Stationary Battery Energy Storage Systems Analysis

A focus on intraday shifting

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Ara Ake
Future
Energy
Development

Contents

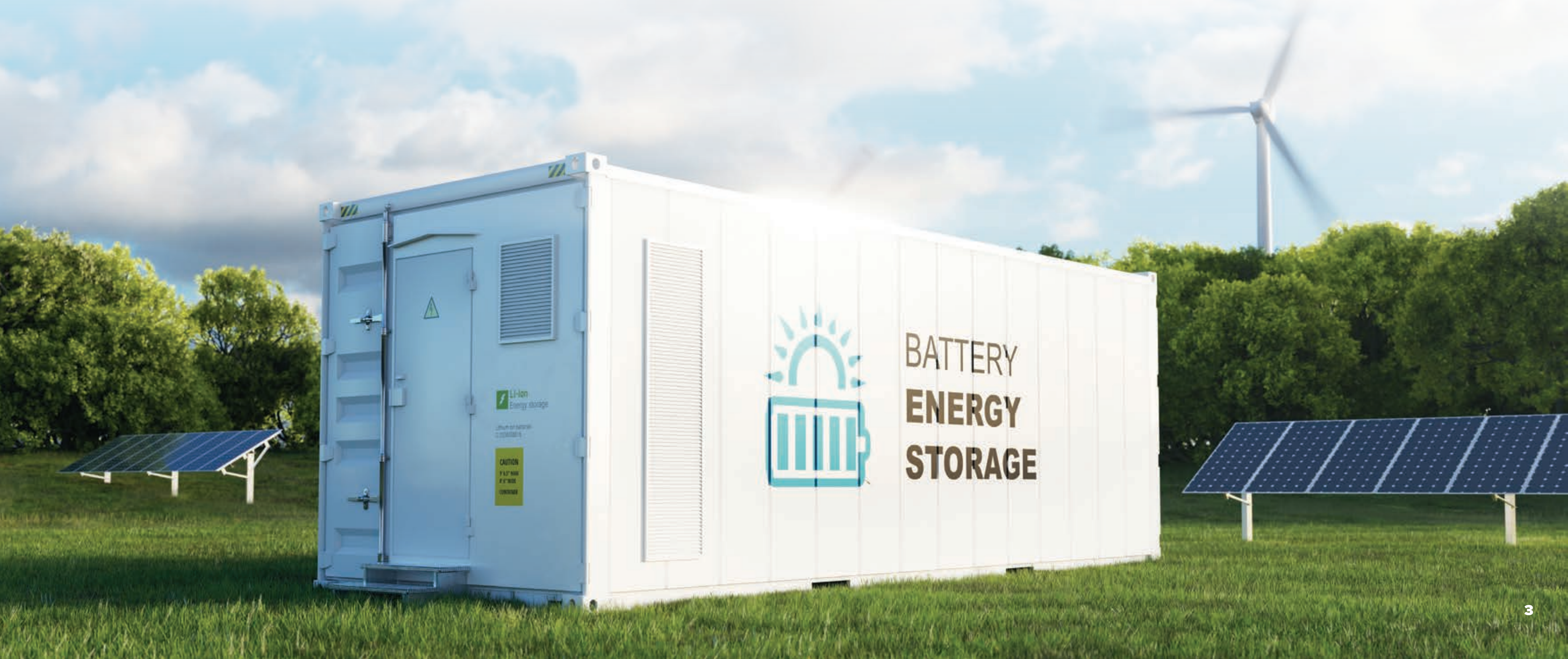
Preface

The purpose of this document is to provide a technical and commercial comparison of various battery energy storage system (BESS) chemistries which are currently available on the market suitable for intraday shifting.

When such a BESS is combined with an intermittent renewable energy system with no inherent storage (wind, solar, run-of-the-river hydro), throughout the day, the resulting hybrid system can divert any excess energy produced at times of low demand to storage. The BESS can subsequently supply the grid at times of high demand, whilst also minimising the use of fossil fuels when attempting to match peak demand and overcome network constraints.

A note on the analysis

The analysis presented in this document was conducted internally by Ara Ake in Q4 2022, and as such, only shows a snapshot of the BESS market in time. Due to the significant growth and innovation occurring in the BESS market, depending upon when this document is picked up by the reader, the results throughout regarding the chemistries presented may be out of date.



