the two tanks of electrolyte to be entirely separate from the stack and the battery management system. This design is used by Sumitomo Electric and results in an even more marked decoupling of power and capacity, enabling greater energy duration capability where this is desired. However, these designs are more bespoke in nature, with a more complex installation process.

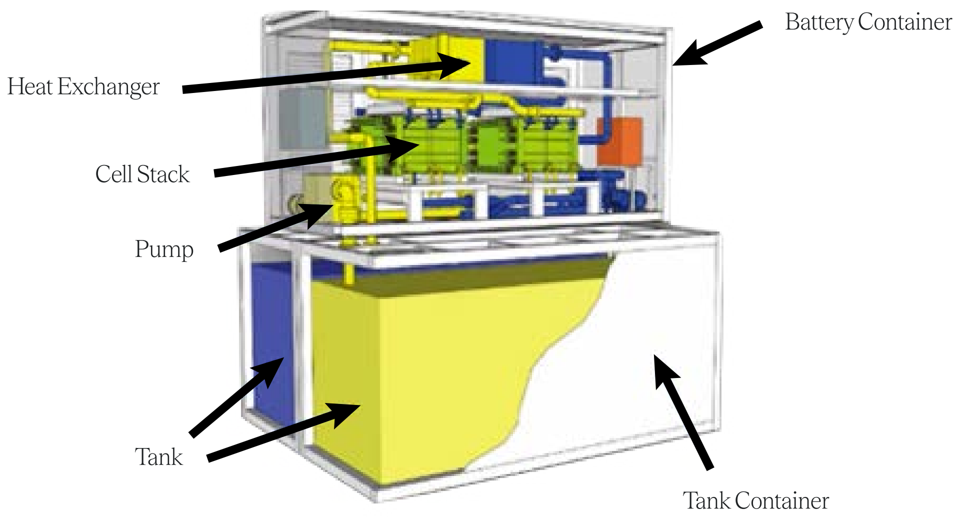


Figure 15: Sumitomo VRFB, showing separation of cell stack and tank

Source: Sumitomo

VRFBs also demonstrate a relatively effective carrying capacity. Once the pumps that carry electrolyte across the stack are switched off, the state of charge remains relatively stable, with very few auxiliary load losses. This means VRFBs can effectively carry significant volumes of charge over extended periods, with relatively low losses. This means they are well placed to support reliability , both in terms of managing seasonal shortfalls in energy, as well providing backup services to support network reliability.

This capability to support network reliability is enhanced by the ability of VRFBs to be located closer to urban load centres. Coupled with their high cycling capabilities, VRFBs can be located in lower voltage distribution networks, to help absorb excesses of solar PV generation. Energy Queensland is trialling VRFBs for precisely this use.[55]

Finally, VRFBs also demonstrate high levels of cycling capability. This means they can repeatedly charge and discharge many times over, without meaningful degradation of the asset. In fact, its understood the main cycling limitations on VRFBs are those associated with the expected life span of the BOP.

In combination, this significant energy duration, carrying capacity and high cycling capability means that VRFBs are well positioned to help manage emerging system operability and reliability challenges, such as daily diurnal ramping and seasonal supply shortfalls.

Another key design element of VFRBs is their resistance to cross contamination between the positive and negative liquids. VRFBs utilise the same element in both tanks – vanadium – but subject to different electrical charges, which means there is no risk of mixing of two

[55] RenewEconomy, *Queensland funds another 12 "solar soaker" batteries, plus two locally made flow batteries.*

different chemicals.[56] In contrast, hybrid flow batteries can be subject to this cross contamination, as they utilise different chemicals. This capability of VRFBs helps to reduces capacity loss, supports a longer asset life, delivers high cycle rates and also a 100 per cent depth of discharge.[57]

VRFBs can also make some contributions to system security, however this is dependent on the ongoing development of grid forming technology:

VFRBs have a short response time due to their electro-chemical design. This means that a VFRB can provide both active and reactive power within a very short timeframe, which enable them to provide services such as fast frequency control and voltage support.

However, the ability of VRFBs to provide other system services, such as inertia and system strength, will be dependent on their use of grid forming technologies. This is an issue common to all flow batteries as well as existing LIB technology. Grid forming inverter technology shows great promise in the NEM, with extensive work underway by AEMO to support widespread integration.[58]

VRFBs also demonstrate good locational flexibility:

A key issue with many forms of long duration storage is that the physical nature of the asset places limits on where it can be located. For example, both PHES and CAES require water or underground air reservoirs respectively, so geologic and hydrologic factors will limit the areas where these assets can be located. Similarly, thermal risks associated with LIB and TES mean these utility scale assets are not suitable for urban locations.

The physical characteristics of VRFBs mean they face fewer locational limitations. The physical footprint of the assets is relatively small and can be located in an area equivalent to a traditional warehouse. There is also no associated thermal risk, as the operating temperature of a VRFB is relatively low with zero flammability associated with the electrolyte.

There are some toxicity risks associated with vanadium pentoxide, the primary component of the electrolyte used in VRFBs. However, these risks are not dissimilar to those associated with other common industrial chemicals and can be managed with standard chemical industrial safety protocols.

These locational characteristics of VRFBs, coupled with their relatively high cycling rates, mean they may be well placed as high capacity / energy community batteries, located within the lower voltage distribution network. Such batteries can provide multiple network services, reducing network costs for consumers. They can also act as a 'solar soak', helping to manage the effects of high levels of rooftop PV.

Input costs may be a limiting factor:

A commonly cited drawback of VRFBs is the volatile price of vanadium pentoxide, the key input material of the VRFB electrolyte.[59] Vanadium deposits are also located in countries with associated environmental, social and geopolitical concerns. As a result, vanadium pentoxide prices can be both high and volatile due to supply chain risks.

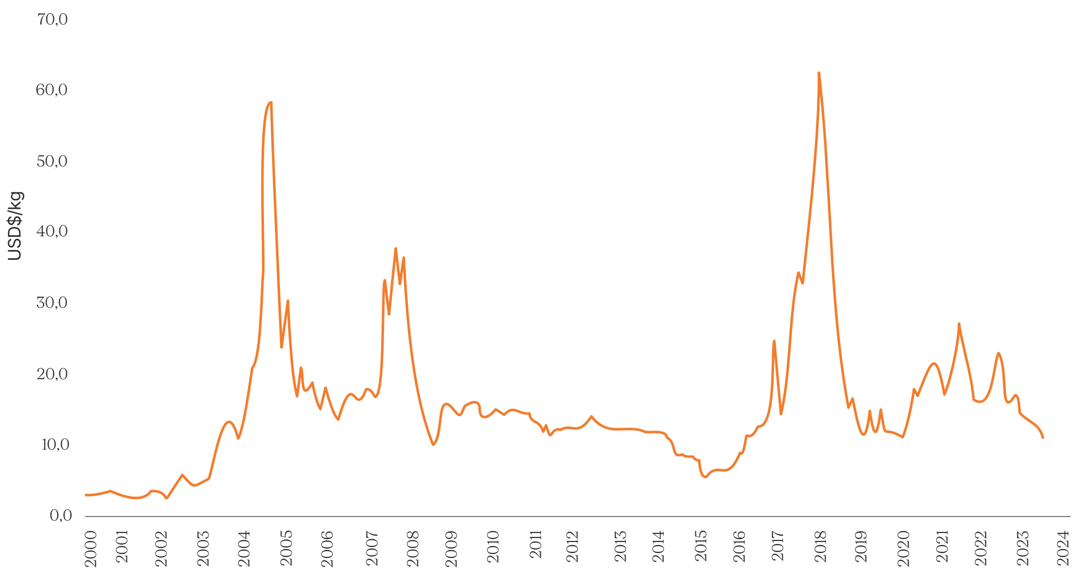


Figure 16: Vanadium pentoxide (V2O5) prices in US$ per kg between 2000 and 2024

Source: Vanadium Price.[60]

[56] Specifically, the positive tank – the catholyte - being VO2+/VO2+ and negative tank – the anolyte - being V2+/V3+.
[57] https://energy.mit.edu/news/flow-batteries-for-grid-scale-energy-storage/
[58] AEMO, Engineering Framework: FY23 Advanced Inverters Actions.
[59] Guarnieri, M., Trovo, A., & Picano, F. (2020). *Enhancing the efficiency of kW-class vanadium redox flow batteries by flow factor modulation: an experimental method. Applied Energy*, 262, 114532-114542.
[60] Vanadium price - daily data, https://vanadiumprice.com/

There have been two main price spikes in vanadium pentoxide, reaching USD$58/kg in 2005 and USD$62/kg in 2019, four times the average price between the two periods.[61] Vanadium prices are linked to steel production, meaning that any volatility in the price of this key commodity may flow through to VRFB input costs.[62] Besides raw materials, the membrane is the other high cost associated with VRFBs.

Various solutions are proposed by VRFB proponents to help manage this input price volatility. For example, electrolyte leasing is being explored as a tangible practical solution, with the electrolyte returned to the seller at the end of the battery's lifecycle. This shifts capital expense to operating expense, in effect reducing the investment risk. For VRFBs this is a particularly attractive option since the electrolyte does not diminish in quality.[63]

Other cost reduction pathways include more efficient reactor and architecture design, and improvements in cell voltage.[64]

The attractiveness of VFRBs in Australia is also linked to the potential for sourcing local supplies of vanadium pentoxide. Australia has the worlds second largest deposits of vanadium after China.[65] There are also various developments underway to progress local vanadium pentoxide production.

For example, miner and manufacturer Vecco Group has opened the first vanadium electrolyte manufacturing facility in Townsville, Queensland. The facility is expected to produce 9 megalitres of electrolyte per year, capable of supporting 175 MWh of annual energy storage capacity. Supply of raw vanadium will initially be source overseas, however the development of Vecco's Debella Critical Minerals Mine, located near Julia Creek, 650 km west of Townsville, is expected to supply 5,500 tonnes of vanadium pentoxide per year. Production will begin in 2024.[66]

An agreement between Vecco Group, Sumitomo Electric and Idemitsu has also recently been announced identifying Townsville as the centre for a complete vanadium manufacturing supply chain, from mining to delivery of batteries.

Finally, VRFBs also demonstrate significant potential for hybridisation with LIB. For example, an ongoing UK trial is harnessing the high cycling potential and long lifespan of VRFB as part of a 50MW hybrid installation with a LIB system.[67] This hybrid utilises the capability of the VRFB to undertake multiple deep cycles of charge and discharge each day, to provide reliable power without degradation, thus extending the life of the LIB component.

[61] Vanadium price – daily data, https://vanadiumprice.com/
[62] Erkan, B, Proactive Investors, 2019, Vanadium prices remain strong into 2019 as further new energy applications are developed, www.proactiveinvestors.com.au
[63] Skyllas-Kazacos, M. 2019. "Performance Improvements and Cost Considerations of the Vanadium Redox Flow Battery." ECS Trans 89, 29-45
[64] MIT Energy Initiative, 2022, The Future of Energy Storage, MIT Energy Initiative
[65] U.S. Geological Survey, Mineral Commodity Summaries, January 2024
[66] Carroll, D., PV Magazine, 2023, State puts vanadium tech to test as "Australian first" manufacturing plant opened, www.pv-magazine-australia.com
[67] Murray, C., Energy Storage News, 2022, Project briefing: World's largest lithium vanadium hybdrid, www.energy-storage.news

Technology Feature: Invinity Energy Systems

Invinity Energy Systems is a leading American manufacturer of VFRB. Their VFRBs are shipped fully tested and loaded with electrolyte, ready to be connected at site. The units do not require separate heating, ventilation, air conditioning or fire suppression systems. The modules are stackable to maximise energy density, with scale achieved by stacking units to match specific storage output needs.

Invinity's VS3 system offers unlimited cycles and throughput with no warranty limits, an asset lifespan of 25 years, with up to 18 hours of energy discharge.

Projects

In Australia, Invinity has installed a solar-powered VFRB at Yadlamalka Energy's Spencer Energy project. The project consists of an 2MW / 8 MWh VFRB combined with 6 MW of solar panels located 60km north of Port Augusta, South Australia. The battery consists of 41 Invinity VS3 flow batteries. The co-located project is expected to deliver up to 10 GWh of dispatchable solar power per year and its nearing full commercial operation.

The project aims to demonstrate the technical and commercial viability of VFRB in providing sustained energy for a duration of four hours and contribute to:

- **Morning energy arbitrage** – storing low-cost energy from the grid during the night and discharging in the morning at peak price
- **Solar shifting** – storing excess solar generation when market price is low or negative and discharging into the grid in the evening at peak price
- **FCAS** – providing frequency control services for the local grid.

The financial viability of the project relies on the distinguishing factor that VFRB do not degrade with use and can be used throughout the day to deliver different services. This provides flexibility, maximum return and viability of solar projects by addressing the solar 'duck' curve.

Zinc-bromine Hybrid Flow Battery

Hybrid RFBs are the other main subtype of battery within the RFB family. With various electro-chemistries available, Hybrid RFBs are an effective complement to both pure RFBs as well as other energy storage technologies.

One of the best known hybrid RFB chemistries is the zinc-bromine flow battery (ZBFB). ZBFBs utilise low cost, relatively abundant materials. They demonstrate a degree of modularity, are relatively safe to operate and provide scalable mid to long duration energy storage. As with pure RFBs, they are also relatively location agnostic and can be located in urban areas.

At a glance: Zinc Bromine flow batteries

Characteristic	Capability of technology type
Rated power output (MW)	Smaller scale, up to 10MW. The physical design and chemistry of ZBFBs is such that max power rating is limited, relative to other ALDES.
Energy Duration	8-12 hours, although limited by physical design.
Round trip efficiency (%)	60% – 70%.[68] Moderate RTE dictated by the cell voltage of the chemistry, operation temperature and auxiliary power needs
Carrying capability + self discharge	High. Once pumps circulating electrolytes are turned off, there is minimal power degradation and minimal auxiliary load.
Cycling capability	Up to 11,000 cycles.[69]
Lifespan	10 - 20 years.[70]
Locational dependency	No location constraints. The system comes in standard shipping containers, ready for use
Generation type	Non-synchronous
Supply of input materials	Low cost. All input materials are abundant and specific compounds are easily manufactured.
Capital cost ($US/kWh)	$US370/kWh -$US1470/kWh.[71]
Construction lead times	1 year.[72] Modular design allows fast installation.
Social and geopolitical considerations	None, reflecting easily accessible raw materials
Environmental considerations and Recyclability	The battery can be almost fully recycled. Despite the complexing agents used, the bromine solution does not require costly environmental management. Bromine itself is a hazardous chemical, however this is manageable under chemical industrial safety protocols.

[68] Hossain, E., et.al., 2020, A comprehensive review on energy storage systems: types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects, Energies, Vol 13, 1651, Table 15, doi:10.3390/en13143651
[69] Gao, L. et.al., 2020, *A high-performance aqueous Zinc-Bromine static battery*, iScience, Vol 23, Issue 8, 101348, doi: 10.1016/j.isci.2020.101348. Note that this represents an upper estimate of cycling rates for ZBFBs.
[70] Nadeem, F., et.al., 2019, Comparative review of energy storage systems, their roles, and impacts in future power systems, IEEE Access, Vol 9, Table 10, doi 10.1109/ACCESS.2018.2888497. Estimates vary between academic research and OEM values.
[71] Rahman, M.M, Oni, A.O, Gemechu, E & Kumar, A. (2020), *Assessment of energy storage technologies: A review*, Energy Conversion and Management, 223, pp113295, Table 6
[72] IRENA, 2020, Electricity storage valuation framework: Assessing system value and ensuring project viability, page 31, Figure 13, www.irena.org

ZBFBs utilise zinc and bromine in ionic aqueous solution. During the charge phase, metallic zinc is deposited as a thin film and bromine forms a thick oil in reaction with an organic amine. Discharge sees the deposited zinc metal return to solution.

This inherent element of ZBFBs affects both their max power rating and energy duration capability, both of which are determined by the size and depth of the zinc plating that can occur during a charge cycle. This is a key differentiating factor between VRFBs and ZBFBs, with implications for the role of ZBFBs in maintaining general power system reliability.

Another key difference between VRFBs and ZBFBs is the need for periodic deep discharges, to fully remove, or "strip" zinc from the stack. This 100% depth-of-charge is an inherent element of the battery design. In practice, most ZBFBs complete three cycles before a "strip" cycle is required. Advances are being made to develop batteries that utilise a gel solution which may eliminate the need for the strip cycle.[73]

Contribution to reliability and security:

ZBFBs can contribute to overall system reliability. This contribution is affected by the limits on max power rating and energy duration inherent to the electrochemical design of ZBFBs. However, this is countered by the limited self discharge and effective carrying capability of ZBFBs, which will allow them to contribute to reliability by delivering sustained energy supply.

Security contributions are more or less equivalent to VRFBs, as described in the previous section.

Input materials are readily available:

A key strength of ZBFBs is the ready availability of both zinc and bromine, as well as the chelating agents used to safely contain bromine produced during the charging cycle. This is a key factor advantaging ZBFBs against other forms of RFB, particularly VRFBs, which are currently affected by volatility in the cost of vanadium pentoxide. The lower cost of materials and an established industry of zinc and bromine processing also allows this technology to be cost competitive with other forms of ALDES.[74]

Importantly, the battery stacks are nearly all plastic and can be recycled. The electrolyte does not pose an environmental risk and since it is not consumed in the battery, it can be removed and reused.

ZBFBs also demonstrate good locational flexibility, supporting low voltage CER integration:

As with VRFBs, the design of ZBFBs provides significant locational flexibility. ZBFBs have been deployed at commercial, industrial and residential scale with good safety performance given the non-flammable nature of componentry. They are also reliable within an optimal temperature range of 10ºC to 45ºC, making them suitable for operation in most urban environments.[75]

However, careful management is required given bromine vapour (a toxic and corrosive substance) can be created during the charging cycle. This is managed through the use of complexing agents, chemicals which reduce any bromine vapour emissions. If these emissions do occur, they can be cleared out through activated carbon filters.

Existing commercial ZBFBs modules have an optimum power rating that is not sufficient for large scale grid-scale deployment. In part this is due to the chemistry of the battery and the management of the electrolyte. However, the locational factors described above mean they can play a key role in supporting integration of renewable energy at distribution network level.

[73] Peacock, B, PV Magazine, 2021, Zinc-bromine battery for stationary energy storage from Australia, www.pv-magazine.com
[74] Alghamdi, N.S., et.al., 2023, Zinc-bromine rechargeable batteries: from device configuration, electrochemistry, material to performance evaluation, Nanomicro Letters, Vol 15, 209, doi: 10.1007/s40820-023-01174-7
[75] Battery performance varies with discharge rate, which decreases as energy efficiency increases and the temperature in the battery increases. Energy must also be diverted to auxiliary systems that include pumps, fan, and battery controller (monitoring SOC, scheduling maintenance cycles, performing temperature management and shunt current protection). Although little publicly available information exists, test pilots and experimental data indicates auxiliary systems take less than a few percent of the total battery usage, further reading: Butler, P.C.; Eidler, P.A.; Grimes, P.G.; Klassen, S.E.; Miles, R.C. Zinc/bromine batteries. In Handbook of Batteries; McGraw-Hill: Columbus, OH, USA, 2001; p. 39.8

Technology feature: Redflow

Redflow is a global Australian company that designs and manufactures long duration zinc-bromine flow batteries for commercial, industrial, and utility applications. Redflow has over 270 active projects and more than 3 GWh installed deployed energy storage capacity. Deployments at distribution level have all been successful.[76]

Redflow batteries are modular, scalable, fire-safe, capable of 100% depth of discharge with an extended life and minimum degradation over time. The ZBM3 battery is the core of Redflow's energy storage solutions. This module is smaller and more compact than previous versions with benefits extend across the technical delivery of energy, operability, and overall recyclability.

Projects

Redflow's projects include stand-alone remote sites, several commercial and industrial applications and some residential installs.

Recently Redflow announced several large projects in California, including a grid connected 20 MWh battery for the Paskenta Band of Nomlaki Indians and a distribution network connected 34.4 MWh battery for Valley Children's hospital.

In Australia, Energy Queensland has partnered with Redflow to supply 4 MWh of energy storage in Ipswich. The $12 million project is part of Energy Queensland network battery program which aims to lower energy bills for consumers, enable uptake of rooftop solar PV and support local businesses.

[76] Redflow, Case studies https://redflow.com/case-studies

Other flow battery technologies

A range of other RFB technologies are in development. Although most are at earlier stages of maturity, they may represent effective complements to the other technologies described above.[77]

Thee are many elements of RFB design that are being optimised through these new developments. Generally however, a key area being explored relates to alternative chemistries, with technology developers exploring ways to reduce input costs or minimise environmental / safety impacts.

A range of alternative chemistries are being developed, many of which make use of commonly available metal or organic compounds, such as iron, complex organic molecules and hydrogen.

Use of these input materials allows utilisation of existing chemical manufacturing and supply chains, helping to reduce the input cost sensitivities. Similarly, many of these chemicals may display reduced toxicity and therefore better safety profiles than more mature technologies.

Reducing input cost sensitivities will help with the economics of these emerging RFB technologies, while improvements in terms of environmental and safety impacts will expand the potential range of locations for new RFBs.

Technology feature: Origin / Allegro

Source: Allegro Energy

Origin Energy is intending to build a 460MW 2-hour LIB on the site of the Eraring coal generator in NSW, with a plan to extend this asset to 700MW and 4-hours.

Complementing the LIB battery will be a redox flow battery.[78] This asset will initially provide 8-hour energy storage (100kW/800kWh). If the commercial trial proves successful, a 5MW (60MWh) RFB is planned, potentially also at the Eraring site.