Summary

Renewable energy is New Zealand's largest source of electricity generation (82%) and provides approximately 41% of New Zealand's primary energy supply.[1] Of the installed renewable electricity capacity, 20% is associated with intermittent renewable energy systems (IRES) with little to no capacity for energy storage.[2]

There is potential to overcome this issue by combining IRES with stationary energy storage systems (i.e. batteries). With this kind of hybrid system, through intraday shifting, any excess energy produced by the plant at times of low demand may be stored to subsequently supply the grid at times of high demand, whilst also minimising the use of fossil fuels when attempting to match peak demand and overcome network constraints.

Ara Ake has identified a number of potential IRES power plants within New Zealand to demonstrate such a hybrid system. Lithium ion technology dominates the battery market across most sectors,[3] including renewable energy storage, but it is of interest to Ara Ake to understand the technical and commercial characteristics of all the various battery solutions available on the market, as well as the safety and environmental impacts of these technologies.

Recommendations

Of the more than 10 containerised BESS studied, nickel-hydrogen (NiH_2) is a standout chemistry for storage of 12 hours or less when considering all aspects due to a useable lifetime of 30 years and 30,000 charge/discharge cycles.

- On a footprint basis, nickel-hydrogen is competitive in terms of useable annual energy output with higher energy density lithium ion and molten salt battery chemistries. On a lifetime basis, nickel-hydrogen has among the highest energy output of all technologies studied, beating all manufacturers, but two lithium ion offerings (CATL and Tesla).
- Nickel-hydrogen is designed for up to three charge/discharge cycles per day, yet is also capable of discharge rates varying between 2 and 12 hours. Competitors have similar charge/discharge rates, but are only designed for a maximum of one to two cycles per day before significantly impacting battery lifetime.
- From a cost perspective, nickel-hydrogen is the best value for 12 hours or less of storage when comparing the levelised cost of storage (LCOS) of the technologies, a measure of the total cost of an energy storage system against the energy discharged over the battery's lifetime.
- The estimated environmental impact of the battery is comparable to a number of competitors, but significantly lower than lithium ion.
- The nickel-hydrogen technology has passed all relevant battery safety standards, including the UL 9540A test for thermal runaway. Many new battery technologies have passed this test, however, few lithium ion manufacturers have with only a single containerised lithium ion battery manufacturer in the UL 9540A database (EVLO).
- The manufacturer, EnerVenue, has been backed by multibillion dollar engineering company, Schlumberger (marketed as SLB), who will support large-scale deployment of nickel-hydrogen battery technology across selected global markets. Current production volume is 60MWh/year, however planned facilities soon to be under construction will result in exceeding 2GWh/year by the end of 2024.

Another battery technology which could be of interest is calcium-antimony (CaSb), given its high energy output and low LCOS similar to nickel-hydrogen. No environmental data for this technology was available, but all things considered, it could be an interesting technology for similar applications.

Definitions

Electrical current (A)

The flow (and amount) of electricity in an electrical circuit, measured in amperes. 1 A is equal to an electrical flowrate of $6.241509074 \times 10^{18}$ electrons per second.

Electrical resistance (Ω)

The opposition to flow of electrical current in a circuit, measured in Ohms.

Voltage (V)

The electromotive driving force in an electrical circuit, measured in Volts. Voltage is the product of current and resistance.

Electrical power (W)

The rate electrical energy is transferred by an electrical circuit, measured in watts. Power is the product of voltage and current.

Battery

A device containing an electric cell or a series of electric cells storing energy that can be converted into electrical power.

Rated power output (kW)

The theoretical maximum amount of instantaneous power, measured in kilowatts, which can flow into or out of a battery.

Rated battery capacity or energy output (kWh)

A theoretical measure of battery power delivered over a given time period i.e. 1 kWh is equivalent to 1 kW of constant power over the period of 1 hour. 1 kWh is also equivalent to 3.6 megajoules (MJ).

Round trip efficiency (%)

The percentage of energy used to charge the battery (i.e. put into storage) which can then be later retrieved. This is essentially a measure of the energy lost during a given charge-discharge cycle.

Useable battery capacity (kWh)

The actual battery power delivered over a given time period, once accounting for round trip efficiency.

C-rating ($hours^{-1}$)

The charge/discharge rate is a measure of how much time is required to fully charge or discharge a battery. Note that the C-rating of a battery impacts power output e.g. a 120kWh battery with a C/2 rating will provide 60kW of power over 2 hours. A C/12 equivalent would provide 10kW over 12 hours.

Battery cycle

The process of charging a battery and discharging it as required. A single charge and discharge is equivalent to 1 cycle.

Lifetime degradation (%/lifetime)

A process which permanently reduces the amount of energy a battery can store, or the amount of power it can deliver. Usually presented on a per cycle or per year basis.