The asset itself will be supplied by Allegro Energy, an Australian company utilising a patented water based RFB chemistry. Although the specific chemistry has not been made public, Allegro state that the battery has a higher energy density than other technologies, is non-flammable, non-corrosive, does not require rare of scarce materials and is entirely recyclable at the end of life.

[77] Sanchez-Díez, E., Ventosa, E., Guarnieri, M., Trovo, A., Flox, C., Marcilla, R., . . . Ferret, R. (2021). Redox flow batteries: Status and perspective towards sustainable stationary energy storage. Journal of Power Sources, 481, 228804. Retrieved from https://doi.org/10.1016/j.jpowsour.2020.228804
[78] Origin Energy, 2023, Origin acquires interest in Newcastle's Allegro Energy and agrees to long duration storage trial at Eraring, www.originenergy.com.au

Technology feature: ESS Iron redox flow battery

Iron flow batteries are an exciting RFB technology development, as it utilises particularly low cost materials to deliver sustained long duration storage capability.

There are several iron flow battery projects underway in Australia, the most notable being several projects being developed in Queensland as part of the QLD Government's commitment to convert existing coal generator sites to renewable energy hubs.

Projects being developed include a 1MW/10MWh iron flow battery system at Stanwell power station and a 1MW/5MWh iron flow battery system to be installed by Energy Queensland the grid in Hervey Bay. The QLD government has also announced a plan for a 150MW iron flow battery through Stanwell.[79]

Iron flow battery company ESS and Energy Storage Industries Asia Pacific is currently constructing a $70 million manufacturing plant in Maryborough, Queensland from which to source 80% of the components for iron flow batteries.[80] The plant will include manufacturing the electrolyte, with an expected annual production capacity of 400MW by 2026.

Tech feature: Lockheed Martin redox flow batteries

Lockheed Martin is an American company involved in development, manufacturing, and integration of energy solutions. They manufacture the GridStar Flow battery using engineered molecules with earth abundant metals, commodity chemical ligands (organic redox flow battery), and a water-based electrolyte. The prototypes to date include:

- Alpha Unit: 200 kW (500 kWh). 2-hours model developed in 2017-2018 with 1 year under testing
- Beta Unit: 250 kW (1,500 kWh). 6-hours model developed in 2018-2020 with 1 year under testing
- GridStar Flow: 250-500 kW (2,500 kWh). 5 to 10 hours model developed in 2020-2022, with 2 years under testing.

Currently, Lockheed Martin has two projects under development in North America. A 10 MWh pilot demonstration battery in Colorado, US and a 5 MW (25 MWh) project in Alberta, Canada. Based on the information provided by the proponent, the technology can provide 6 to more than 12 hours energy storage, is able to cycle multiple times a day with little degradation, has a long usable life, has a non-flammable battery chemistry, and is modular, providing flexibility in how it is operated and sized.

Most importantly, Lockheed Martin is looking to develop flow batteries that are free from input material constraints by utilising abundant chemicals. The company's maturity allows the company to pursue new chemistry design that address environmental concerns.

[79] RenewEconomy, *Stanwell signs major deal for Australian-made long duration iron flow batteries*, May 3 2024. Available at www.reneweconomy.com.au.
[80] Peacock, B, PV Magazine Australia, 2022, Iron flow battery arrives at Queensland testing centre ahead of major perfectly suited manufacturing play, www.pv-magazine.com

Thermal Energy Storage

Thermal energy storage (TES) systems utilise the ability of different materials to hold heat as a means of storing energy. The system is 'charged' with an input of heat into a storage medium which may include water, molten salt, a ceramic or metallic alloys. Discharge involves circulating a working fluid through the storage medium or by circulating the storage medium itself.

A further element of TES design is whether sensible or latent heat storage is used. Sensible heat TES utilise a material, such as sand or concrete, which is heated to high temperatures but does not itself go through a "phase change' – ie, it does not change from gas to liquid to solid. Latent heat storage utilise materials that go through a reversible phase change, such melting metals or parrafin wax.

This report explores two key types of TES

- **Concentrating solar power (CSP):** This sensible heat TES utilises solar energy to heat a storage medium – such as water or continuously molten salt - with that heat later used to generate electricity or to provide direct process heat. There are in turn several subtypes of this technology – in this report we have focussed on solar tower CSP.

- **Miscibility Gap Alloy (MGA):** This latent heat TES utilises electricity from the grid to heat specially designed blocks that encapsulate a melting alloy in a matrix. This technology enables much higher temperatures to be reached, which in turn enables longer duration energy storage.

	Materials types	Efficiency	Temperature / Storage	Cycles / 2030	Maturity	Cost (2030) USD/kWh
SENSIBLE	Ceramics, silica & sand Molten Salts Concrete Rocks Water	50%-90%	150-1000ºC Months	1,000-3000 Expected 5,000	Medium-high	0,1-25
LATENT	Encapsulated Metals Inorganic salts Sodium Paraffin Wax Salt Hydrates	75%-90%	50-850ºC Days	1,000-3000 Expected 5,000	Medium	60-95
THERMO-CHEMICAL	Chemical reaction Storage Absorption	75%-100%	500-900ºC Seasonal	<100 Expected 1,000	Low-medium	80-160

Figure 17: Overview of key features of TES storage processes[81]

Technology summary

CSP currently represents the most widely commercialised TES technology, however multiple innovative phase change materials are being tested and are entering early commercial phase.

Both types of TES effectively discharge in the same way, by utilising stored heat to run a turbine generator. Different working fluids are used to drive the turbine, depending on the temperature of the stored heat. In lower temperature applications this turbine may run on an organic Rankin cycle[82], or in higher temperature applications steam is the working fluid.

The processes described above enable both CSP and latent/sensible TES to meet a range of system transition needs, as well as supporting broader efforts toward industrial decarbonisation.

Contribution to security and reliability: Both TES technologies have good duration and energy carrying capability and can utilise synchronous generation technologies, making them well positioned to support reliability and security of the grid. Characteristics here are similar to CAES.

Environmental sensitivities and location: While requirement for good solar resource and overall asset footprint necessitate locating CSP assets outside urban areas, other forms of TES may be more readily located in industrial areas closer to main load centres.

Provision of process heat and steam: Perhaps the most promising near-term application of TES relates to the wider electrification and decarbonisation of industrial processes. TES solutions are uniquely positioned in that they can provide direct heat and steam for industrial and commercial processes, while also supplying electricity back to the grid.

Most of the energy consumption in industry is concentrated in high-temperature applications as per Figure 18. Many TES technologies can reach high temperatures across this entire range, including temperatures well in excess of 500ºC.[83]

[81] Data in the graph is based on information from the International Renewable Energy Agency (IRENA): Innovation Outlook: Thermal energy storage, page 23, Figure 7 and Medium- and high-temperature thermal energy storage. The information is from 2022 / 2021 and since more projects have been developed and new materials have been tested in pilot scale projects.

[82] An organic Rankin cycle makes use of liquids with a lower boiling point than water, allowing for capture of thermal energy at lower temperatures. Working fluids may include perflourocarbons or ammonia, as used by RayGen at the Carwarp plant.

[83] Long Duration Energy Storage Council, 2022, Net Zero Heat: Long duration energy storage to accelerate energy system decarbonisation, page 21, Figure 4, www.mckinsey.com

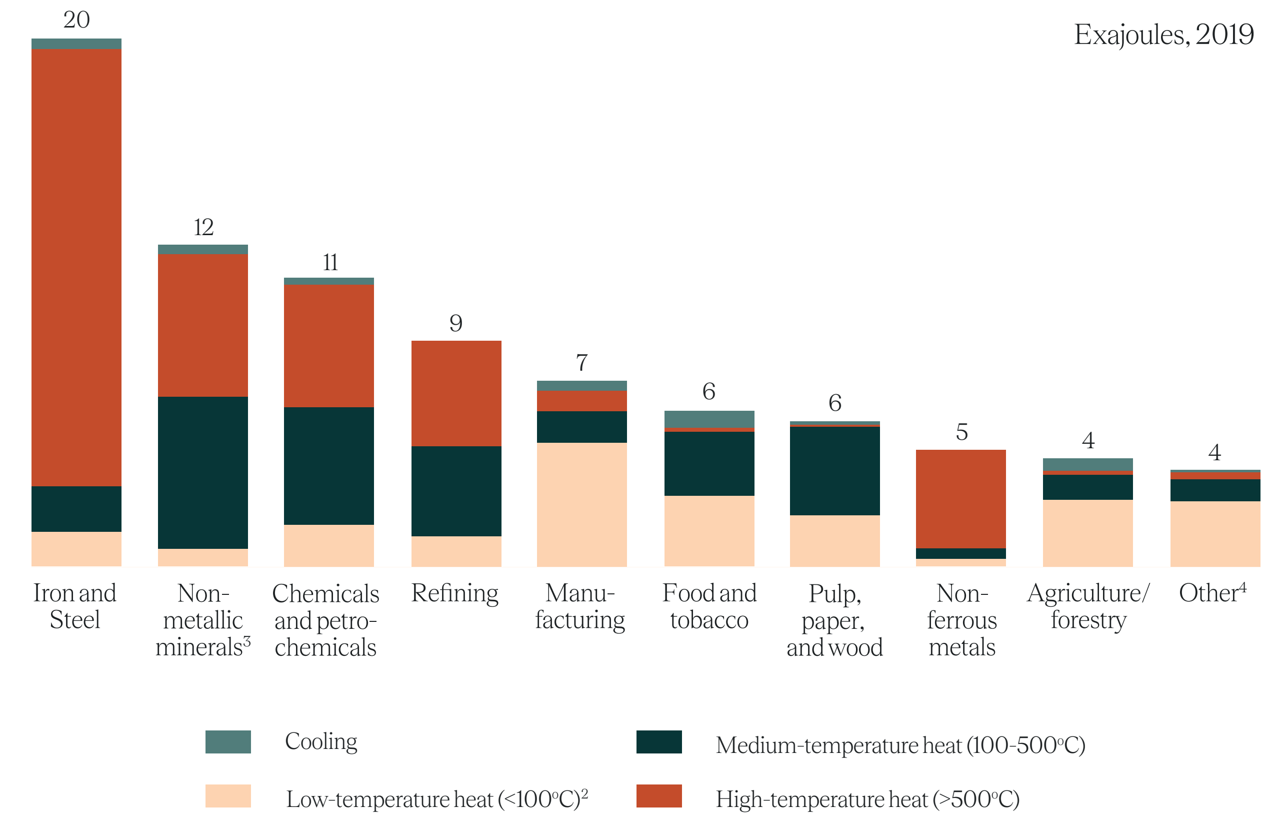


Figure 18: Global end-used industrial energy consumption by sector (exajoules = 109 gigajoules)

Source: Long Duration Energy Storage Council, Net zero heat Report, 2022.

In Australia, process heat includes 10% of applications under 150°C, 50% of applications between 150°C and 800°C and 40% in applications over 800°C. Process heat generated from zero carbon electricity or renewables is rapidly becoming a commercially preferable option in Australia, due to rising gas prices.[84]

The unique characteristics of TES make them particularly capable of reducing and smoothing process heat costs for industrial users. TES can build up a heat 'charge' sporadically over time – for example by running an electric resistive heating coil only during periods of low electricity prices - but can generate steam consistently, by 'drawing down' on the heat generated when electricity prices were low. This provides a consistent source of heat and steam at a low cost, even where the input cost of electricity might change.

Cost implications:

Studies suggest TES capital costs could potentially decline between 25 and 40 per cent by 2040.[85] The significant drive toward industrial decarbonisation and electrification of process heat is likely to further support TES, supporting learning improvements and overall cost reductions.

In terms of operating costs, the main issue for TES are their relatively low RTEs. These are caused by the significant losses associated with the operating a turbine during the discharge cycle.

RTE in TES power-to-heat applications is in the order of 97 to 94 per cent. However RTEs in power-to-power applications are affected by the relative heat rate of the turbine – that is, the total thermal energy needed to generate a MW[86]. Higher temperature turbines enable higher rates of radiative heat transfer, which increases the efficiency of the system. For example, combined cycle turbines operating at 1,200°C have an efficiency of 60%, compared with organic Rankine cycle turbines operating at 300°C turbines with an efficiency of 20%.

Overall, these heat losses mean the RTE of TES can be relatively low, at least when compared to the various other forms of ALDES explored in this paper. Because of this, power-to-power applications are often secondary to power-to-heat in many current TES applications.

[84] ARENA and ITP Thermal Pty Ltd, 2019, Renewable Energy Options for Industrial Process Heat, page 29, Table 1,
[85] Long Duration Energy Storage Council, 2022, Net Zero Heat: Long duration energy storage to accelerate energy system decarbonisation, page 21, Figure 4, www.mckinsey.com
[86] Heat rates normally associate the fossil fuel used to power a turbine with a given heat rate. In this instance, heat rate refers to the

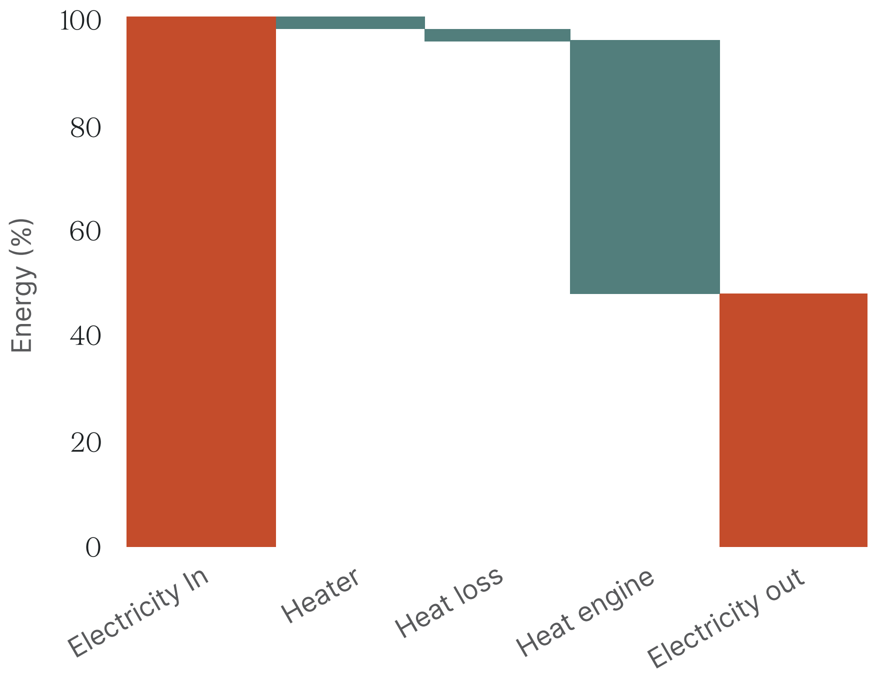


Figure 19 Energy losses for each step of a generic TES system.

Source: The Future of Energy Storage, MIT Study[87]

Despite these factors, there are a number of reasons to expect that TES solutions will reduce in cost:

- **Unique capability to directly replace coal generation.**

The power-to-heat component of TES make them ideal for installation at existing coal generation power stations when those assets reach end of life or are retired to meet emissions reductions goals. A TES asset could be used to replace the existing heat source while reusing the existing generation equipment and balance of plant infrastructure, helping to reduce overall cost to the system and for the TES asset itself. Studies have shown this approach has capital costs and delivered energy LCOE at levels comparable to other forms of LDES.[88]

- **Multiple revenue sources from industrial process applications:**

Many TES technologies can switch between supplying process heat and generating electricity, by redirecting steam from the industrial process to the turbine generator. This creates multiple revenue streams for TES assets, either as a direct input to the industrial process or through payments from the energy market. Given current RTE limitations this may mean electricity generation from TES is limited to peaking periods, where spot prices are high. However, as per discussions below regarding input energy costs, this may change over time.

- **Abundance of electrical energy will reduce impact of low RTE:**

As noted above, the low RTEs of TES can make these technologies less competitive. However, growth in grid connected renewable generation – particularly solar – is consistently suppressing electricity prices. These reductions in the cost of input electricity will in turn reduce the cost of losses, reducing the impact of a relatively poor RTE.

- **Ongoing technical developments to increase temperature:**

Developments in latent and sensible heat storage materials will enable higher temperatures for energy storage, well above what is currently being deployed commercially. This would improve the efficiency of TES and provide multi-day energy storage, to deliver significant MWh volumes.

- **Additional revenue streams associated with synchronous generation and duration:**

As described above, TES assets are synchronous and can therefore offer a full suite of system services. This will provide multiple additional revenue streams.

[87] MIT Energy Initiative, 2022, The Future of Energy Storage, page 114, Figure 4.1, MIT Energy Initiative
[88] Qingqing Yong, Yanpei Tian, Xin Qian, Xiaobo Li, Retrofitting coal-fired power plants for grid energy storage by coupling with thermal energy storage, Applied Thermal Engineering, July 2022. https://doi.org/10.1016/j.applthermaleng.2022.119048

Concentrated solar power with thermal energy storage

CSP is an advanced technology that utilises sensible heat energy storage in a medium such as molten salt or water. This heat is then used for industrial processes and /or to drive a steam turbine. More than 70 per cent of CSP plants are complemented with a thermal energy storage system.[89]

Source: Raygen. Available at https://raygen.com/carwarp/

At a glance: concentrated solar with thermal energy storage key characteristics.

Characteristic	Capability of technology type
Rated power output (MW)	300 MW [90,91]. Note this figure is likely to change as the technology continues to develop and scale-up.
Energy duration	12 hours and more, with the potential to discharge for 24 hours. Energy duration is a function of the heat stored in the system.
Round trip efficiency (%)	60% to 80%. Most CSP sit at the lower end of this range due to efficiency of each stage involved in producing, storing and discharging electricity. However innovations along this energy conversion chain, coupled with more efficient utilisation of captured solar energy, can boost RTE values towards 80%.
Carrying capability + self discharge	Weeks, suitable for maintaining energy storage for longer periods of time to address seasonal shortfalls
Cycling capability	CSP is not limited to any particular number of cycles, other than standard wear and tear on turbines and balance of plant.
Lifespan	+40 years. Much of the kit involved in operating the plant has long life since it uses standard turbines, heat exchanger, condenser and pumps.
Locational dependency	CSP will face some requirements for land, based on the availability of the best solar resources. They are also affected by safety considerations around high temperature risks, although lower temperature applications in some forms of CSP will reduce these safety implications. Overall, this means rural and regional locations are more likely.

[89] Desideri U, C. P. (2014), Analysis and comparison between a concentrating solar and a photovoltaic power plant. Applied Energy, 113, 422-433. doi: http://dx.doi.org/10.1016/j.apenergy.2013.07.04
[90] Hossain, E., et.al., 2020, A comprehensive review on energy storage systems: types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects, Energies, Vol 13, 1651, Figure 16, doi:10.3390/en13143651
[91] Nadeem, F., et.al., 2019, Comparative review of energy storage systems, their roles, and impacts in future power systems, IEEE Access, Vol 9, Table 9 and Table 10, doi 10.1109/ACCESS.2018.2888497
[92] Some forms of CSP run a boiler to power a synchronous turbine – see Vast Solar project below. RayGen has developed a PV technology that can generate non-synchronous power directly through PV assets, while also capturing heat directly to power a turbine.

Generation type	Synchronous and non-synchronous.[92] The turbine can also be fitted with a clutch so that it can operate in synchronous condenser mode when not generating, allowing for the provision of inertia, system strength and voltage regulation.
Supply of input materials	No material issues. Materials and equipment are based on existing technology. Installation also involves known construction equipment and traditional civil works
Capital cost	US$47/ kWh - US$84/kWh.[93] Costs vary depending on the type of CSP and duration. For parabolic trough collectors the cost of energy is higher than solar power tower types.
Construction lead times	1-2 years. Constructions involves conventional earth works that do not require highly specialised equipment.
Social and geopolitical considerations	No geopolitical implications since no critical materials are used and all materials are abundant, easily accessible and low-cost.
Environmental footprint	Low impact due to use of materials that are both abundant and safe. Much of the components of the plant can be recycled.

As an alternative technology to co-located large-scale solar and LIB, CSP has seen a renewed interest since 2018, particularly in countries in the Middle East and Asia. By 2023, worldwide there were 6.6 GW of CSP in operation and 1.6 GW under construction.[94]

The most widely used type of CSP is parabolic trough collectors (PTC) with the largest installed capacity. However, solar power tower (SPT) can achieve high temperature differences in the thermal storage system, reducing the amount of input materials needed and ensuring longer discharge durations.[95]

As a general working principle, CSP utilises mirrors to concentrate sunlight onto receivers that contain a heat transfer fluid (which may also be used to store thermal energy). The heat transfer fluid is used to heat a boiler and run a turbine to generate electricity. With the falling price of solar panels, a TES additionality has been essential to drive the overall cost effectiveness of CSP.

The efficiency of CSP with TES is dictated by the type of mirrors and receiver, the operating temperature of the receiver, thermal losses in the system and the medium of storing heat. One of the most mature systems uses molten salt as the storage medium.

CSP with TES performs a similar function as solar PV / LIB hybrid assets. It draws the highest value from direct charging through CSP and utilising cheap TES, smoothing the demand curve and providing longer energy storage duration.[96]

CSP with TES increases power system flexibility and reliability by enabling energy to be produced on demand. It also has the potential reduce reliance on gas powered generation and meeting additional demand at higher levels of VRE penetration.

[93] Rahman, M.M, Oni, A.O, Gemechy, E & Kumar, A. (2020), Assessment of energy storage technologies: A review, Energy Conversion and Management, 223, pp113295, Table 7

[94] Solar Power and Chemical Energy Systems, CSP Projects Around the World, www.solarpaces.org /

[95] There are four main types of CSP configuration: Parabolic Trough Collectors (PTC), Linear Fresnel Reflectors (LFR), Solar Power Towers (SPT) and Parabolic Dish Collectors (PDC). For more details on each type please read Müller-Steinhagen, H. (2004). Concentrating solar power: a review of the technology. Available at https://www.researchgate.net/publication/224797493_Concentrating_solar_power_-_A_review_of_the_technology

[96] Kathleen M. Kennedy et.al.2022, The role of concentrated solar power with thermal energy storage in least-cost highly reliable electricity system fully powered by variable renewable energy, Advances in Applied Energy, Vol 6, page 100091, https://doi.org/10.1016/j.adapen.2022.100091

There are two key exemplars of CSP in Australia – Raygen and Vast Solar.

RayGen

Founded in 2010, RayGen introduced their integrated renewable energy and water-based thermal storage concept to the market in 2019. The technology provides flexible and reliable long duration energy storage for on-grid and off-grid industrial applications.

Their solar-only pilot project in Newbridge Victoria has been providing RayGen with valuable lessons and has set the foundation upon which several further innovations have been introduced:

- RayGen's field of self-powered tracking mirrors focuses sunlight onto a central receiver of high-efficiency, silicon-free photovoltaic modules specifically engineered with an efficiency of 38%.
- Water run through heatsinks behind the modules is used to maintain module surface temperatures and in doing so returns water at 95°C.
- Hence, under concentration, each 10×10 cm2 solar module generates 2.5 kW electricity and 5 kW heat in the form of 95°C water.
- The bi-product heat is stored in a hot water reservoir, while electricity is used for chilling the cold water reservoir.
- The storage medium is therefore simply water stored in two pits, one at 90°C and the other at 0°C. The pits are covered and highly insulated, with <10% heat gain/loss over a 6-month period.
- The temperature difference between the two water pits drives an organic Rankine cycle (ORC) turbine with ammonia as the working fluid in the turbine in a closed loop. The ORC turbine drives a synchronous generator that can operate as a synchronous condenser when de-coupled from the turbine.
- For every 1 MW input to the cold resevoir, 70-80 per cent is recovered when running the turbine.
- Accompanying the hardware offering, the solution includes integrated control and operating software.

Today, RayGen offers a renewable energy generation and long duration energy storage solution that can be flexibly configured and operated to meet the needs of large industrial customers and the electricity grid. It is reliable, cost comparative with alternative established technologies and utilises abundant natural resources.

Project details and benefits

In 2023, RayGen opened its flagship hi-tech solar and thermal hydro storage project in Carwarp, Victoria. This 4MW solar and 3MW/50MWh storage project can provide 17 hours of long duration energy storage. The project feeds electricity into the local 22kV distribution network, further demonstrating the technology's ability to support grid security and reliability.

RayGen's technology is highly scalable, with the size of hot and cold water reservoirs determining the energy storage duration. The Carwarp project has two 17,000 m3 reservoirs providing 17-hours storage duration and driving a 3 MW turbine. Bigger projects can be scaled up to increase ORC capacity and continue to provide energy storage for 12 to 24 hours (or more) with equivalent size reservoirs of 150,000 to 250,000 m3. On the generation side, to increase capacity simply requires multiplying the number of 1MW towers and heliostat fields.

Importantly, RayGen's storage technology uses no critical minerals for manufacturing and installation entails typical civil works, largely unconstricted by location requirements. In a world with limited materials for renewable energy projects, RayGen's technology offers a cost competitive solution for energy storage.

To support the delivery of larger, utility-scale deployments of RayGen's technology, the company is commissioning Australia's largest solar manufacturing facility, a 170MW p.a. satellite-grade solar module manufacturing line in Melbourne.

Vast Solar

Established in 2009, Vast is an Australian company developing and promoting concentrated solar thermal technology in Australia. Vast has 230 MW of projects under development and a total of 3.7 GW in the pipeline across 22 expected projects. Vast demonstrated its CSP v3.0 technology at its 1.1 MW, grid-synchronous pilot project at Jemalong, New South Wales. The pilot plant was commissioned in 2018 and operated for 32 months.

Vast has pioneered the use of sodium as a heat transfer fluid (HTF) due to sodium's excellent thermal conductivity properties, the low cost of the material and the ability to deliver higher temperatures with greater reliability and stability. Vast has developed proprietary instrumentation and control systems to deliver precise HTF control at high temperatures. The heat from the storage tanks can also be used directly in industrial processes or green fuel production.

Projects

Following the success of the pilot plant in New South Wales, Vast will build a 30 MW/288 MWh (9.6 hours energy storage) in Port Augusta, South Australia. The VS1 project has received $65 million in funding from ARENA to demonstrate technical and operational performance of CSP technology at utility scale to further unlock investment and provide pathways for Australian industry to decarbonise. Construction is expected to commence in late 2024 following financing and development activities. Commissioning is scheduled in late 2026 and the plant will provide electricity to the NEM and participate in market services such as energy arbitrage and FCAS.

In addition to electricity generation for a variety of applications, Vast is also building SM1, a solar methanol demonstration plant co-located with the VS1. This project consists of a 10 MW electrolyser producing green hydrogen for methanol production, powered by heat and electricity from VS1. The Australian Government via ARENA is providing $19.48 million of funding through the HyGATE Initiative, with the German government doing likewise.

The technology has demonstrated the ability to produce electricity for grid-connected applications. However, industrial applications are a core future focus, particularly processes requiring higher temperature.

Miscibility Gap Alloy

Source: Smartcompany, Shell-backed energy storage startup MGA Thermal powers up with $5.7 million investment, available at: www.smartcompany.com.au

MGA thermal energy storage systems utilise both sensible and latent heat storage. They typically comprise of modular blocks which contain two components: a high melting point solid with good thermal conductivity, within a lower melting temperature material encapsulated in a matrix. Heat is applied to the blocks, initially storing sensible heat, until the internal material undergoes a phase change – ie, melts – storing latent heat. This heat can then be used to run a generating turbine or to provide industrial process heat.

At a glance: Miscibility Gap Alloy key characteristics

Characteristic	Capability of technology type
Rated power output	Based on current technology trials, rated power is up to 100 MW.[97]
Energy duration	12–24 hours. Longer durations are associated with higher temperature systems. The materials and mode of encapsulation determines the temperature, which in turn controls the discharge time. However, these systems can charge and discharge at the same time ensuring continuous energy supply
Round trip efficiency	In power-to-power applications, the RTE is determined by the turbine rating and ranges between 20% and 50%. In power-to-heat applications, losses are minimal and RTEs may be as high as 94%
Carrying capability + self discharge	Weeks to months. The high temperatures reached in MGA blocks, coupled with their specific physical structure, allows heat to be stored for extended periods. The assets can be continuously and simultaneously charged and discharged, allowing for top ups in energy without interrupting energy supply.
Cycling capability	10,000+. Cycling of MGA TES is not comparable with other ALDES technologies due to the ability for these assets to charge and discharge simultaneously. In theory, the asset can be cycled until the blocks show signs of degradation which is a function of how the asset is operated. Individual MGA blocks can be replaced without needing to decommission the entire plant.[98]
Lifespan	20+ years.[99] The technology is modular and be flexibly modified to extend the life of the plant. As noted above, the way the plant is operated dictates the operational lifespan.
Locational dependency	The technology can be adopted at industrial sites and performs well in isolated or microgrids. High temperatures may create safety issues for location in urban environments.
Generation type	Synchronous. It is able to provide all synchronous services when generating, including system strength and inertia.
Supply of input materials	Raw materials are all commonly available and includes aluminum, magnesium, carbon, graphite, copper.
Capital cost	US$30/kWh - US$60/kWh[100]
Construction lead times	1-2 years. Once the MGA blocks are manufactured, assembly in the units and larger plant can be relatively quick.
Social and geopolitical considerations	Materials are all readily sourced and no supply chain or geopolitical issues has been observed to date. Moreover, technologies like MGA (and others that do not depend on critical minerals) will ease the pressure on other supply chains, while still connecting large volumes of power to the grid.
Environmental footprint	All the materials used are non-toxic. Graphite and aluminium can both sourced from recycled material. Other input materials have minimal environmental pressures. Materials can be separated and recycled for the purpose of being reused in the same application or for other purposes.

MGA TES blocks offer several advantages as a energy storage technology. Firstly, a wider range of melting temperatures that can be matched with various industrial process applications, based on operating temperatures. This includes temperatures ranging from 250 ºC for space heating, 600 ºC for steam turbine electricity generation and 1,400 ºC for high temperature industrial processes.

This heat can also be stored for a relatively long time, given the encapsulating matrix. Issues around liquification and solidification of the heat storage medium are also avoided.[101]

[97] Long Duration Energy Storage Council, 2021, Net Zero Power: Long duration energy storage for a renewable grid, page 11, Figure 9, www.mckinsey.com
[98] Kisi, E., et.al., 2018, Miscibility gap alloys: A new thermal energy storage solution, World Renewable Energy Congress XVI
[99] Srinivasan, V. et.al. (2023). Renewable Energy Storage Roadmap, page 183. CSIRO, www.csiro.au
[100] Nadeem, F., et.al., 2019, Comparative review of energy storage systems, their roles, and impacts in future power systems, IEEE Access, Vol 9, Table 10, doi 10.1109/ACCESS.2018.2888497. Note – given the relative early stage nature of this technology, only one reference could be found regarding capital cost and should be considered accordingly.
[101] Cuskelly, D; Fraser, B; Reed, S; Post, A; Copus, M; Kisi, E, Thermal storage for CSP with miscibility gap alloys, AIP Conference proceedings (2019) https://doi.org/10.1063/1.5117728

MGA thermal energy storage is a nascent technology in late stages of demonstration, however its high energy density per unit volume and capability to sustain high temperatures for a long period, mean it is well placed to provide 12+ hours energy storage, as well as being able to carry that energy through relatively long periods of time.

The leading requirement for successful manufacture of MGA TES systems is that the components are neither soluble nor chemically reactive with each other, the materials must remain macroscopically solid and immobile at operational temperatures and the phase change component is well dispersed within the material.[102] There are multiple material options currently being developed to meet these requirements as shown in the figure below.

Lastly, the technology is relatively modular since energy is stored in small individual blocks that form the fit-for-purpose system and benefits from relative system simplicity with no auxiliary energy requirements to keep the system in phase change..[103]

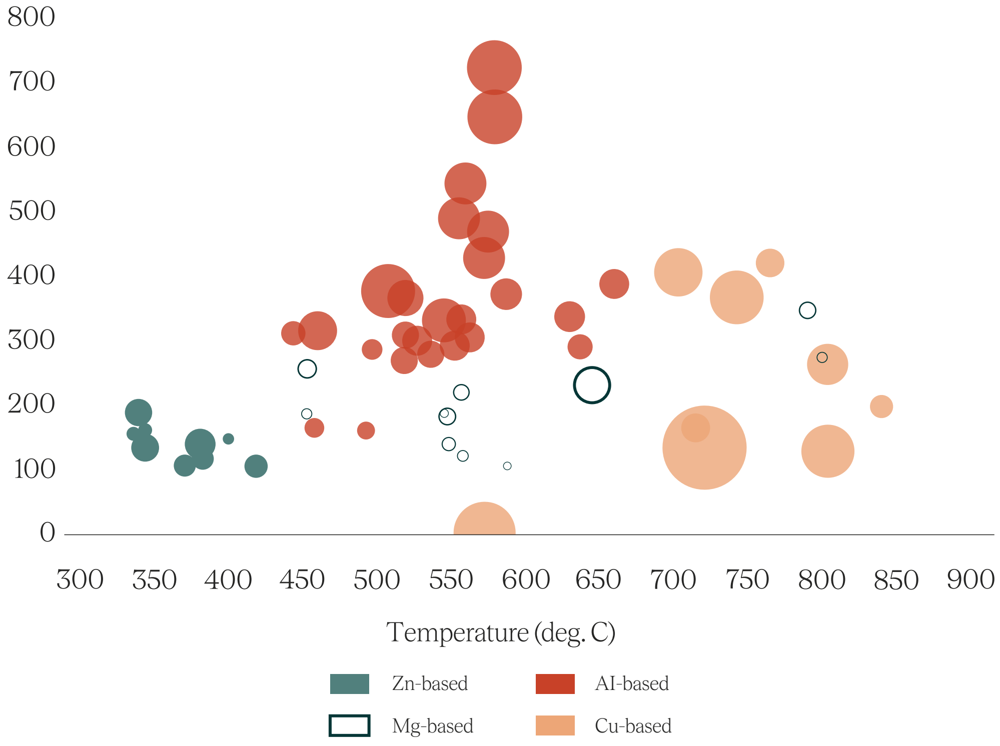


Figure 20 Latent heat of fusion forphase change materials with medium melting temperatures >300ºC.[106] The diameter of the circles represents the volumetric heat capacity. [104]

The key variables of candidate systems are the melting temperature and the energy density. Melting temperature determines the charge-discharge temperature, thus the suitability of materials for a given application. The diameter of the circles represents the volumetric heat capacity.

Common materials used in MGA includes aluminium based (aluminium-tin, aluminium-silica, graphite matrix C-Al), zinc-based graphite matrix (C-Zn)., magnesium-based (iron-magnesium, graphite matric C-Mg) and copper-based (iron-copper, graphite matric C-Cu).

Each alloy covers different temperature ranges, and the most useful alloys are those that have a low melting point temperature[105] and high temperature output. As a rule, alloys with high silicon content have higher melting temperature and copper-based alloys provide high temperature output.[106]

MGA system costs are related to material costs and manufacturing with operating and maintenance costs only a fraction of the lifetime cost of the plant. These costs are low due to the high thermal conductivity of the material mitigating the need for major pumping infrastructure and the resulting parasitic losses. The materials are also not damaged by daily thermal cycling and less likely to overheat due to high thermal diffusion.[107]

[102] Reed, S., Kisi, E. *Miscibility gap alloys with a ceramic matrix for thermal energy storage*. SN Appl. Sci. 2, 2148 (2020).
[103] Alva G, Lin Y, Fang G (2018) *An overview of thermal energy storage systems.* Energy 144:341–378
[104] Volumetric heat capacity of a material is the amount of energy that must be added, in the form of heat, to one unit of volume of the material in order to cause an increase of one unit in its temperature.
[105] Solids can be heated to the point where the bonds holding molecules together break apart and form a liquid - better known as melting, or heat of fusion.
[106] Costa, S.C. and Kenisarin, M., 2022, *A review of metallic materials for latent heat thermal energy storage: thermophysical properties, applications, and challenges*, Renewable and Sustainable Energy Reviews, Vol 154, pp. 111812
[107] Post, A. et.al. (2017), *Price estimation for miscibility gap allow thermal storage systems*, Renewable energy and Environmental Sustainability, Vol 2, pp 32

MGA Thermal

MGA Thermal is an Australian clean energy company with a form of thermal energy storage at scale that can provide 24/7 clean steam and power for industrial and grid sectors. After nearly a decade of research at the University of Newcastle, MGA Thermal is now supported by ARENA and Shell to complete a 5 MWh demonstration unit.

Several key characteristics make this technology attractive. The cost of energy storage is relatively low, with an upfront capital cost of $50/kWh. For industrial applications, MGA TES would have the lowest levelised cost of heat, providing 24-hours steam supply.[108]

MGA Thermal blocks can store energy on a range from 2 to 24 hours+ with minimal energy loss, presenting a real solution to long periods of VRE lulls. This allows integrating more VRE and dispatch energy when needed at low cost and without being site dependent.

Unlike LIBs, the TES system can charge and discharge simultaneously. Electricity is generated by driving a steam turbine with the heat stored inside the block. In addition to electricity, MGA Thermal delivers renewable heat for multiple industrial heat application between 150°C and 650°C.

The MGA blocks are designed with circular economy principles in mind. They can be made with recycled materials and recycled at the end of their usable lifetime. The materials used to make the storage material are low cost and abundant. The technology also is safe to operate.[109]

MGA TES can replace the furnace and boiler in coal fired power stations repurposing the facility and grid connection to large-scale renewable energy storage. Under this scenario, energy distributed through steam supports synchronous generation, providing essential grid stability services.

Project

MGA Thermal is currently building a demonstration plant in Tomago, New South Wales. The project is a 500 kW thermal power, delivering 10 hours of storage (5MWh) using approximately 3,700 MGA blocks. The project has received a $1.26M grant from ARENA.

[108] ARENA, 2023, Market Context Report – MGA Thermal Energy Storage Application in Australia, www.arena.gov.au
[109] Note that a recent incident at the pilot testing facility during commissioning led to suspending progress of the project, Peacock, B, PV Magazine Australia, "Haven't seen anything like this", fire crews called to thermal energy storage pilot plant, www.pv-magazine-australia.com Since the incident, MGA Thermal has addressed these issues and resumed the schedule of commissioning.

The role of ALDES in a high renewables power system

ALDES show great potential to reduce total power system costs, by reducing the total amount of capacity needed to maintain a reliable supply of electricity. The many ALDES pilots and projects being developed around the world demonstrate how this technology is already playing a key role in meeting the core challenge of a rapid, reliable and low cost transition.

This section explores several of the key roles played by ALDES in the transition. This analysis builds on the key system needs and capabilities identified in Part 1. It then supports the various policy recommendations made in Part 3.

We engaged Endgame Economics to provide some focussed modelling to explore the roles of ALDES. The modelling shows that ALDES can play multiple roles, including supporting increased penetration of renewables, reducing reliance on gas powered generation (GPG) and complementing transmission build, all the while reducing costs to consumers.

In more detail...

Modelling is a complex process and not everyone wants to understand exactly how the model works. For those who do, we have provided some 'In more detail' boxes below to explain what's happening, with further detail provided in Appendix A.

ALDES are a central element of the future power system

The ALDES considered in Part 1 of this report have specific capabilities which support reliability, security and operability of the power system. In doing so, they help keep the costs of the power system transition as low as possible for consumers.

The key ALDES characteristics identified in Part 1 included:

- **Long duration energy supply:** provision of a sustained energy supply of 12 hours or more
- **Carrying capability:** carrying that energy supply through time, with only minimal losses
- **Cycling capability:** repeat charge and discharge, with low levels of asset degradation
- **Synchronous services:** provision of key services needed to maintain system stability

This section explores how these capabilities interact with a changing power system, to drive cost and reliability benefits. This includes consideration of the:

- extent to which ALDES can help reduce total system costs;
- the intersection of emissions reduction targets, renewable penetration, GPG and ALDES
- how ALDES can support any changes in the relative penetrations of wind and solar; and
- interactions between transmission and ALDES build out.

Introduction to modelling approach

Endgame Economics were engaged by the CEC to model the role and function of ALDES in a future, carbon constrained power system. The full details of Endgame's modelling methodology is provided in Appendix A.

Endgame's analysis explored the role of ALDES in a series of future scenarios, related to gas costs and carbon constraints, delays in transmission build and the effects of increased storage cycling due to growing diurnal demand spreads. These results are laid out in a series of cell matrices, which explore the relationship of key variables with the cost and duration capability of a generic ALDES.

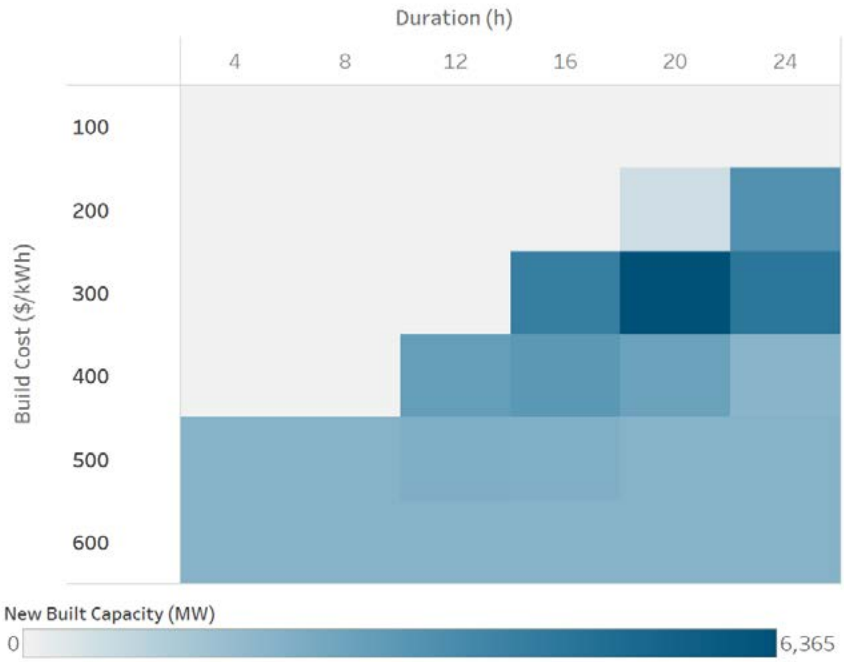


Figure 21: Example - Volumes of non-ALDES built by reference to ALDES costs and durations

In essence, the question being answered in each cell of the different matrices is: **if an ALDES technology existed with this specific cost and duration characteristic, how would it impact the system?**

This approach also allows us to map existing and developing ALDES technologies against the representative ALDES. This allows us to identify commercial thresholds, or points at which these existing and developing ALDES may begin to drive major change in the power system.