Battery lifetime (years or cycles)

Battery lifetime is equivalent to the number of cycles before the battery will either no longer hold charge or performance is significantly reduced. This lifetime may also be converted to years.

Context

Renewable energy is New Zealand's largest source of electricity generation (82%) and provides approximately 41% of New Zealand's primary energy supply.[1]

Of the 7682MW of renewable electricity capacity installed in New Zealand by the end of 2021, 1703MW are generated by intermittent renewable energy systems (IRES).[2] Such systems include:

- Run-of-the river hydropower (586MW),[3] where electricity is generated from water flowing in a river or stream (as opposed to conventional hydro which generates power from the gravitational potential energy of dammed water)[†];
- Wind (913MW), where turbines generate electricity from the wind's kinetic energy; and
- Solar (205MW), where photovoltaic (PV) cells convert sunlight into electrical energy.

The key difference between the above systems and conventional hydropower and geothermal plants is that they have little to no capacity for energy storage and are subject to ambient conditions such as seasonal river flow, wind speed/direction and solar radiation. This makes these plants' electricity supply irregular with the inability to co-ordinate electrical output with consumer demand.

There is potential to overcome this issue by combining IRES with stationary energy storage systems (i.e. batteries). With this kind of hybrid system, through intraday shifting, any excess energy produced by the power plant at times of low demand may be stored to subsequently supply the grid at times of high demand. Having access to this stored renewable energy will minimise the use of fossil fuels when meeting peak demand and also has the potential to provide more effective embedded generation, to match peak load and network constraints.

Ara Ake has identified a number of potential IRES power plants within New Zealand to demonstrate such a hybrid system to support intraday generation shifting and lines company constraint management. Lithium ion technology dominates the battery market across most sectors[4], including renewable energy storage, but it is of interest to Ara Ake to understand the technical and commercial characteristics of all the various battery solutions available on the market, as well as the safety and environmental impacts of these technologies.

† There is an argument that a number of New Zealand's large conventional hydroelectric plants are essentially run-of-the-river because of their limited storage, however a distinction is made that if the river is impounded to create a reservoir of significant size then the plant is technically not run-of-the-river. [5]

Examples of BESS projects and installations

By the end of 2021, the installed capacity of grid-scale BESS around the world exceeded 16GW and global investments approached $10 billion USD[6]. Some recent examples of both domestic and international renewable energy battery storage hybrid projects include:

- In March 2022, WEL Networks and Infratec announced that they had entered into major contracts for the supply and build of New Zealand's first renewable energy BESS hybrid[7]. Along with the proposed battery facility, consisting of a 35MW lithium ion unit from SAFT, a new solar farm is being explored to reduce the cost of renewable power for consumers. Construction began in August 2022 and, once commissioned, the facility will store enough energy to meet the daily demands of over 2,000 homes and will be capable of providing fast reserves support for the North Island grid.
- AES Chile submitted an Environmental Impact Assessment in late February 2023 for an $800M USD hybrid park in the Antofagasta region. The project will involve the construction of a 140MW wind farm, 252MW of solar and a 623.5MW, 3,100MWh lithium ion BESS[8]. This proposed BESS hybrid follows on from the 2019 installation of a 10MW, 50MWh lithium ion energy storage system at its 178MWh run-of-the-river hydropower facility at the Cordillera Complex near Santiago, Chile. Prior to this 2019 installation, AES Chile (then AES Gener) conducted an analysis on a range of storage options, finally choosing lithium ion batteries because the technology is scaling exponentially and was most favourable in their assessment when considering factors including cost, safety, energy density, charging and discharging rates, and overall lifecycle.[9]
- In January 2023, RWE, a German energy provider, commissioned 117MW, 128MWh of lithium ion batteries across two of their run-of-the-river plants.[10] The systems at Gersteinwerk in Werne and Emsland station in Lingen have energy capacities of 79MWh and 49MWh respectively. Through these installations, RWE can make additional electricity capacity available to the grid and also balance the flow of energy from the power stations, helping to keep the frequency of the power grid stable.
- New Zealand gentailer, Meridian Energy, announced in December 2022 that construction of the Ruakākā BESS at Marsden Point will begin in Q1 2023.[11] Upon completion and commissioning (expected H2 2024), the 100MW, 200MWh SAFT lithium ion unit will be hybridised with a new 130MW solar PV plant to reduce costs.[12]
- Portland General Electric commissioned the United States' first facility to co-locate wind and solar generation, coupled with battery storage, in September 2022.[13] The Wheatridge Renewable Energy Facility has a 300MW wind farm, a 120MW solar farm and a 120MWh lithium ion BESS. At maximum output, the facility located near Lexington, Oregon produces more than half of the power that was generated by Oregon's last coal plant (demolished the same month this facility became operational) or enough emissions-free energy to power about 100,000 homes.[14]