In more detail: How the modelling works

Endgame's analysis consisted of the following elements:

- A least-cost capacity expansion model, which identifies the lowest cost (CAPEX + OPEX + Fuel costs) portfolio of generation and storage assets to meet a provided demand forecast.
- The model is a greenfields approach, meaning that it develops an optimal portfolio as if it was building the power system from scratch.
- The model determines an optimal power system in 2040, which is consistent with the assumption of a greenfields approach – this is the power system we should be building now
- The modelled base scenario includes the following assumptions:
    - A carbon budget of 2% of 2022 levels, which is broadly equivalent to a 98% VRE penetration. This is used to reflect an ambitious level of decarbonisation, beyond the target of 82% renewables by 2030.
    - Gas is priced at $18/GJ. This gas price reflects the CEC view that supply and pipeline constraints mean that gas is unlikely to be priced at current levels of around $12/GJ over the longer term.
    - VRE and LIB costs are taken direct from 2023 Inputs, Assumptions and Scenarios Report (IASR) from the 2024 ISP.
    - A round trip efficiency RTE of 81% for ALDES, based on research of academic papers and reported OEM capabilities, also reflecting typical LIB RTEs

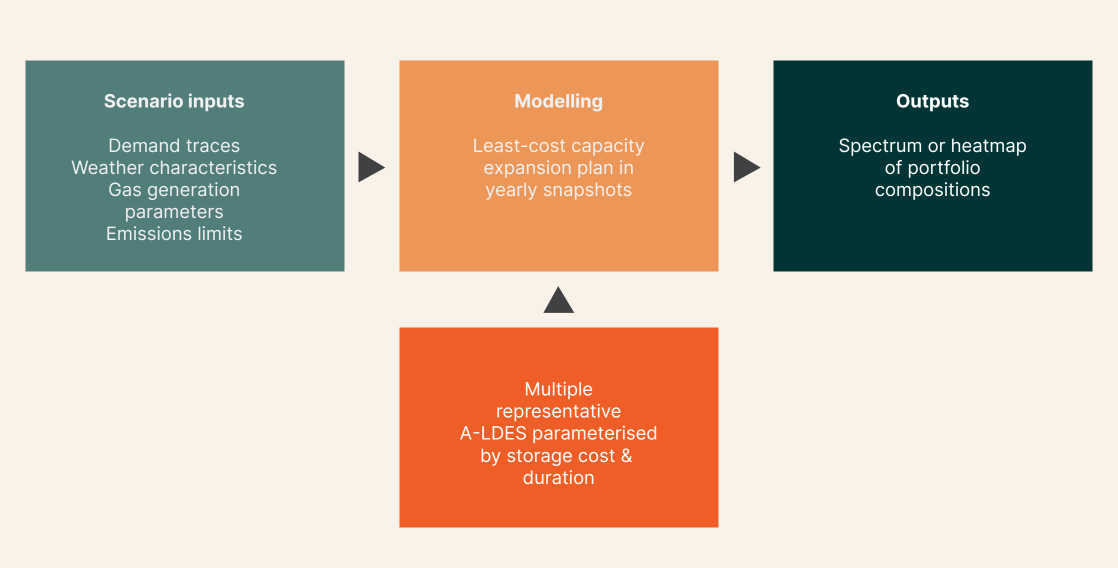


Figure 22: Approach to modelling

The model itself utilises a series of representative A-LDES candidates parameterised by 6 different storage costs (from $100/kWh - $600/kWh in $100/kWh steps) and 6 different durations (4-24 hours in 4h steps), together this creates a set of 36 (6 × 6) representative A-LDES candidates. These representative numbers were determined based on a survey of available data from OEMs and peer-reviewed sources.

These representative ALDES are then used to produces a 36 cell matrix (6×6 cells), which explore how ALDES at different storage costs and durations affect various power system outcomes.[110] Each cell is effectively a separate run of the model, with other inputs held constant, to assess the impact on total system outcomes from a change in the key parameters of ALDES storage cost and duration.

[110] 'Storage cost' in this paper refers to total capital cost of the ALDES, including all balance of plant, normalized by duration. This measure was used on the basis that it is simpler than other measures, such as levelized cost of storage.

Effect of ALDES on total system cost

ALDES will play a key role in reducing the total system costs of the transition.

The figure below demonstrates how the long run marginal cost (LRMC) of the power system generally decreases in line with reductions in ALDES storage cost, particularly once costs begin to fall below the $200/kWh mark and around 12 hours duration. It also maps the cost of some current ALDES to give a snapshot of the current cost frontier of these technologies.

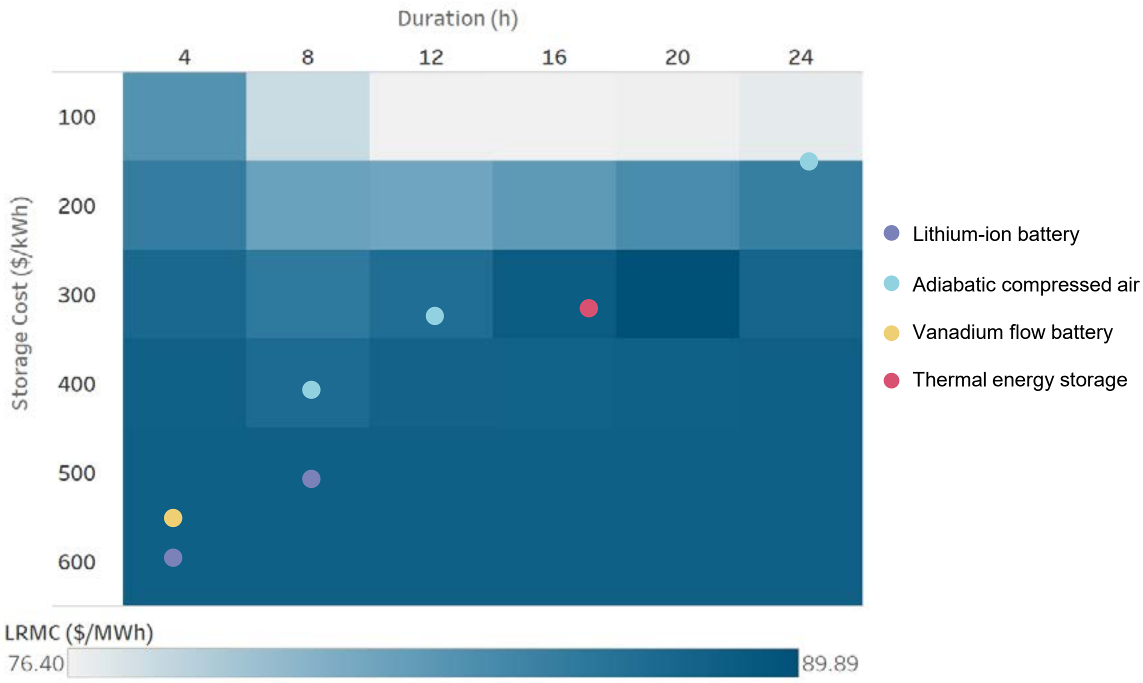


Figure 23: ALDES, system LRMC and current candidate technologies

Low cost ALDES are central to reducing total system costs. Modelling indicates a reduction of up to 15% in long-run marginal cost (LRMC)[111] if ALDES reach a storage cost of $200/kWh and energy storage duration of 12 hours or more.

The generation and storage system build cost, represented by LRMC), gives an indication of the optimal pathway to meeting demand. ALDES play a role in bringing down LRMC since these are technologies with low operating costs, long asset lifespan and an ability to access multiple revenue streams.

ALDES reduce total system costs by reducing the total generation and storage capacity build needed to meet energy demand at a given level of reliability. The ability to carry large volumes of energy through time reduces the need for other assets to be constructed – such as reducing the need for additional wind, solar and gas generation as well as other forms of storage.

Current estimates of existing ALDES storage costs have also been plotted across the representative ALDES cells – these are the coloured dots in Figure 23 above. Sourced from original equipment manufacturers, the CSIRO and various academic papers, these figures provide a snap-shot of the current cost of the range of ALDES explored in this report.[112]

The closer these existing ALDES costs get to the lighter parts of the figure – at the 12+ hour at $100/kWh mark - the closer they become to being competitive. Although LRMC is an admittedly limited metric, reductions in overall capital costs of these technologies means they will be selected by market participants on the basis of expected return.

[111] Long run marginal cost is the long term incremental cost of producing an additional unit of output. LRMC reflects the cost of an increased change in demand assuming all factors of production can be varied, including capital expenditure. Note that LRMC in this context only focuses on the cost of ALDES asset itself, not the cost of supporting infrastructure such as transmission.

[112] Readers should consider these values in the current context of rapid technological and commercial development of ALDES, which means they offer only a snapshot of costs relevant at a particular point in time. Some of the cost estimates are also more than 12 months old and, given the pace of change of development in this area, are likely to have come down relevant curves in the intervening time.

Relatively small reductions in some existing ALDES costs can therefore be expected to drive material changes in investment outcomes. We consider that targeted government support can therefore do much to bring ALDES down respective cost curves and foster large scale uptake across industry. Increased uptake accelerates learning rates, further reducing costs in a virtuous cycle.

The figure above also demonstrates the significant cost variance between different ALDES. Adiabatic compressed air, by some estimates, is either at or close to the point where it is market viable, while others ALDES appear further away from the point at which they are market viable.

These differences are at least partly due to the limited availability of accurate cost data for some ALDES technologies. Some technologies are also relatively more advanced, or have come further down cost curves, due to earlier adoption by industry. Equally, some technologies can make use of already established equipment, reducing installation and operational complexity.

However, many of these other forms of ALDES are rapidly catching up. VRFB and ZBFB, for example, are currently enjoying something of a developmental renaissance, with multiple firms developing modular and scalable solutions while input costs and supply chain issues are also being addressed. All of these factors suggest that overall ALDES costs will reduce. Thermal energy storage costs will also likely be reduced as part of the broader trend toward industrial decarbonization.

The key question – which will be explored in Part 3 of this paper – is what targeted assistance is best able to accelerate these developments and get ALDES to a point where they can be selected by the market on a commercial basis, to enable reductions in transition costs in their own right.

System costs of getting to 100% renewables

The Australian government has committed to a reduction in carbon emissions of 42% from 2005 levels by 2030. This translates into the specific target of sourcing 82% of energy supply from renewables by 2030. The 2030 target will require significant investment in generation, storage and transmission – this is a key focus of the CEC's immediate policy work.

An emerging debate is what happens after 2030. Discussions focus on what needs to be done now, to ensure we maintain reliability and keep the costs of the transition as low as possible.

Increasing the penetration of ALDES leads to direct reductions in the long term cost of the system. Below, we explore the role this technology can play in reducing costs as we get closer to 100% renewables.

To begin our assessment of the role of ALDES, we have considered the total system costs of moving to 100% renewables – that is, a power system that can reliably meet demand with zero carbon emissions.

To explore this, the model examined a range of carbon budget scenarios, ranging from a system operating on a carbon budget constraint of 0% of 2022 levels through to 10%.[113]

As shown in Figure 24 below, total system costs increase as total system emissions approach zero. This occurs because additional renewable generation and storage capacity needs be built to meet the last few percent of demand. A lot of this additional capacity is utilised occasionally – such as to meet seasonal shortfalls or dunkelflaute events – so it markedly increases total system cost.

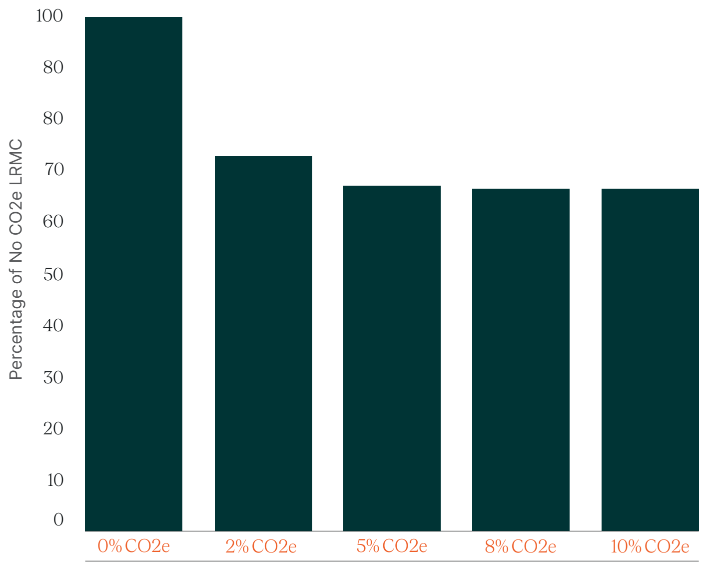


Figure 24: Change in total system costs associated with reaching a zero carbon 100% renewables

[113] In modelling terms, a carbon budget constraint is simply a hard limit imposed on the mathematical model which prevents it from building and / or operating generation that will result in the carbon limit being breached. In the 0% carbon budget scenario, this means that only renewable generation and storage can be selected. In the base case 2% scenario, gas powered generation can be built, but its actual output must be strictly constrained by the model in order to comply with the overarching carbon constraint.

In more detail: what is the basis of this cost increase?

These significant increase in total system costs of moving from a 2% to 0% carbon constraint reflect a particular trade off that occurs only once the power system approaches levels near 100% renewables.

To meet customer energy demand under the 0% carbon budget, the model has to build significant additional volumes of renewables and storage, which are utilised very infrequently. For example, to ensure that demand can be met even on extreme low wind/solar days that occur only once every 5 years, the model has no option but to build large amount of wind, solar and storage capacity, all of which only operate for those few days.

This means the marginal cost of meeting these final increments of demand is equal to the additional capital cost of this rarely utilised renewable generation and storage, plus the capital cost of this rarely utilised additional energy storage.

If the carbon constraint is relaxed slightly – say in the 2% CO_2e world - the model is able to build and operate very small volumes of gas powered generation (GPG), to meet the final increments of demand. These GPG are built and operated very infrequently, primarily to provide backup generation to meet occasional seasonal shortfalls.

The marginal cost of meeting demand is therefore the capital cost of the GPG and the variable cost of the small amount of gas the GPG burns.

The trade-off is therefore between how the marginal increments of demand are met in either scenario. The costs of meeting these final increments of demand are:

- In the zero carbon world, the capex of wind/solar + the capex of storage
- In the 2% carbon world, the capex of GPG + the opex of the small amount of gas burned

Given that capital costs are significantly higher than operating costs, the model naturally shows a major increase in total system costs as it moves to this zero carbon world and is required to build a lot more capital intensive generation and storage.

Standard industry understanding[114] of the transition aligns with this modelled outcome – namely, that the final steps of fully decarbonising the power system may be expensive, at least with current technologies. Under this understanding of the transition, GPG plays a role at the margins, allowing the power system to get to a very high, but not 100%, penetration of renewables.[115]

This paper does not question the underlying logic that GPG, or some kind of fuel based generation, may play a role at the margins, to meet these final increments of demand. Rather, it considers what can be done in the steps before, to ensure that reliance on GPG is minimised. This is consistent with the goal of reaching net zero by 2050 and the broader imperative to reduce reliance on carbon.

At a more practical level, reducing reliance on GPG also reduces overall risks to the power system. As discussed in Part 1 of this paper, AEMO and others have identified various issues with gas supply and transportation infrastructure, which will make it increasingly difficult to rely on GPG to meet demand during seasonal shortfalls or wind droughts.

ALDES can play a key role in reducing the reliance of the power system on GPG. ALDES can be used to help meet peak demand periods, support daily ramping needs as well as providing sustained energy during seasonal shortfall, wind drought and dunkelflaute periods. These are all roles traditionally played by GPG, which ALDES can deliver at lower cost and with zero carbon emissions.

This is demonstrated in Figure 25 below, which shows how reductions in the cost of ALDES almost halves the amount of GPG needed in the power system.

[114] Gilmore J., Nelson T., Nolan T., Firming technologies to reach 100% renewable energy production in Australia's National Electricity Market (NEM), Jan 2022. Available at Microsoft Word - Firming technologies to deliver 100 percent VRE.docx (energy.gov.au)

[115] Of course, it may be possible to decarbonise this last increment of the supply curve, for example by moving to hydrogen fueled turbines, or using low carbon liquid fuels such as biogas or biodiesel. At this stage, these alternative fuels are expensive, however future developments may reduce these costs.

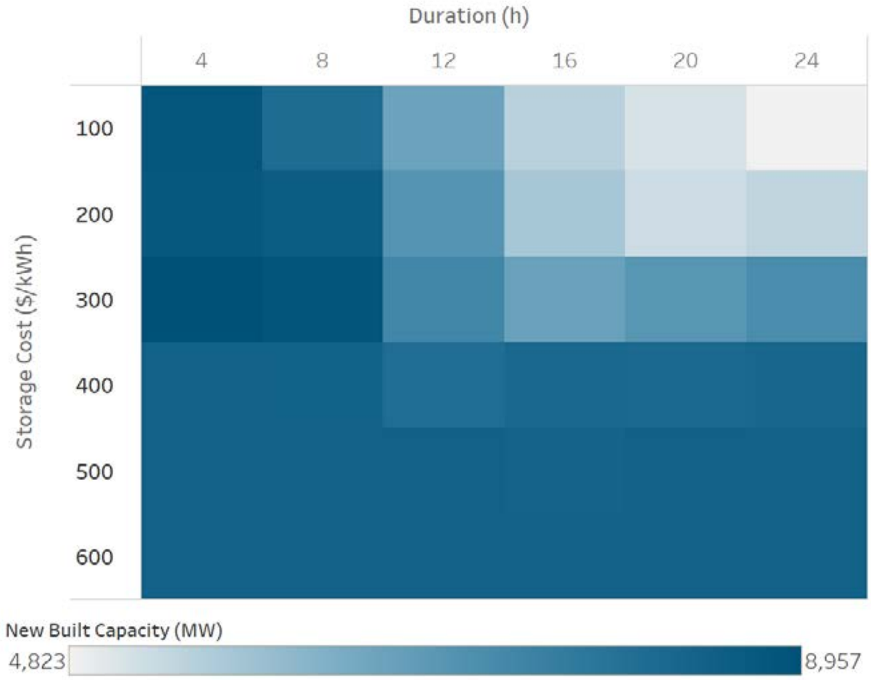


Figure 25: New build GPG capacity under different ALDES costs

In more detail – Why ALDES is better for the power system than GPG

There are many factors which suggest an even more significant substitution of ALDES over GPG.

Firstly, the model assumes that the gas fuel used by GPG is available at a price of $18/GJ. However, the upstream gas supply and transportation issues identified in Part 1 of this report, coupled with the inexorable trend toward explicitly costing carbon, all point to actual future gas prices being higher in future.

Secondly, gas pipelines are not physically or commercially designed to support the sporadic but significant offtakes that would occur under a seasonal, backup operational mode of GPG. As others have shown[116], there are many issues associated with operating GPG in this manner. Supply may simply not be available, while pipeline offtake arrangements are entirely unsuitable to support these rare but extreme spikes in gas demand for GPG.

At this stage we have not been able to quantify and model these real world limitations. We expect that if they can be effectively quantified and incorporated into modelling at their true costs, we would expect to see GPG become less credible as a form of generation in the model.

[116] Gilmore J., Simshauser P., Solving for 'yy': demand shocks from Australia's gas turbine fleet, available at Fuel Poverty in 2022 (griffith.edu.au)

In reducing reliance on GPG, ALDES also act to increase the total renewable penetration of the power system. Perhaps counterintuitively, this is best illustrated by seeing what happens when carbon budgets are relaxed and the model is allowed to build and operate more GPG to meet demand. The outcomes of this analysis are laid out in Figure 26 below.

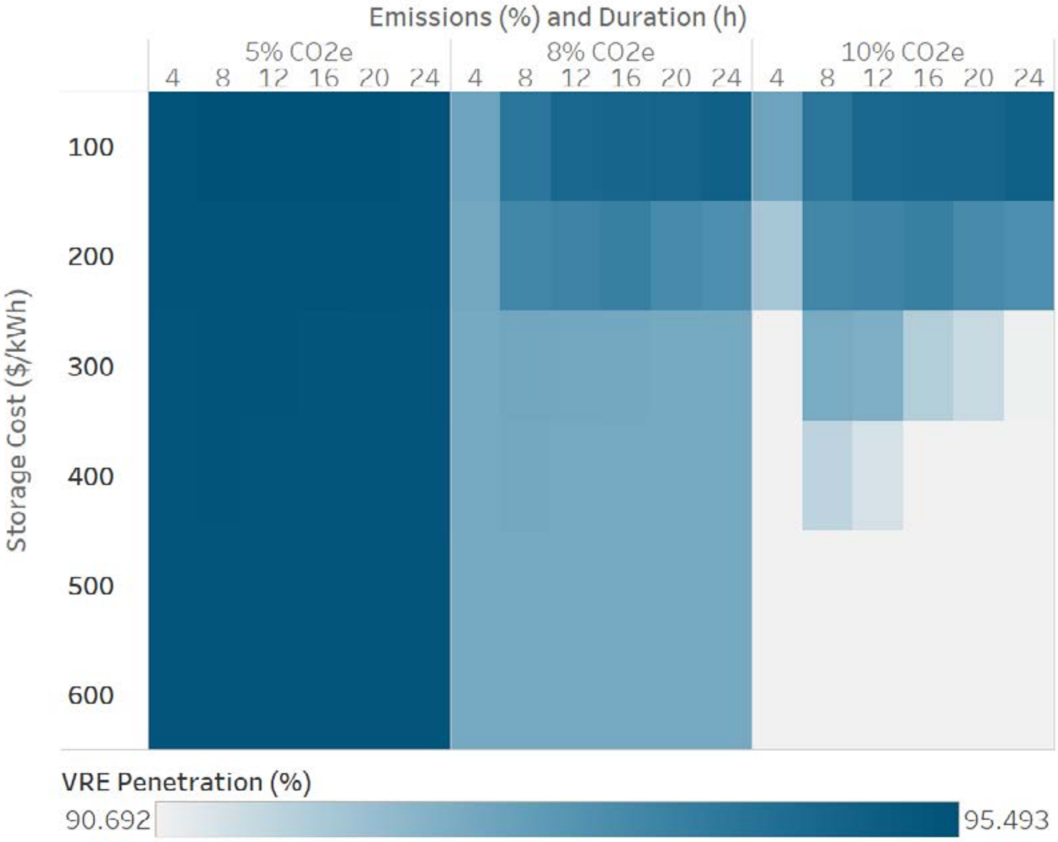


Figure 26: Levels of VRE penetration enabled by lower ALDES costs

This graph maps the relative penetration of renewables (variable renewable energy, VRE) as a function of carbon budget and cost of ALDES. Moving from left to right the carbon budget constraint is relaxed, allowing the model to build more GPG under three carbon budget scenarios (5%, 8% and 10% of 2022 levels respectively).

Under each scenario, the model then explores the relationship between ALDES cost / duration and the respective renewable penetration of the power system.

The key takeaway is that even if the carbon budget is relaxed - and the model is *allowed* to build and operate more GPG – the presence of lower cost ALDES means less GPG is built. Expressed another way, reductions in ALDES cost mean the model prefers to meet demand by building storage and renewables, instead of GPG, increasing the overall renewable penetration of the system and lowering overall system costs.

This demonstrates two key trends that are relevant to the role of gas vs ALDES in meeting demand in a carbon constrained world.

Firstly, ALDES provides a powerful enabling effect, driving higher penetration of VRE and reducing the need for GPG. ALDES does this by enabling better utilisation of renewable generation, improving the ability of the system to carry energy effectively through time. ALDES reduces the amount of renewable generation wastage – energy lost due to curtailment – allowing total demand to be met with a smaller, lower emissions generating fleet.

Secondly, it also demonstrates how the cost of fossil methane gas increasingly affects the viability of GPG relative to ALDES, in a carbon constrained world. We have found that if the model is allowed to consider higher future gas prices, ALDES build increases.

In more detail – carbon budgets and GPG operation in the model

As noted above, the model seeks to minimise total system costs. It does this by trading off the capex of renewables and storage, vs the capex and opex of GPG, to meet the final increments of demand.

In the base case – which includes a carbon constraint of 2% of 2022 levels – these GPG opex costs are low, as the model does not allow the GPG to run very frequently, to remain within its carbon budget. In a sense, the model's own carbon budget tends to make GPG look favourable, as it allows it to run in a manner that is not reflective of physical or market realities.[117]

This changes if the model is allowed to run more GPG and if the cost of gas increases, as we consider is a reasonable future outcome. To illustrate this, we relaxed the carbon budget to 10% of 2022 levels. We also explored a high gas scenario, with gas priced at $27/GJ – a price more likely to reflect future gas prices and which approaches the liquid fuel price of $33/GJ.[118]

Once higher gas prices are accounted for, less GPG is built – as shown by the consistent lightening of cells between the base case to the high gas scenario. This effect is heightened with lower ALDES costs, as shown by the lightening of cells moving to the top right of both scenarios.

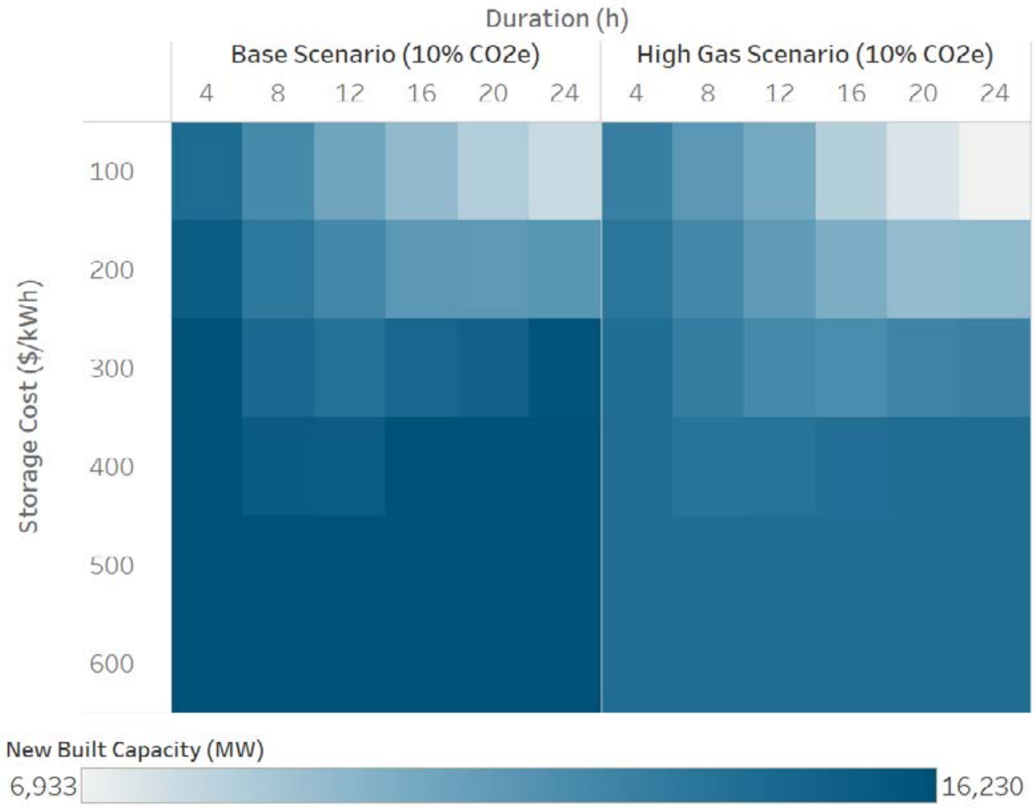


Figure 27: New build gas capacity under relaxed carbon budget and higher gas price

[117] In practice, the GPG generation fleet is not kept in reserve and used only as 'backup' sporadically to meet seasonal shortfalls – this is not a commercially viable model and, as illustrated earlier in the paper, is also inconsistent with the physics of gas pipeline supply and transmission infrastructure. By requiring GPG to run in this manner, the model makes these assets appear lower cost than in practice they would be.

[118] As noted in Part 1 of this paper, it's more likely that future fuel based generation will need to have onsite fuel reserves – such as diesel or kerosene – as opposed to sourcing gas from transmission pipelines.

Further work is needed to explore the full suite of costs associated with GPG, in order to understand the role it will play in the future power system. This analysis needs to consider the physical and commercial realities of operating GPG as seasonal backup generation. Furthermore, work is needed to understand the costs of decarbonising GPG, or other fuel generation, if this generation remains necessary to meet the final increments of demand in a high renewables power system.

ALDES and renewables buildout

One of the key challenges in the transition is achieving a balanced mix of wind and solar generation. Each of these technologies brings a particular set of physical capabilities which complement and reinforce each other. Different balances between the two technologies also give rise to a need for different types of energy storage, to maintain a reliable and secure supply of energy.

Solar - both utility and rooftop PV - and wind renewable generation have the following characteristics which in turn influence outcomes on the power system.

Solar generation:

- Has a lower upfront capital cost than wind
- Is faster to build than wind, due to modularity and fewer technical connection issues
- Has a lower capacity factor than wind
- Is subject to a relatively predictable diurnal solar energy resource availability, driving the 'duck curve' effects of minimum demand and steep residual demand ramps on the power system

Wind generation:

- Has a higher upfront capital cost than solar
- Slower speed of build time due to more complex technical connection issues
- Higher capacity factor and system size increases contribution to system reliability
- Can complement diurnal output patterns of solar, helping to ameliorate some of the effects of the duck curve
- Increases system vulnerability to wind drought effects and therefore reliance on GPG

These characteristics make wind and solar very effective complements to each other. AEMO has identified that by 2040 the optimal combination of installed solar and wind capacity will comprise of 64% solar (combined rooftop and utility scale) with wind generation at approximately 36%.

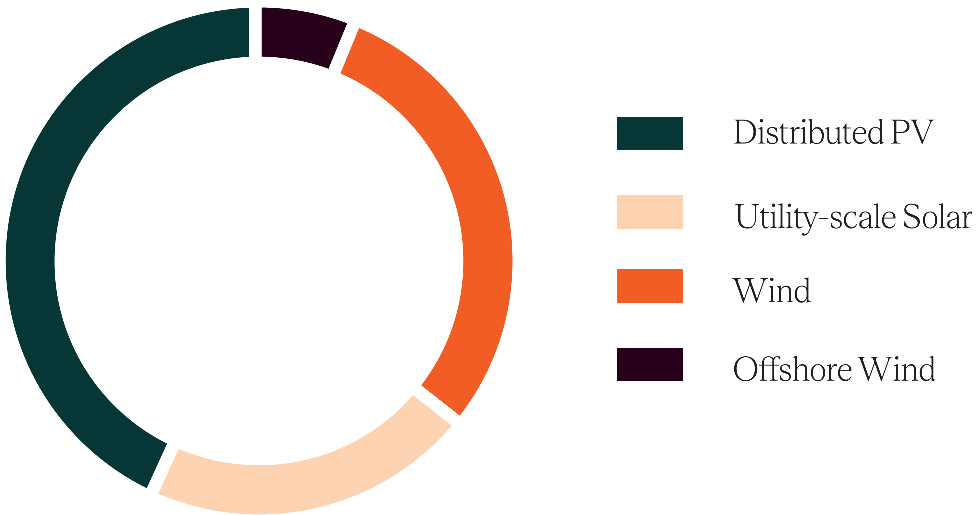


Figure 28: Installed wind and solar capacity, NEM 2040[119]

Source: AEMO data sheet, Draft 2024 ISP generation and storage outlook, summary NEM generation by year. Not shown are penetrations of storage, gas, hydro, coal and demand response.

[119] Note that AEMO's projections in the ISP are based on a long run economic optimization model that differs markedly from the analysis undertaken by Endgame in this report. AEMO's analysis considers multiple complex variables and is designed to co-optimise generation and transmission build over time. It also takes as given state based emissions targets and programs, such as the NSW Energy Roadmap and Queensland Jobs and Energy Plan, which further impacts its results. Any differences between the ISP values and Endgame's analysis should be viewed with this in mind.

Current solar and wind ratios sit at around 70:30 solar to wind. Current project development patterns are also consistent with a trend towards these penetrations of solar relative to wind, with cumulative installed solar generation capacity growing at a faster rate than wind generation capacity over the last five years.

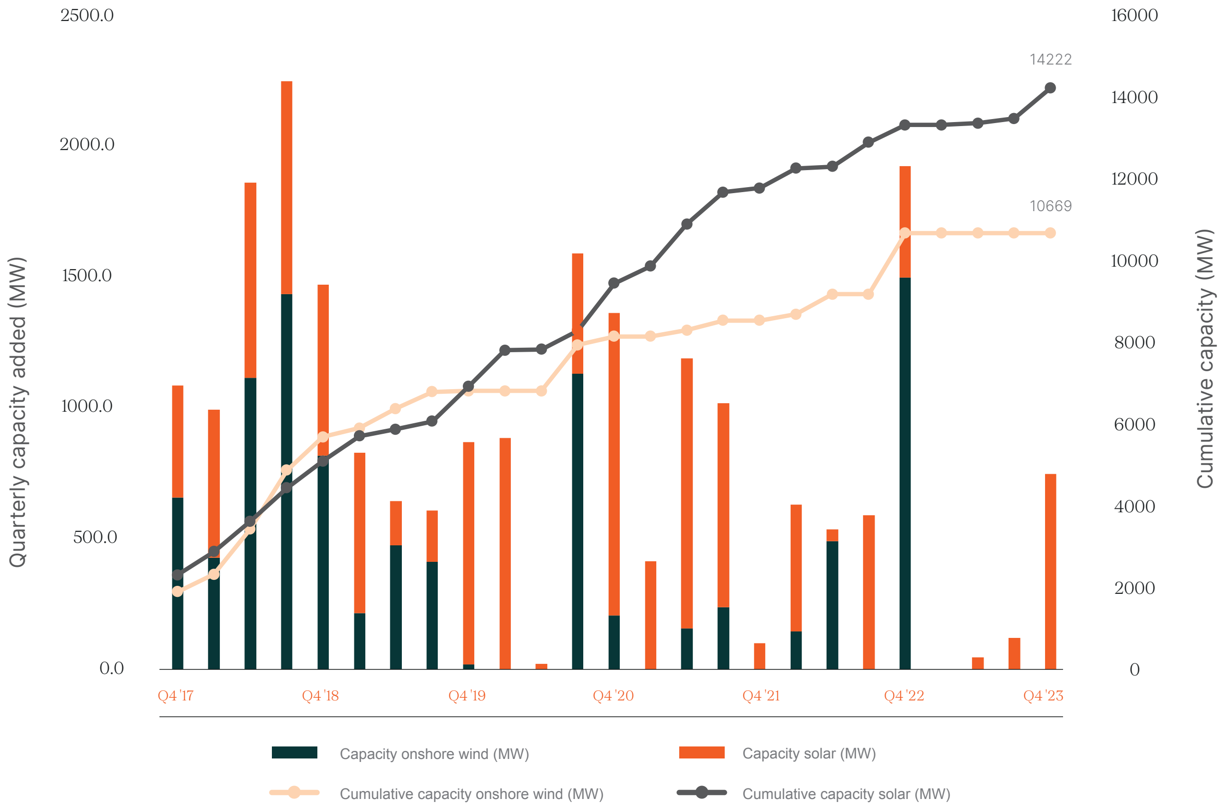


Figure 29: Wind and solar capacity reaching financial close, 2024[120]

Source: CEC

As discussed in Part 1 of this paper, a key system outcome of increases in solar generation to wind is an increase in the diurnal spread of energy demand, or the duck curve. This gives rise to an increased need for storage capacity to carry this energy from midday – when it is abundant – to the later periods of the day when it is needed to meet demand.

Those ALDES with high cycling capabilities are well suited to meet these needs, as they are a natural complement to these regular diurnal spreads. The good cycling capability of ALDES allows them to go through daily charge and discharge cycles, to carry energy throughout the day, with reduced degradation of the asset.

ALDES can also play a role in supporting relatively higher penetrations of wind, should that occur. A key effect of increase penetrations of wind is to increase system susceptibility to wind drought effects. The traditional solution to this has been GPG; as we have seen above, ALDES are a natural and cost effective substitute for GPG.

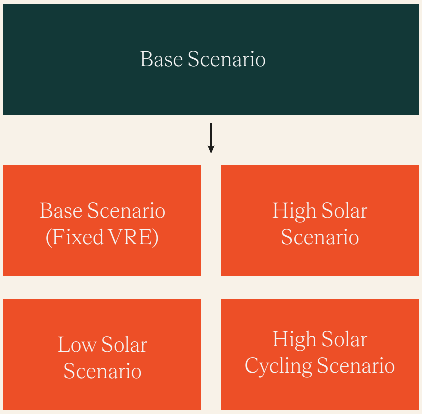
To explore this potential role of ALDES under different levels of wind and solar, we modelled several different renewable penetration scenarios in the NEM in 2040. Our key findings were:

- Increases in solar relative to wind increases daily demand spreads, which in turn creates a demand for storage assets that can undertake repeat daily cycles
- Increases in wind relative to solar increases the sensitivity of the power system to seasonal shortages and wind droughts, increasing the requirement for other forms of generation or storage to help meet demand during these periods

[120] Clean Energy Council, Renewable Energy Projects Quarterly Report Q4 2023, p.9.

Endgame ran a series of scenarios to assess how different levels of solar generation in the system would affect ALDES build out.

The model explores these scenarios as follows.



Modified Methodology

1. Run the base scenario through the model with **A-LDES disabled.**
2. Identify the new VRE built capacity from the results
3. Create the 3 required scenarios from the identified new VRE capacities

Base Scenario (Fixed VRE): Fix the optimal VRE capacity found in the previous step(60:40 solar to wind ratio)

Low Solar Scenario: Adjust the optimal VRE capacity to achieve target ratio (50:50 solar to wind ratio)

High Solar Scenario : Adjust the optimal VRE capacity to achieve target ratio (70:30 solar to wind ratio), the same for the High Solar Cycling Scenario but also includes an increase in Li-ion costs

4. Run the new cases through the model with **A-LDE5 enabled** but **new VRE build disabled** and analyse the results

The final High Solar Cycling scenario increases the cost of lithium by 20% from the base case, as a proxy for the effects of increased cycling on LIB asset lifespan.

More solar means more cycling

A key finding of this analysis is that as solar penetration increases, ALDES play a growing role in minimising total system costs. The capability of many ALDES to undertake a larger number of deep cycles, with relatively less degradation than other forms of storage, makes them a natural choice to manage the daily diurnal demand spreads, colloquially known as the duck curve.

Those ALDES with an appropriate safety profile are also well positioned to act as community battery 'solar soaks', to help manage the impacts of increased rooftop PV generation in residential areas.

Under scenarios of increasing penetrations of solar relative to wind, the model selects for increasing volumes of ALDES, particularly at a 4 to 8 hour duration. This mirrors the typical duration of a daily ramp / diurnal spread associated with a high solar power system. However, longer durations were also selected. ALDES can provide this repeated 4 – 8 hour duration service, while also providing longer durations.

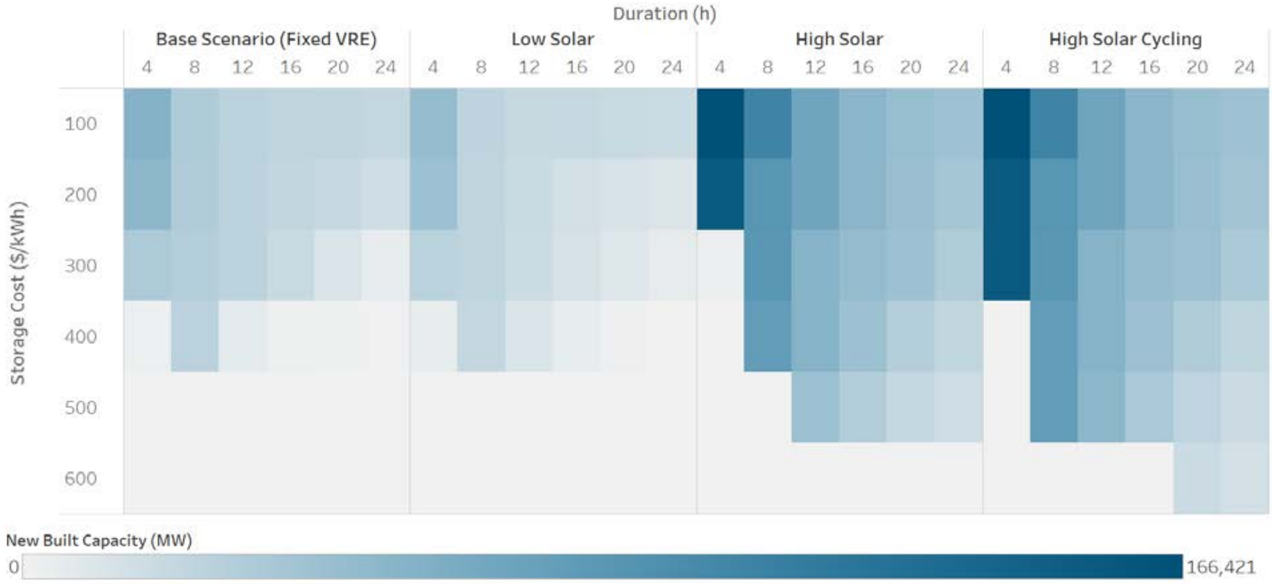


Figure 30: New ALDES build by solar build out scenario

A further implication of the repeat cycling necessary to support a high solar system is that storage types with a lower higher total cycling capability will be at an advantage. Currently, some ALDES demonstrate cycling capabilities that exceed some LIB technologies.

Current estimates are for LIB assets to be able to deliver up to 8000 cycles before energy output drops below a level that is commercially viable. In contrast, many of the ALDES examined in this paper are capable of delivering 20,000 or more cycles during their operational lifespan.

In more detail – LIB cycling capabilities

Currently, estimates of total cycling capability of utility scale LIB assets range widely, with values ranging up to 8,000 cycles quoted.

Importantly, estimates of cycling capability are highly dependent on a raft of factors, both in terms of physical design and operational patterns. The term 'cycling' itself can be interpreted in different ways, although the standard interpretation is that it entails close to the full MWh energy capability of the battery being discharged over a defined timeframe, typically once a day.

Cycling of LIB assets results in decomposition of the electrolyte over the anode and the deposition of unwanted materials on the electrolyte interface.[121] This reduces the capacity of the cells in the battery, by reducing the cathode voltage, which in turn reduces the amount of power the battery can produce.

This reduction in output effectively shortens the asset's commercial life, on the basis a minimum level of power output is necessary for the asset to be commercially viable.

The number of cycles that a utility scale LIB asset can deliver is affected by a number of variables. While OEM's typically supply LIB with a given number of cycles for the duration of the asset life, this is affected by multiple operating factors such as depth of discharge and standard operating temperature.

Required output of the asset is also relevant to the number of cycles – 'oversizing' the battery and only using some of the total cell capacity allows for shallower depth of discharge, in turn extending the number of cycles the asset can deliver.[122]

Developments in LIB chemistry itself are also extending the number of cycles that standard utility scale assets can provide. The move from nickel / manganese / cobalt (NMC) chemistries to lithium ferro-phosphate (LFP) has increased the number of cycles that most LIB assets can provide, while also reducing thermal runaway risks.

Finally, emergent technologies, particularly the development of lithium titanate (LTO) batteries, has the potential to significantly extend the cycling capability of lithium based batteries, potentially upwards of 20,000 cycles. However, currently this technology has a lower energy density and is more expensive than NMC and LFP lithium batteries.

The 'high solar cycling scenario' explores this effect of repeat cycling on LIB lifespan. To model this effect, we increased LIB costs by 20% from the base case. This is used as proxy for a shortening of the commercial life of the LIB asset caused by an increase in repeat cycling.

The effects of this scenario are significant, with increased uptake of ALDES both at 4-8 hour durations, but also at much longer durations.

The are various real-world implications of this analysis. The most obvious is that in a world with much deeper diurnal demand spreads – duck curves becoming 'duck canyons' – LIB batteries may not always be the optimal solution. Repeat cycling of LIB assets, particularly to a deeper level of discharge, will result in a reduction of their power output, shortening their commercially viable operating life.

The commercial implications of this are that storage operators will need to replace cells and other elements of their LIB assets more frequently, increasing overall costs.

However, continued improvements in LIB technology development and manufacturing will somewhat mediate this effect, reducing the cost of replacement LIB assets.

This trend is also likely to accelerate the battery recycling industry, to manage the impacts of these LIB assets reaching end of life. Various LIB industry participants are already developing recycling processes.[123] Generally this is a growing focus area for the clean energy industry and will become more important under this scenario.

The locational dependencies of different storage technologies will also be relevant. Many ALDES display physical characteristics that make them appropriate for location close to, or even within load centres. This means ALDES are particularly well positioned to operate as community batteries – assets located close to residential load that can help soak up excess rooftop solar generation. These solar soaks offer value to customers as well as networks, helping to manage wholesale price impacts as well as supporting stable network voltages.

[121] Rashid, M. Gupta, A., Effect of Relaxation Periods over Cycling Performance of a Li-Ion Battery, DOI 10.1149/2.0201502jes
[122] Viswanathan, V., Mongird, K., Franks, R, Li, X., Sprenkle, V., Baxter, R., 2022 Grid Energy Storage Technology Cost and Performance Assessment, Energy Storage Grand Challenge, US Department of Energy
[123] See: Tesla, Impact Report 2022.,

Redox flow batteries may be particularly effective here as they have a safety profile which makes them ideal for location within load centres with high volumes of rooftop PV. RFB also demonstrate a high cycling capability of between 10,000 and 20,000 cycles, with most components fully recyclable, helping to reduce end of life waste issues. This is evidenced by developments in Queensland, where redox flow batteries have been deployed to act as solar soaks and help manage these effects.[124]

Finally, it is worth noting that the cycling effects on LIB assets can be effectively managed through coupling of LIB assets with other forms of ALDES. For example, a trial being run in Oxford has paired a 55 MWh (50 MW/50MWh) Wartsila LIB asset with a 2MW/5MWh Invinity VRFB.[125] This project will harness the low degradation / high cycling capability of the VRFB to extend the lifespan of the LIB.

This hybrid approach increases total revenue by increasing the number of markets the asset can participate in, while also extending the total lifespan of the LIB asset.

More wind means greater requirement for energy duration

Wind generation is central to the overarching reliability of the power system, a role that it will continue to play as the transition continues.

Wind generation tends to have a higher capacity factor[126] than solar generation. This means that for every MW of wind capacity built, more energy will be produced. This reduces use of resource and increases overall efficiency of the power system.

Wind generation also follows a different energy production profile to solar. Most obviously, wind is not subject to solar availability and can therefore generate at night when solar generation is not available. This makes it a good complement to solar generation, in terms of maintaining overall reliability of supply.

The energy output of wind generation is more stochastic, or probabilistic, as compared than solar. This means that its output is more 'random' than solar – ie, it does not operate on as clearly a predictable daily output pattern.

This means that wind generation is also susceptible to lower probability but higher consequence events, such as sustained wind droughts. While *wind drought* is not a strictly defined term, it is generally held to describe a sustained period of lower wind speeds, resulting in a prolonged reduction wind generation output. These periods can occur as part of more predictable seasonal shortfalls and are sometimes coupled with sustained reductions in solar generation.

However, from time to time they can be more severe, or occur at times when less expected. Most recently, the NEM experienced a period of approximately a week of sustained reduction in wind generation in April, with wind contributing approximately 6% to total demand, down from the 12 month average of 13%.[127]

As the penetration of wind generation in the system grows, so does the overall susceptibility of the system to wind drought events. Under much higher penetrations of wind, reliability issues may become apparent under these conditions.[128]

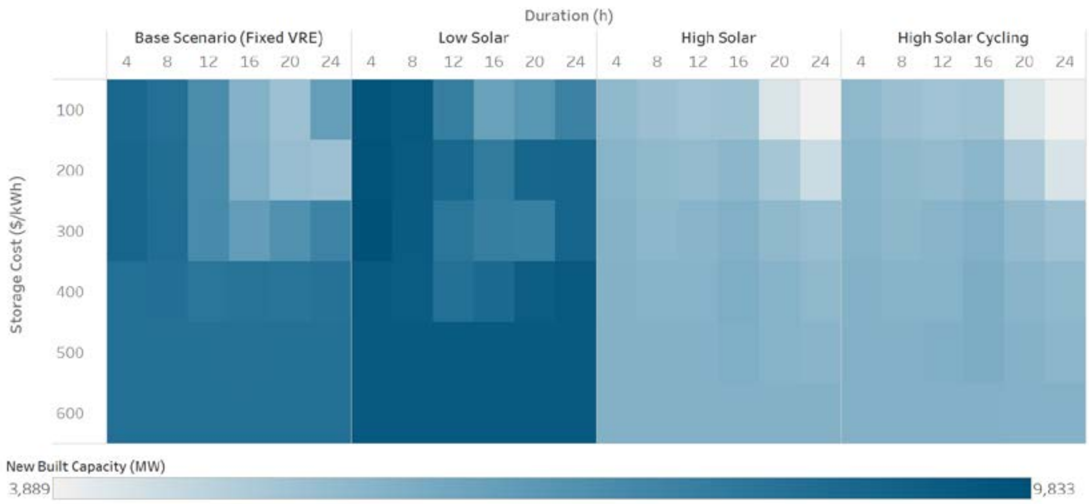


Figure 30: Gas powered generation under higher wind penetrations

[124] RenewEconomy, Queensland funds another 12 "solar soaker" batteries, plus two locally made flow batteries, Jan 2024
[125] Murray, C., Energy Storage News, 2022, Project briefing: World's largest lithium vanadium hybdrid, www.energy-storage.news
[126] Capacity factor is the ratio of actual electrical energy output over a given period of time to the theoretical maximum electrical energy output over that period. The theoretical maximum energy output of a given installation is defined as that due to its continuous operation at full nameplate capacity over the relevant period. See USNRC, available at Capacity Factor (net) | NRC.gov.
[127] WattClairty, Generation gone with the wind, 18 April 2024. Available at www.wattclarity.com.au
[128] It is noted that the Reliability Panel has advised that more events are expected to remain rare, even in higher penetrations of renewables and that the existing reliability standard will be capable of capturing more likely events.

Additional dispatchable energy supply is required to maintain reliability during these wind drought conditions. As discussed in Part 1 and above, GPG has been identified as providing this additional energy supply to support reliability during wind droughts.

This is borne out in the modelling, which finds that under higher penetrations of wind – as shown in the "low solar' scenario – greater GPG capacity is built.

As discussed above, there are multiple limitations associated with GPG, such as upstream supply availability and the physical capabilities of pipelines to transport gas to GPG units, under these extreme conditions.

ALDES is well positioned to substitute for GPG in this scenario. ALDES can provide sustained energy supply for long durations and can also carry substantial volumes of energy over long time periods. In combination, these capabilities make ALDES well suited to support power system reliability during periods of wind drought.

Furthermore, wind droughts can occur as part of standard winter seasonal demand patterns, which can give rise to coincident demand for methane gas for residential space heating, industrial uses and fuel for GPG. This further disadvantages GPG relative to ALDES, which are not susceptible to these pressures.

ALDES and transmission build

Storage and transmission are natural complements. Transmission carries power through space, while storage carries it through time. Storage can increase the amount of power carried by transmission infrastructure. It can also help maintain overall power system reliability and cost, if delays arise in the development of transmission.

Major transmission projects can be subject to delays for a number of reasons. Social license issues have arisen with some major transmission projects, while supply chain issues can also contribute to delays. Given the critical linkage between renewable generation development and transmission build out, these delays can have material impacts on the cost and reliability of electricity supply.

ALDES can help manage the impacts of these delays. If transmission is unavailable to transport power across large distances between remote generation centres and load, ALDES can be used to carry more energy through time, to meet customer demand as it arises.

In more detail – modelling the effects of transmission build delay

Endgame's model includes the key transmission In more detail – modelling the effects of transmission build delay

Endgame's model includes the key transmission lines being built to transport energy from REZs to load centres.

To assess the overall system impact caused by a delay in transmission, Endgame modelled a scenario where VNI West - a major transmission line - is removed. This means that transmission connection with two key renewable energy zones (REZs) - the Western Victoria and Murray River REZs – is no longer available. The generation in these REZs is therefore no longer available to the model.

These are two high quality REZs, with good solar and wind resource availability. This resulted in the model seeking to meet demand from generation built elsewhere.

Two key results can be observed from this analysis.

Firstly, in order to meet demand, more solar generation is built. This is demonstrated in Figure 32

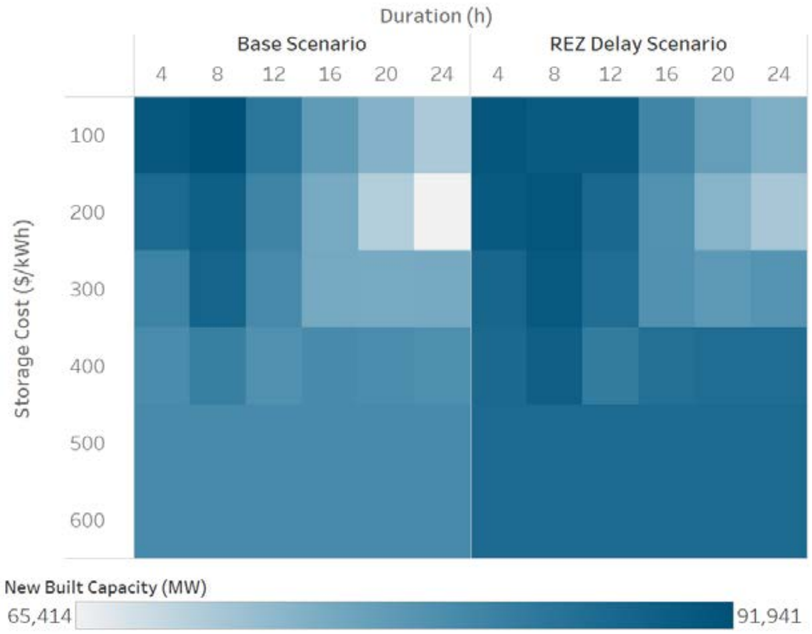


Figure 32: New build solar capacity under REZ delay scenario

As discussed earlier, increased solar in turn increases the demand for ALDES, particularly around the 4-8 hour mark. This is more reflective of the capability of ALDES technologies to provide effective cycling capability, although note the model does also select for some additional longer duration storage around the 12+ hour mark. These trends are illustrated in Figure 33 below.

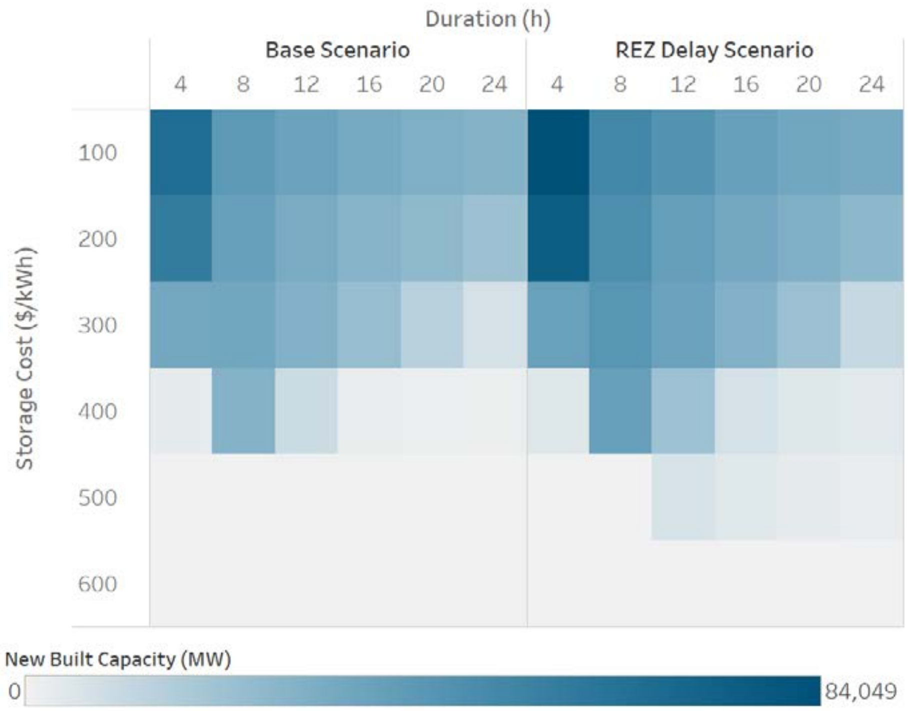


Figure 33: New build ALDES under REZ delay scenario

We also see a change in the volumes of 8 hour duration LIB assets built, relative to ALDES, for longer durations. However, 8 hour LIB assets show a marked increase in the 4 to 8 hour mark, particularly where lower cost ALDES are unavailable (ie, ALDES costs are above $400/kWh). This reflects the relative roles of each storage technology over different durations and the trade offs that occur between ALDES and LIB at shorter durations, where LIB is more traditionally dominant.

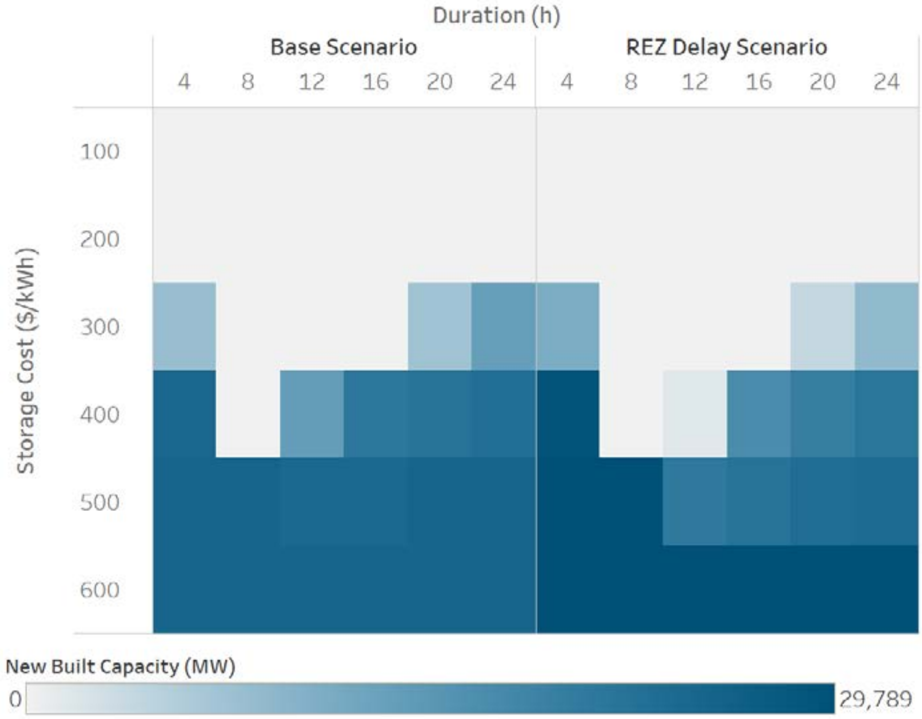


Figure 34: New 8 hour LIB capacity relative to ALDES cost under REZ delay scenario

Delays in different transmission lines will have different effects on the power system and ALDES can be expected to play a different role in those circumstances. Generally however, ALDES can play a key role in managing these impacts.

These findings should be read as a general illustration of the broader power system effects associated with transmission delay, particularly the role that ALDES and different forms of generation can play in substituting for transmission build.

Although separate to the specific case modelled here, the general capability of energy storage to replace or complement transmission has already been translated into several real projects. This include the:

- Hornsdale Power Reserve in South Australia, which provides multiple system support services that protect the South Australian region against major blackouts, if the Heywood interconnector were to trip
- Victorian Big Battery, which compensates for potential loss of the NSW-Vic interconnector, allowing greater power sharing between the regions during summer periods, reducing prices and supporting reliability
- Silver City ACAES project in Broken Hill, currently in development, which will provide reliability 'back up' services as an alternative to either network augmentation or use of diesel generators to maintain reliability

This complementarity with network build is a key way that energy storage will help to reduce total system costs to consumers in future. The policy implications of this complementarity are explored in more detail in the following section.

Policy Implications

This section explores some policy reforms to support ALDES in becoming a key component of the NEM energy storage portfolio.

Many of these recommendations apply to all long duration energy storage solutions, including PHES and the range of ALDES explored in this paper.

Our key recommendations include the following, which are unpacked in more detail in the rest of this section:

A new energy reserve service

Consideration should be given to the development of an energy reserve service, through the upcoming post-2030 NEM review. Such a service should be designed around meeting system needs, in particular reliability and security requirements to manage the transition away from coal and gas powered generation (GPG). This service should be designed around considerations of energy duration, timing and location of storage assets out to 2040. The service could be procured through various models.

Commitment to zero carbon energy reserves to manage reliability

In considering new mechanisms to support investment, the post 2030 review must prioritise zero carbon solutions and recognise the limitations of reliance on GPG in maintaining reliability in the face of coal generation exit.

Enhancements to the CIS and NSW LDS LTESA frameworks

Longer duration storage, including the ALDES discussed in this paper, can be enabled by targeted changes to existing underwriting mechanisms. This may include lengthening of contract tenors in the CIS, as well as more clearly defined merit criteria. Government should also consider measures to enhance competition in tender processes, such as providing partial refunds of bid costs to better enable PHES and ALDES proponents to participate in CIS and LTESA tenders.

Long duration targeted underwriting mechanisms

Policy makers should consider separate underwriting mechanisms for longer duration storage, beyond the current CIS and NSW long duration storage LTESAs. As with design of any energy reserve service, new underwriting schemes should be developed with a focus on system needs.

Tailored financial support

We recommend policy makers also consider different models of financial support, to recognise the public good element of many forms of longer duration storage. Such approaches should be designed to minimise market distortion and should be complements to new services and underwriting schemes.

Industry knowledge sharing

ARENA and CEFC to continue and expand programs related to supporting pilots and trials for ALDES, as well as sharing knowledge and learnings of these schemes across industry.

Reforms to DUOS and non-network option (NNO) frameworks

ALDES can play a key role in supporting outcomes at both transmission and distribution networks. A range of reforms to the network charging and NNO frameworks are necessary to enable the capability of ALDES to reduce network costs and improve reliability.

Long duration energy technologies, including the ALDES discussed in this report, can play a key role in minimising the costs of the transition. They enable an increasing share of renewables and support industrial decarbonisation, while reducing network costs and enhancing system security and resilience.

Perhaps the most important role ALDES can play is supporting reliability as the system transitions away from coal generation. While gas powered generation is often suggested as the solution to manage the reliability risk associated with coal exit, gas supply and pipeline capacity issues make this increasingly unrealistic.[130]

The pace of the transition is accelerating, with the system likely to be largely free of coal generation by the mid 2030s. The pace of this transition is uncertain as the economic and physical viability of coal generating units decreases. It is therefore critical to begin work now on developing the storage portfolio that is critical to replacing these coal generating assets.

Long duration energy storage technologies reduce the reliance on GPG to maintain reliability, while enabling further reductions in carbon emissions. This is best achieved with a mix of different storage durations and technologies. LIB and PHES will play a key role, complemented with ALDES to develop a portfolio approach. Enabling diversity of technologies and duration within the portfolio mix is key to reducing total costs for consumers.

Bringing ALDES into this portfolio requires coordinated and targeted support. If complemented with careful and purposeful reform of energy market frameworks, these support measures need only be minor. Once technologies have been pushed into market viability, commercial signals can take over and support is no longer needed.

Our analysis shows that many ALDES are close to this point of market viability. However, there are gaps in current policy and market frameworks.

- Currently there are few financial support measures available to incentivise investments in longer duration energy storage, especially many of the forms of ALDES explored in this report.
- Government underwriting schemes, particularly the CIS, do not appear likely to support substantial investment in ALDES or longer duration storage more generally.
- The NEM energy only market is not designed to incentivise investment in ALDES or longer duration energy storage generally.
- While ancillary service markets may offer some incentives for ALDES, more work is needed to ensure these frameworks are working effectively.

These factors may lead to underinvestment in ALDES and long duration energy storage generally, at precisely the time when development of new sources of energy storage is especially critical.

This section describes some of the policy support and market design reforms we consider will help bring these valuable technologies down the cost curve to a point where they are market viable, allowing commercial forces to take over. If designed well, these mechanisms will impose little upfront cost on consumers, while delivering substantial long-term benefit.

We begin this discussion by exploring the development of LIB technology in Australia. The story of how this technology came to be the dominant form of energy storage provides insights into how targeted financial support, coupled with proactive market design, can quickly bring new technologies to market, helping to reduce overall costs of the transition.

What can we learn from lithium?

LIB technologies are currently the dominant form of stationary energy storage in Australia. This was initially triggered by rapid technological development and cost reductions. However, mass uptake of the technology was also a product of purposeful financial support and market design.

LIB technologies are highly cost competitive. Scale manufacturing has enabled steep industry learning rates, with cost reductions driven further by modularity of design and ease of construction. LIB technologies continue to move rapidly down the cost curve, with costs falling by 97% between 1991 through to 2018, including a halving in just four years between 2014 and 2018.[131]

As shown in Part 1 of this paper, LIB technologies have been deployed rapidly since the first utility scale asset was built at Hornsdale. Almost $5 billion was invested in these technologies in 2023 alone. Along with PHES, LIB technologies are the storage workhorse of the energy transition.

The LIB success story demonstrates how the correct combination of financial support and market design can quickly enable new technologies to become market viable. A virtuous cycle of four factors influenced the uptake of LIB: targeted financial support, technology capabilities and cost, changing system needs and purposeful development of new markets to incentivise investment.

[130] AEMO has acknowledged the reliability risks associated with reliance on GPG as coal generation exits, in Appendix 4 of the 2024 Draft ISP. We acknowledge that AEMO is currently reassessing its approach GPG, following the Australian Government's review of the ISP.
[131] Hannah Ritchie (2021) "The price of batteries has declined by 97% in the last three decades" Published online at OurWorldInData.org.

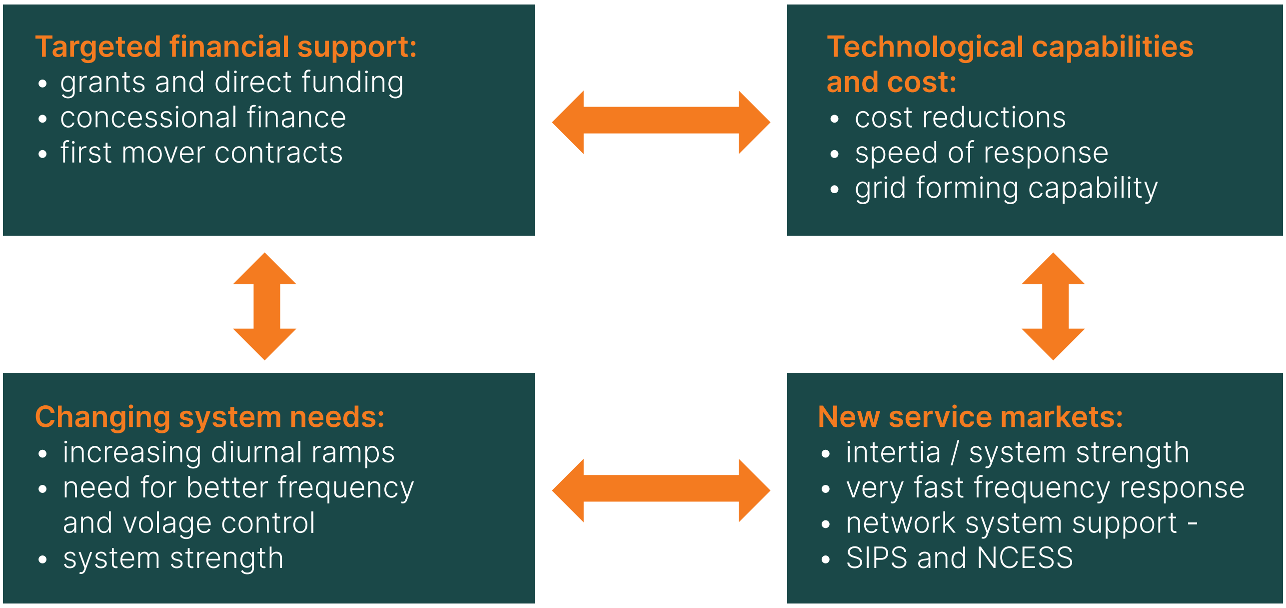


Figure 35: The virtuous cycle that drove LIB uptake

All of these factors reinforced each other, to make LIB the dominant storage technology it is today.

Technological capabilities and cost are central to whether a technology class offers material benefit to the system and to market participants, and whether it makes a good candidate for targeted financial support. The capability of LIB to provide rapid active power injection and grid forming capability, coupled with high energy density and modularity of design, meant that LIB offered a low cost solution to meet key system and market needs.

Changing system underpin the demand for new services, whether from market participants, network businesses or system operators. In the case of LIB, growing diurnal spreads, degrading frequency and voltage stability as well as requirements for system strength created a market and system demand that LIB has helped meet.

Targeted financial and policy support can quickly bring a technology to the point where it is market viable on its own. In Australia, targeted support for LIB – such as from the CEFC, ARENA and state governments[131] – demonstrated the viability of the technology and led to rapid uptake by the private sector.

New service markets need to be designed to incorporate the above factors. In the case of LIB, the development of services such as very fast FCAS, inertia/system strength and system integrity protection schemes reflected the capabilities of LIB as well as changing system needs. The establishment of these markets has reduced the need for further financial support.[132]

The rest of this paper describes a range of financial / policy supports, coupled with market redesign, which in combination can accelerate ALDES towards market viability. Many of these reforms are equally applicable to pumped hydro energy storage (PHES), which is the most mature and well understood form of LDES.

Changing system needs - why do we need ALDES?

There are several key market and system demands that can be effectively met by ALDES. These are summarised here for readers who have not read earlier sections.

- **The accelerating exit of coal:**

All coal generation is due to exit the system by the 2040s, with most gone by the mid 2030s. In practice this may occur more rapidly and/or in a more unpredictable manner as ageing thermal assets become more prone to failure. The sudden removal from the system of the

[130] See for example ARENA, CEFC and SA State government support for HPR expansion and more general support to unlock grid forming capability. RenewEconomy, Parkinson, G., Tesla big battery adds new capacity and services on march to 100pct renewables grid, available at www.reneweconomy.com.au. See also Arenawire, ARENA backs eight big batteries to bolster grid, available at www.arena.gov.au.

[130] Noting of course the ongoing underwriting support delivered through mechanisms such as the NSW Roadmap and the CIS, which are designed to bring forward capacity investment beyond that which the market is likely to deliver of its own volition.

synchronous capability and large energy reserves of coal generation can impact both reliability and security. Coal exit may impact wholesale market prices, secondary contract market liquidity and retail market competition. Equally, measures to prolong the life of coal assets are both expensive for energy consumers, as well as running contrary to emissions reduction targets. ALDES can help on both fronts, through their capability to offer multiple essential system services, energy duration and extensive energy carrying capability.

- **Risks associated with reliance on gas powered generation (GPG):**

GPG has been suggested by some stakeholders as the key source of energy backup in a high renewables power system. Aside from the carbon intensity of GPG – including upstream fugitive emissions - there are risks associated with this reliance. Trends in gas supply and underlying transmission pipeline capacity do not necessarily align with such a future. ALDES form a preferable replacement to GPG, providing both energy duration and carrying capability, without any carbon emissions.

- **Changing power system reliability at risk periods:**

As renewable penetrations increase, the nature of reliability risks in the power system will change. Seasonal shortfalls, wind droughts and dunkelflaute events may have an increasing impact, especially when compounded by increasingly frequent coal unit outages. The capability of ALDES to carry large volumes of energy, through long periods of time, position them well to manage these new reliability challenges.

- **Diurnal demand spreads:**

The duck curve and associated system impacts are likely to become more intense as levels of solar generation increase. ALDES demonstrate good cycling capability, supporting reliable, low cost movement of energy through time to manage the effects of these deepening demand spreads.

- **The need for synchronous capability:**

AEMO has identified that it needs a certain number of synchronous units online to maintain stability and operability of the power system. Some ALDES bring innate synchronous capability and can replace that currently provided by synchronous gas and coal units. Other ALDES can provide grid forming capability.

- **Reducing network costs while maintaining reliability:**

Significant volumes of new transmission network will be needed in the coming decades. Wherever possible, alternatives to network build should be promoted, from both an economic and social license perspective. ALDES demonstrate multiple capabilities, including essential system service provision, duration and energy carrying capability, which make them excellent candidates for supporting or replacing network infrastructure.

Despite growing system demand for ALDES, market frameworks do not yet recognise their capabilities. We therefore consider that targeted financial support may be justified, to help address immediate barriers and help bring these technologies to a point of market viability.

Targeted financial support

There are a range of targeted financial supports that may be employed to accelerate ALDES toward market viability. Many of these measures do not actually impose significant costs, while there are material benefits associated with increasing the portfolio of available storage technologies.

Targeted support for ALDES can help overcome hurdles including the relative technological immaturity of some ALDES. It can also help overcome issues related to the longer lead times and unique siting / construction risk associated with some forms of ALDES. Targeted financial support may assist where existing markets cannot value a particular public good provided by the asset.

Many forms of long duration storage, such as PHES and ACAES, face specific construction and development risk profiles. These risks can be associated with longer lead times to construction and hydrologic/geologic risks. This is exacerbated by the very long return periods, which for PHES may extend well over 80 years, and for ACAES over 50 years.

Long lived assets are particularly impacted by the effect of discount rates on required rates of return.[133] This in turn makes the higher returns typically required from private investors challenging for longer lived assets like PHES and some forms of ALDES.

Governments and government agencies like the Clean Energy Finance Corporation (CEFC) are well placed to provide concessional financing and associated support to help address these issues. This can be applied in conjunction with underwriting mechanisms to further reduce costs.

As discussed in the box below, hybrid options for financing have also been proposed, with a semi regulated return being provided to those assets that can be shown to provide a ‘public good’ benefit, such as increasing aggregate VRE penetration or supporting reductions in emissions intensity.

[134] A higher discount rate negatively impacts the present value of a project with high upfront costs and longer-term revenues. See: Egis, *Levelised cost of electricity*, May 2024. Available at www.cleanenergycouncil.org.au

Semi regulated financing of LDES

Hybrid financing arrangements can be developed that target long lived (or otherwise higher risk) assets that provide a system benefit not currently valued in market frameworks.

As discussed in the paper 3–Party Covenant Financing of "Semi Regulated' Pumped Hydro Assets, Simshauser and Gohdes lay out a financing model that utilises a blended private and public financing to bridge the gap between available market revenues and the capital cost of storage.[135]

This model effectively provides a separate regulated revenue for the public good component of an LDES asset – ie, such as the ability to support additional VRE penetration and decrease carbon intensity of dispatch – while leaving the private component of the asset to participate in competitive markets – such as participation in arbitrage and other system services.

This model lays out one potential way that funding bodies might support LDES to bridge the gaps that exist in current energy market design, where the value of longer duration and long asset life are not yet reflected in market design.

We recommend governments consider whether concessional finance models, or regulated support models as per the above, can be developed to recognise and value the public good components of long duration storage. This is especially important where existing market frameworks do not, or cannot (in the case of true public goods) reward the provision of these components.

Industry knowledge sharing

Technological immaturity, whether real or perceived, increases the risk premiums attached to ALDES projects. This is compounded by a lack of industry understanding. One way to overcome these hurdles is to facilitate technology trials and industry knowledge sharing.

Support here is needed to highlight the capabilities of these technologies, while rewarding innovators who experiment to deliver the learnings that enable subsequent technologies to come further down the cost curve. This can take the form of Australian Renewable Energy Agency (ARENA) grant funding and knowledge sharing exercises, or CEFC financial support, to trial new solutions.

Currently, ARENA is running a trial exploring the capabilities of LDES in remote grids, which includes an objective of improving the technical readiness of ALDES technologies such as zinc bromine flow batteries.[136] ARENA has also supported the development of a Market Context Report with Australian ALDES developer MGA Thermal, which explored the potential costs and applications of miscibility gap alloy ALDES in Australia[137]

Various other agencies may play a role in supporting the development of ALDES. For example in NSW, the state government has announced $1 billion in funding to establish the Energy Security Corporation, which will support investment in storage projects and address gaps in the current market.[138]

Government underwriting mechanisms

While there are two key underwriting schemes available to energy storage in the NEM, it is not clear whether either scheme will support significant investment in longer duration energy storage, particularly lesser known ALDES solutions.

Underwriting mechanisms to support the renewable transition have taken various forms. In Australia, target based certificate schemes such as the RET and energy efficiency measures have been very successful, while contract for difference (CFD) models, such as the Victorian Renewable Energy Target (VRET) have also supported renewable investment.

More recently, governments have moved toward hybrid contract models. Hybrid contracts are intended to effectively integrate with wholesale and contract markets, maintaining some of the function of existing market signals. These contracts typically provide a swap or annuity, structured as an option and/or by reference to a revenue collar or cap. Outside of this

[135] Simshauser, P., Gohdes, N., 3-Party Covenant Financing of 'Semi Regulated' Pumped Hydro Assets, available at https://www.eprg.group.cam.ac.uk/wp-content/uploads/2024/05/text2405.pdf
[136] ARENA, Long Duration Energy Storage Trials in Remote Microgrids, available at www.arena.gov.au.
[137] ARENA, Market Context Report MGA Thermal Energy Storage Application in Australia - Australian Renewable Energy Agency (ARENA), available at www.arena.gov.au
[138] NSW Government, Further $1.8 billion to power NSW to a clean energy future | NSW Government, available at www.nsw.gov.au

collar, revenue sharing mechanisms apply, subject to a hard limit of total payments.

The Dispatchable contracts of the Commonwealth Capacity Investment Scheme (CIS) and the NSW Long Duration Storage Long Term Energy Service Agreements (LDS LTESA), as part of the NSW Energy Roadmap, are the two primary examples of these hybrid contract types that are applicable to energy storage.

Both schemes are focussed on delivering 2030 targets. This translates to specific procurement dates within each scheme, particularly the requirement in the CIS for projects to have reached commercial operation date by 2030. Longer lead time assets, such as PHES and some forms of ALDES, or those assets that are not yet as mature as LIB, will struggle to meet these timeframes.

These target dates, combined with an emphasis on targeting lowest cost bids, make it challenging to simultaneously address both near and long term reliability issues. This is acknowledged directly in the recent NSW Government paper exploring the how to incentivise investment in long duration storage in NSW, which states that:[139]

> "The challenge NSW faces is finding a cost efficient path between addressing near term system needs in meeting 2030 targets and building the storage and system strength infrastructure required for a high penetration of variable renewable energy system in the 2030s, which is likely to require longer durations of storage."

Target dates and a near term reliability focus mean that, subject to significant policy shifts, both schemes will tend to incentivise investment in shorter duration energy storage. Given its technological maturity, low cost and high levels of industry understanding, this is likely to be LIB storage technologies.[140]

Despite this, both schemes do include measures designed to recognise the value of longer duration storage. Both include merit criteria that recognise specific system benefits that can be met by ALDES, such as alleviating congestion, providing system strength and inertia, as well as reliability support.

The CEC has consistently called for greater clarity around these merit criteria, to support efficient investment decisions. This could include ex-ante, quantitative metrics defining how contributions to system reliability will be assessed. Specific locational signals could also help guide tendering parties to propose particularly high value projects – such as identifying specific transmission constraints that might be most efficiently addressed by a longer duration asset.

Another approach to reflect the unique risk profile of longer duration storage assets – including PHES and the various forms of ALDES – would be to provide partial government refunds of the costs incurred by tendering parties in preparing bids. This reflects the significant complexity that feeds into the development of bids for higher capex projects which face unique construction risks. There is precedent for this kind of approach through the NSW Pumped Hydro Recoverable Grants scheme.[141]

Such an approach would be equally applicable for some of the newer ALDES, where technology risk is still a relevant factor. It would benefit immediate tender rounds by increasing competition, while later rounds would benefit though the learnings accrued by earlier participants.

A similar approach could allow for some risk sharing once an initial tender round has been awarded. This approach would allow for earlier stage tenders to take place, reflecting the increased complexity and longer lead times associated with technologies such as PHES and ACAES. This approach includes ex-ante contingency risk sharing

[139] NSW Government, *Review of Long Duration Storage (Part 6 of the Electricity Infrastructure Investment Act) Consultation paper*, May 2024.
[140] NSW EnergyCo, *Pumped Hydro Recoverable Grants* | EnergyCo (nsw.gov.au), available at www.energyco.nsw.gov.au
[141] It's acknowledged that the NSW LDS LTESA scheme has underwritten an ALDES project, the Silver City ACAES project in Broken Hill. Furthermore, the NSW Government has expressed a general desire to support longer duration storage technologies through the broader Roadmap design.

arrangement that activate after a contract is awarded, under specific circumstances.

Finally, the longer asset life of PHES and ACAES suggest that longer contract tenors may be appropriate to support these technologies. This is necessary to attract investors to these assets, which typically have asset lives beyond standard credit horizons. The NSW Long Duration LTESAs provide a good example of this, with contract tenors of 40 years assumed for pumped hydro.[142] However, we note that the lives of many long duration assets, particularly PHES, may be double that.

Given that tenders for both the CIS and NSW LTESA are well advanced, some other form of support mechanism may be needed to incentivise investment in long duration energy storage. As discussed in the section above, this could involve targeted financial support. Equally, a separate contract mechanism, similar to and building on the CIS or LTESA, could be designed to support longer duration storage, including ALDES or PHES.

At the time of writing, the NSW Government is actively consulting on what such a mechanism might look like. The NSW Government is considering 'measures to signal to investors the long term need for storage with a duration of 8 hours or more to mitigate tail risks'. This includes measures such as requiring the Consumer Trustee to prioritise longer duration tenders, or the establishment of a minimum long duration storage objective for 2035.[143]

This latter suggestion – to establish a 2035 target – is one design option for a separate, targeted, longer term underwriting mechanisms to bring longer duration storage, including PHES and ALDES – into the system, in time for when they are most needed. Such mechanisms would need to reflect the specific characteristics and system value that is sought, as described above.

If complemented with new service markets carefully designed to reflect the specific value to the system of longer duration storage, these underwriting mechanisms - and their impact on taxpayers - can be minimised. Below we step through some of the gaps in existing markets and explore what a potential new energy reserve service might entail.

Existing energy markets and long duration energy storage

The NEM energy only market is not currently designed to incentivise investment in long duration energy storage. This may have reliability implications in the medium to long term. Policy makers may consider an energy reserve market, as a complement to the existing energy market, to support necessary investment in long duration energy storage to reduce reliability risks.

Since its inception in 1998, the NEM[144] has delivered investment in the generation capacity needed to deliver on more immediate reliability needs. This investment has mainly been in new GPG and LIB assets, to manage traditional peak demand periods. This investment reflects the design of the NEM wholesale market, which is in turn shaped by reliability requirements.

The NEM wholesale market design is an energy only market. This means that participants must recover all costs – fixed and variable – from their daily sales of energy into the spot market. Derivative contracts are then struck around these wholesale market exposures.

The structure of the NEM wholesale market is designed to send signals to incentivise investment to maintain reliability. The market operates within an envelope defined by two key price settings: the **market price cap (MPC)** which is currently set at $16,600/MWh – with the market price allowed to continue at this level until the rolling average 7 day price exceeds the **cumulative price threshold (CPT)**, which is currently set at $1.49M. Beyond this, administered pricing applies.

These price settings are known as the NEM reliability price settings. They are determined and reset by the AEMC and Reliability Panel every four years. This is based on whether the price settings will drive sufficient investment to meet the Reliability Standard, which requires that no more that 0.002% of demand for energy should be unmet in any given year.

[142] King & Wood Mallesons, *LTESA (Long Duration Storge) – Draft Term sheet*. Available at www.aemo.com.au
[143] Although it is noted this is occurring as part of a consultation that is considering removing the current hard requirement for 8 hour storage duration in the NSW Energy Infrastructure Investment Act. See: NSW Government, Review of Long Duration Storage (Part 6 of the Electricity Infrastructure Investment Act) Consultation paper, May 2024.
[144] With respect to Western Australian readers, this section is focused on east coast market issues. The presence of the reserve capacity mechanism in WA gives rise to a different set of issues regarding ALDES, which, unfortunately, we have not been able to address here. This will be included in future work and subsequent papers.
[145] Recognising that other drivers, such as managing system strength obligations as well as the effects of both economic and physical curtailment have also incentivised LIB uptake.

Historically, the NEM price settings have incentivised investment in peaking assets, such as GPG and later LIB assets. These assets are good at delivering a lot of power, for a relatively short period of time. This aligns well with the current analysis of meeting the reliability standard, which has typically focussed on the traditional peak demand reliability at risk periods.

The Panel and AEMC have reviewed the price settings and made changes to increase the MPC and CPT, to encourage new investment over the medium term.[146] This included consideration of changes in reliability risks and the need to incentivise storage, particularly longer duration storage, to support reliability in a future power system with higher levels of VRE and with associated gas supply issues. The Panel identified that:[147]

"market price settings should adjust over time to a level sufficient to incentivise storage investment of appropriate duration. It considers this particularly important as the NEM transitions from being a capacity-limited thermal power system to high VRE penetrations with reliability supported in part by storage of sufficient duration. [footnote] - Incrementally improved incentives for longer duration storage may assist investment that limits undue reliance on gas investment in some regions given any possible future gas availability issues.

Despite this acknowledgement, increases in both the CPT and MPC were limited and are still based around sending investment signals for more GPG investment. They are also unlikely to drive significant investment in longer duration energy storage. This has occurred for several reasons.

The Panel and AEMC generally make changes to the price settings in a manner that is smoothed and gradual, to minimise shocks to market participants and maintain overall market stability. The Panel therefore noted that while the price settings may need to be raised further to incentivise longer duration storage, this would need to occur in future reviews of the price settings. This would occur after 2028, being the time horizon for the current round of price setting. Given the need to begin work on longer lead time storage assets today, these long term price adjustments will come too late.

The Panel also noted that marginal scarcity pricing, which is the primary mechanism by which the NEM energy only market sends investment signals, may not be the optimal mechanism to signal for investment in longer duration storage. This argument was reinforced by other market participants, particularly those with retail exposures, who argue that increases in risk associated with large increases in the price settings would not necessarily translate into additional investment.[148]

There is merit in this argument. The nature of some emerging reliability risks are inherently uncertain and difficult to predict. Accounting for them in price settings would likely expose market participants to prolonged periods of high prices, even if those prolonged periods only occurred every few years. It is difficult to strike meaningful contracts around these uncertain and hard to predict events, hence the extent to which they can support investment is limited.

[146] AEMC, *Amendment of the Market Price Cap, Cumulative Price Threshold and Administered Price Cap*, Rule determination, 7 December 2023.
[147] Reliability Panel, *2022 Review of the reliability standard and settings*, Final report, 1 September 2022
[148] Hedging contracts traded in secondary markets can support new investment in the NEM. Traditional peak demand pricing risk can be relatively easily modelled and translated into these hedging contracts. In contrast, the kinds of tail risks associated with dunkelflaute type events are inherently uncertain and difficult to quantify. This makes it difficult to develop hedging contracts to manage these price risks, meaning that expansions of the price settings to reflect these risks may not necessarily translate into new contracts and therefore investment.

The Panel suggested that 'complementary measures' to the energy only market might instead be the most effective way to drive investment in longer duration storage. These measures would sit outside of the NEM wholesale pricing frameworks.

The Panel returned to this theme in its subsequent review of the form of the reliability standard. In that review, the Panel found that the nature of reliability risk is changing in the NEM and is likely to become more weather dependent.[149] However, the Panel also considered it was not appropriate to drive investment to manage more extreme weather events through the price settings, but instead through external measures such as the CIS, the retailer reliability obligation and interim reliability reserve.[150]

It is important to note the intention and context of the AEMC and Reliability Panel analysis. The purpose of this analysis is to forecast expectations of USE and whether market price settings can deliver sufficient investment to keep those USE expectations within the standard. Similarly, the Panel's work exploring the form of the Reliability Standard is focussed on examining the ongoing accuracy and effectiveness of the standard. The Panel's work is not intended to select for optimal technologies, nor to set out an optimal development pathway for the NEM. We therefore understand the AEMC and Panel did not assess the impact of underlying gas supply and pipeline issues on GPG availability, on the basis that these issues were not in scope.

Nevertheless, as discussed throughout this report, assumptions underpinning modelled assessments of reliability adequacy may not reflect future conditions, especially where modelling assumes that gas supply and pipeline capacity are effectively limitless resources to underpin GPG availability in modelling.[151] We consider the AEMC and Panel's methodologies and subsequent conclusions may therefore warrants further reassessment in future reviews of the price settings and reliability standard.

The Panel and AEMC have decided that, in the medium term at least, the price settings will not be changed in a manner that will drive investment in longer duration storage. While the AEMC has suggested further increases in the price settings may occur after 2028, it also suggests that out of market solutions are necessary to enable investment in long duration storage.

On this basis, the rest of this section will explore what kinds of additional mechanisms might support investment in long duration storage.

A new energy reserve service to support reliability

A perennial debate in the NEM has been whether the energy only market design remains appropriate, or whether a move to a capacity market is necessary.[152] The CEC has argued against historic capacity markets, on the basis that proposed models were not consistent with the objective of emissions reduction.

The upcoming post 2030 market framework review will have a key focus on NEM investment trends. On that basis, we consider that policy makers should consider whether a targeted energy reserve service might form a complementary measure to support investment in longer duration storage.

The Energy Security Board ran an extensive work program in 2022, exploring the potential design of a capacity market in the NEM.[153] This project did not progress beyond initial design consultation, primarily on the basis that it failed to take account of the urgent need to decarbonise Australia's power systems.

The CEC argued against the ESB's proposed capacity market design on the basis that a single mechanism could not be relied upon to both control the exit of coal generation while supporting investment in replacement renewable and storage capacity.[154] Instead, we argued for targeted mechanisms to support new investment, with separate processes to deliver coordinated coal closure.

One of the reasons the ESB's design failed was because it did not account for carbon emissions. Adherence to the so-called principle of technological neutrality resulted in the mechanism being unable to discriminate between zero carbon and carbon intensive forms of energy supply.[155]

Energy Ministers have committed to undertake a review of the post-2030 energy market frameworks.[156] At the time of writing, this review had not yet commenced.

[149] AEMC Reliability Panel, *Review of the form of the reliability standard and administered price cap*, April 2024
[150] Ibid., p.19.
[151] That the IES modelling underpinning the AEMC's decision to change the price settings does explore the limitations associated of GPG, by imposing a 4 hour energy limit on these forms of generation in the modelling. See: IES, *Reliability Standard and Settings Review 2022 – Final report*, August 2022, p.82. Further, in its review of the form of the standard, one of the sensitivities (4a) run by the Reliability Panel removed large volumes of GPG from the modelling run, resulting in large volumes of unserved energy. This suggests that the assumption of large volumes of available GPG remains key to maintaining reliability in modelled assessments of power system reliability - which we have shown to be problematic. See: AEMC Reliability Panel, *Review of the form of the standard and APC – Directions Paper*, November 2023. p.54.
[152] In this analysis, we consider the CIS to be a hybrid contract underwriting scheme, rather than a full capacity mechanism, on the basis that it is not a standalone market as per more traditional capacity mechanisms.
[153] Energy Security Board, *Capacity Mechanism High Level Design Paper*, June 2022.
[154] Clean Energy Council, *Capacity Mechanism High Level Design Paper – CEC submission*, July 2022.
[155] To be fair, this is also due to emissions reduction having not yet been integrated into the national electricity objective (NEO).
[156] Energy and Climate Change Ministerial Council, *Meeting Communique,* March 2024

However, it's expected the paper will include discussions around mechanisms to drive additional investment.

Any future mechanism design should be focussed on zero carbon forms of generation and energy storage. A failure to do so would be at odds with the urgent need to decarbonise our power system and broader economy. Practically, it is also difficult to design carbon intensity metrics to incorporate GPG and other forms of fossil generation into a capacity mechanism, in a manner that captures all emissions accurately – including upstream fugitive emissions - and is consistent with the NEO.

Beyond this, the key discussion is whether any mechanism should focus on *capacity* – being investment in MW capacity of generation or storage assets – or *energy* – being the actual MWh output of those assets at certain times of system need.

As discussed throughout this paper, management of future reliability challenges will require provision of sustained energy supply to meet demand, focussed around specific reliability at risk periods. This will include traditional peak demand periods, where capacity is key. However it will also increasingly include sustained winter demand periods, where sustained energy supply will be key.

A future mechanism may therefore be recast as an *energy* reserve service. Instead of providing incentives mainly to build generation and storage *capacity,* an energy reserve service would reward the provision of sustained delivery of energy. This energy delivery would be focussed around specific duration, location and timing requirements, to reflect system needs.

There are precedents to this kind of service already in the NEM. For example, the Victorian Big Battery has a system integrity protection scheme (SIPS) contract with AEMO, to provide energy reserves over the summer peak season.[157] Similarly, the proposed reliability reserve contract for backup reserve in Broken Hill requires the Silver City ACAES project to keep 50MW / 250MWh of capacity in reserve, to manage supply interruptions from network outages.[158]

An energy reserve service could broadly take two forms. Firstly, an energy reserve might be based around a certificate / credit based mechanism, similar in form to the Western Australian Reserve Capacity Mechanism. The costs of a certificate scheme can be borne directly by government as offtaker, or redistributed across energy retailers.

Another option would more closely resemble frameworks like the Reliability and Emergency Reserve Trader (RERT), where AEMO procures bilateral contracts through a tender process, holding capacity outside of the market to maintain security and reliability under specific conditions. The cost of these contracts could again be recovered in various ways.

There are upsides and downside to each approach and the CEC does not yet have a preference. However, either model should be selected based on maintaining effective function of the wholesale energy market and accompanying derivative secondary markets.

There are various design choices to be made in any energy reserve service.

Energy reserves may only be needed during periods of heightened reliability risk. The VBB SIPS, for example, requires energy reserves to be held only during peak periods, when there are clear reliability and price benefits associated with increased flows on the Vic-NSW interconnector. An expanded energy reserve service could include similar temporal elements, such as focussing on maintaining energy reserves during periods of likely seasonal supply shortfall over the winter months, or to cover contingent loss of coal generating units during periods of system stress.

There is also a locational component to a potential energy reserve service. As evidenced by the Silver City ACAES project, energy reserves may be more valuable in those areas of the power system prone to network outages. Supply of backup energy reserves can reduce total system costs, by substituting for more expensive network augmentation. Ultimately, these services may even negate requirement for network augmentation, allowing parts of the network to become self-sufficient microgrids.

An energy reserve service could also be broken up into required duration categories, reflecting specific system needs in different locations and over different time periods. Shorter duration energy reserves are likely to be appropriate for managing more traditional reliability at risk periods, such as summer peak demand - although it's noted that current energy market settings appear capable of delivering sufficient capacity to manage these traditional reliability risks.

Medium to long duration energy reserves may be needed for emerging reliability at risk periods, particularly seasonal demand events.

Procurement of an energy reserve service could also be linked to coal generator retirement. Investment in renewables and long duration storage must be brought forward in time, so that replacement capacity is connected and energised well in advance of either planned or unplanned coal generation exit. This is necessary to prevent price spikes and reliability risks. This has been a key element of the CEC's advocacy to state governments regarding coordinated coal exit.

A key implication of coal generation exit is the removal of large volumes of energy reserves from the system. These energy reserves can be replaced with a combination of renewable generation backed up by a mix of storage durations. Energy reserves could therefore be linked both spatially and temporally to the exit of coal generators.

[157] The VBB SIPS is relatively limited in terms of the actual energy output it will provide when activated. The contracted SIPS capacity is for 250MW and, although no public information is available on contracted duration of this response, the max capacity of the battery is listed by AEMO at 300MW. This suggests that the ability to export at 250MW will be limited to under 2 hours.

[158] PV Magazine, Carrol,D., *Australian town to host 200 MW/1,600 MWh compressed air storage facility*, December 2023. Available at www.pv-magazine.com

We also note the presence of Renewable Energy Transition Agreements that will form part of the Commonwealth CIS, which may be targeted towards managing coal generation exit. RETAs should recognise the value of longer duration storage in addressing the reliability risks of thermal coal exit.

Finally, an energy reserve service should be structured around considerations of system resilience. Resilience is a general term that describes the ability of the power system to survive the unexpected. The power system must be able to adapt to an increasingly uncertain future affected by climate change. This includes the ability to survive uncertain but high impact events, such as the so-called "1 in 100 year" weather events identified by the Reliability Panel in its analysis of the reliability standard. An energy reserve service could form a key component of the portfolio mix of solutions necessary to deliver power system resilience.[159]

The ALDES discussed in this report demonstrate characteristics that dovetail with the design and incentives created by an energy reserve service. Such a service is also expected to reflect the needs of the power system, as coal generation retires and VRE levels continue to grow.

The CEC recommends the concept of an energy reserve service be further explored through the post-2030 market review. As described here, there are many detailed policy design choices to be made. However overarching design principles should include: any new service is based on clearly defined system needs, is technology neutral, recognises the necessity of decarbonisation and minimises impacts on the effective function of the wholesale energy market.

Ancillary service markets and network support

In addition to providing energy reserves, the ALDES discussed in this report also deliver key essential system services, while also playing a role in complementing and reducing the cost of transmission network buildout through the provision of network support services. Many of these have already been described throughout this report and include the following:

- **Frequency control services:**

As discussed earlier in this report, LIB technologies have transformed the way that frequency control is delivered in the NEM. ALDES demonstrate capabilities that will further contribute to stable frequency control, including rapid active power response across the full FCAS range.

- **Inertia and system strength support services**

Both synchronous and non-synchronous forms of ALDES can provide these services, often in conjunction. System strength is particularly locational, meaning ALDES in specific parts of the power system can potentially offer this service at a lower cost than major network augmentation.

- **Voltage control.**

As above, these services can be provided by ALDES, reducing the need for network augmentation.

- **Transitional services:**

As part of its recent Improving System Security Frameworks rule change, the AEMC introduced the category of transitional services which allows AEMO to contract with parties to develop innovative new services to support the transition. Both synchronous and non-synchronous ALDES are well suited to provide these services.

- **System restart ancillary services (SRAS):**

SRAS enable the power system to be restored following a major supply interruptions and widescale blackouts. The power and energy capability of ALDES make them ideal candidates to replace the historical sources of SRAS - such as coal units and GPG.

- **Network support and control ancillary services (NSCAS), SIPS and other network support services to deliver non-network options (NNOs):**

As discussed throughout this report, LIB technology has already demonstrated the effectiveness of energy storage to provide key network support services to increase system stability, network power transfer and overall network reliability. ALDES are well positioned to enhance the range of NNOs available to network businesses, helping to reduce the overall cost of delivering network infrastructure at both the transmission and distribution level.

- **New service markets – ramping response:**

The potential for an operating reserve, or a ramping service, has been explored previously in the NEM with the AEMC deciding not to introduce this service.[160] However, deepening duck curves and regional requirements may mean such a service becomes necessary in future. Certainly such a service has been introduced in other jurisdictions.[161] The power, duration and cycling capability of ALDES make them ideal candidates to provide such a service.

[159] AEMC, *Mechanisms to enhance resilience in the power system*, 12 December 2019. Noting that events once described as …
[160] AEMC, *Enhancing reserve information final determination,* Rule determination, 21 March 2024
[161] California ISO, *Flexible ramping product*, available at: www.caiso.com

- **New service markets – solar soak:**

Increased PV generation in distribution networks are driving various effects such as changes in power flow and network voltages. The cycling and voltage control capabilities of many ALDES make them well positioned to manage this in distribution networks.

In most instances these various service markets are developed and ALDES should be able to participate. However, there are some changes in underlying regulatory frameworks that may need to be addressed to ensure that ALDES - and energy storage more generally – can effectively participate.

The ability of all forms of storage to offer services at the distribution network level is affected by the current approach of levying distribution use of system (DUOS) charges on connecting storage assets. While the approach to DUOS charging varies, levying charges on storage assets acts as a disincentive to locate these assets where they can add significant value.

A broader set of issues relates to the ability of network businesses to enter into network support agreements with storage providers, to provide NNOs. The existing frameworks for NNOs were developed around assumptions of relatively small project costs, predominantly delivered by demand response. Storage projects can enable much larger NNOs, both in terms of capacity but also cost.

Changes to the network support agreement / NNO frameworks are needed to better reflect these increased costs. Most immediately, changes are needed regarding the allowance of regulatory passthroughs for these costs, as well as the approach to calculating the NNO allowance. Beyond this, issues arise around risk management for NSPs who enter into NNOs as well as questions of the appropriate economic tests applied to the costs of NNOs.

The CEC is working with several key members to explore these issues. Rule changes are expected to be lodged this year.

Appendix A: Modelling Methodology

Objective

To investigate the operational and commercial conditions which promote alternative LDES

Model

The model is classified as a **least-cost capacity expansion model.** This type of model will identify the lowest cost (in terms of CAPEX + OPEX + Fuel costs) portfolio of generation and storage assets to meet a provided hourly **demand forecast** for one year from a set of generation and storage **candidates** (with various operating and commercial parameters such as build cost, fuel price, storage limits, VRE availability etc).

In this project, there is no "existing or committed" assets, hence we call this a greenfields model. In other words, the model is determining the optimal portfolio if it had to build the system from scratch to meet the requirements of one particular year. This assumption is relatively realistic for years in the distant future where the existing system will have to be nearly completely replaced.

Methodology

Representative A-LDES

To capture the influence of various A-LDES parameters on the future system portfolio we will artificially create representative A-LDES candidates parameterised by 6 different storage costs (from **$100/kWh - $600/kWh** in $100/kWh steps) and 6 different durations **(4-24 hours in 4h steps)**, together this creates a set of 36 (6 × 6) representative A-LDES candidates, the default RTE for these technologies will be **81%** (though we will test a different RTE in one of the sensitivities).

The candidates will be used in the model to compare their viability with other generation / storage assets to meet demand, this will assist in determining what parameters are important in the various scenarios under investigation.

These numbers were determined based on a survey of available data from OEMs and peer-reviewed sources, we have found that these 36 candidates provide a good coverage of the various sources and various technologies. These representatives are technology agnostic, so if a completely new technology emerged, but its parameters were found to be very similar to one of the representatives then the results can still be used to inform the developers of the new technology.

Modelling

For each scenario the model will simulate 36 different worlds, one for each representative. In each of the world: The set of investment candidates available to the model will also include one A-LDES representative. The model will determine the least-cost portfolio in each of these 36 worlds, the least-cost portfolio could include the A-LDES candidate if it reduces the cost the portfolio if it wasn't in it the portfolio. If the parameters of the A-LDES are not conducive to reducing the cost of the overall portfolio, then it will not be chosen by the model. The difference in new build capacity of the A-LDES (or other metrics from the results) based on the parameters of the representatives will assist in informing the conditions which are suitable for the A-LDES.

Fixed Build Modelling

This is relevant to the renewable composition scenarios group (See below). In this group of scenarios the composition of renewables is fixed and adjusted to see its impact on A-LDES. This is departure from the other scenarios as the VRE composition is determined by the model and is not fixed.

To facilitate these models, we use the model first to identify the optimal composition of wind and solar. We do this by simulating the model with the assumptions related to the scenario without any representatives present in the candidate set. The identified composition of wind and solar is fixed and no more investment in wind and solar is allowed in the model, if the ratio of wind and solar needs to be changed (to meet the requirements of the scenario) then the composition is adjusted to meet the ratio defined in the scenario while still maintaining the total vre capacity identified in the base model run.

This new set of assumptions is then run in the 36 worlds (one for each representative) to determine the optimal system portfolio like the procedure described above, except that this second set of runs will not have any additional wind or solar.

Results

The results will be displayed in the form of 6×6 heatmaps where the columns indicate the duration of the A-LDES and the rows indicate the storage cost (See example below). This form of chart is very helpful in identifying the trends and relationships with the representative A-LDES parameters.

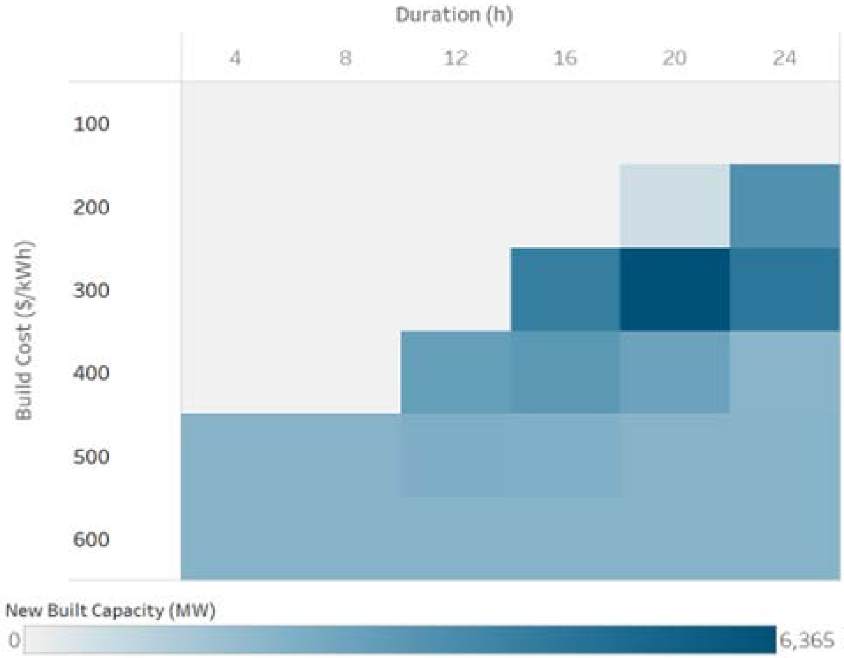


Figure 35: The virtuous cycle that drove LIB uptake

Scenarios

Scenario Group	Scenario / Sensitivity Summary	
Base	Base Scenario	This is the base set of assumptions. All other scenarios and sensitivities are developed relative to the base scenario
Low RTE Sensitivity	Low RTE Sensitivity	The RTE is reduced to 60%, to see the effect RTE has on viability of A-LDES
Emissions sensitivities	Emissions sensitivities	The emissions limit will be changed to see what effect emissions targets has on the viability of A-LDES
Renewable composition scenarios	Base (Fixed VRE)	A modified base scenario where the VRE is fixed to the optimal levels identified in the simulation without A-LDES representatives present, the identified composition was found to match a ratio of 60:40 (solar to wind)
	Low Solar	The fixed composition in the Base (Fixed VRE) is adjusted to meet a 50:50 ratio (solar to wind)
	High Solar	The fixed composition in the Base (Fixed VRE) is adjusted to meet a 70:30 ratio (solar to wind)
	High Solar Cycling	The fixed composition in the Base (Fixed VRE) is adjusted to meet a 70:30 ratio (solar to wind), the build cost of Li-ion is also increased by 15%, this reflects the increased need for cycling from Li-ion in a world with excess solar.
Li-ion cost scenarios	High Li-ion scenario	Build cost of Li-ion technologies is increased by 20%
	Higher Li-ion scenario	Build cost of Li-ion technologies is increased by 40%
Gas price scenario	High gas scenario	The gas price is increased to $27/Gj (50% increase). This reflects the view of greater difficulty in sourcing gas to meet electricity requirements
	High gas + High emissions scenario	Gas price is increased to $27/Gj and emissions are increased to 10% of 2022 emissions. A larger emissions budget allows the model more flexibility to reduce gas emissions (in a world of 2% emission gas is already used very rarely and only for periods of relatively high system stress)
Transmission Scenario	REZ delay scenario	No investment is allowed in western Victoria and the Murray river REZ. These REZs relate to the VNI-west project and are 2 very high quality REZs (in terms of solar and wind availability).

Benefits of approach:

- Generalisation of results: The results are not specific to a particular OEM or peer reviewed data source
- The results can be used to inform emerging technologies and participants whose technology can be related to one of the representatives
- Anonymisation of OEM data

Definitions

Model: Quantitative representation of a real-world process, in this context the model refers to a quantitative representation of the investment and operation decisions made in the east-coast electricity market.

Scenario: A broad collection of assumptions that are used to simulate and investigate one view of the future world.

Methodology: The procedure that defines how the model will be used to investigate each scenario and identify the conditions that promote A-LDES

CLEAN ENERGY COUNCIL

Level 20, 180 Lonsdale Street
Melbourne VIC Australia 3000

+61 3 9929 4100
info@cleanenergycouncil.org.au

cleanenergycouncil.org.au