The examples listed here reflect that lithium ion battery storage currently exhibits a clear dominance in the rechargeable battery market, accounting for more than 90% of all BESS deployments in both 2020 and 2021.[6] This dominance however is likely due to a variety of factors, such as manufacturing capability, as many newer technologies capable of competing with lithium ion on a technical and commercial level do not yet have the manufacturing capacity to supply large MW-scale energy storage systems.

Technologies and manufacturers

An analysis has been conducted on stationary, long duration battery solutions suitable for application to intermittent renewable energy systems.

A typical 20ft containerised BESS producing greater than 100kWh of energy, over 12 hours or less, has been used as a baseline for this analysis, so only perceived competitors to such a product have been included.

The battery solutions and manufacturers which have been identified are detailed in the subsequent section. Although identified here, some companies associated with the technologies of interest do not provide sufficient information to allow for any kind of analytical comparison between products and therefore have not been included in the analysis.

Lithium ion batteries

Lithium ion batteries utilise solid electrodes of typically carbon and metal oxide with a liquid organic electrolyte containing a dissolved metal salt. Metal ions travel between electrodes via a porous membrane, generating an electrical current.[15] The two most common chemistries are lithium iron phosphate (LFP) and nickel manganese colbolt (NMC). Manufacturers are moving more towards the former as despite NMC typically having a higher energy density, LFP is cheaper to produce, has a longer lifecycle and is less susceptible to thermal runaway.

Lithium ion

- CATL[16]
- Corvus Energy[17]
- Eaton[18]
- EVLO[19]
- SAFT[20]
- Tesla[21]

Redox flow batteries (RFB)

In RFBs, redox (reduction and oxidation) reactions within electrochemical cells enables energy to be stored in a flowing liquid electrolyte solution during battery charge and discharge. Battery power is dependent upon the size of the electrochemical stack, whereas battery energy depends upon the volume of electrolyte. This separation of power and energy is a key distinction and advantage of RFBs when compared to other electrochemical storage systems as system vulnerability to uncontrolled energy release is limited by system architecture to a few percent of the total energy stored.[22]

Vanadium (VRFB)

- CellCube[23]
- Invinty Energy Systems[24]
- Rongke Power[25]
- VRB Energy[26]

Zinc-Bromide ($ZnBr_2$ flow)

- Redflow[27]

Zinc-Air

- Zinc8[28]

Iron flow (IFB)

- ESS[29]

Organic (non-metal)

- CERQ (formerly Jena Batteries)[30]

Molten salt batteries

These batteries operate well in excess of 100⁰C and the anode and cathode are typically liquid separated by a salt electrolyte or ceramic membrane capable of conducting metal ions to generate an electrical current.

Calcium-Antimony (CaSb)

- Ambri[31]

Sodium-Nickel-Chloride ($NaNiCl_2$)

- FZSoNick[32]

Sodium Sulphur (NaS)

- NGK Insulators[33]

Other metal batteries

Nickel-Hydrogen (NiH_2)

Nickel hydroxide and nickel alloy electrodes in the presence of an alkaline electrolyte create an electrical charge, producing and consuming hydrogen gas on charge and discharge.

- SLB (partnered with EnerVenue)[34, 35]

Zinc-Bromide ($ZnBr_2$ non-flow)

Typically a redox flow battery chemistry, oxidation reduction chemistry occurs between zinc and bromide electrodes via either a solid gel or aqueous electrolyte allowing zinc ions to flow through a membrane, subsequently generating current.

- EOS Energy Enterprises[36]
- Gelion[37]

Lead (Pb)

Interestingly, no lead-based batteries have been identified in this particular space, likely due to the chemistry's low energy density, short lifetime and, as a result, high price when compared to lithium-ion, the dominant chemistry in today's battery market.

Non-metal batteries

Conductive polymer

Solid carbon-graphene hybrid electrodes combined with a liquid electrolyte and a permeable separating membrane enable ions to travel between the anode and cathode, creating electrical current.

- PolyJoule[38]

Commercialisation considerations

The previous section details a subset of the players in the stationary BESS market, however an important discussion point beyond the chemistry is how far through the commercialisation journey are each of these chemistries and/or companies.

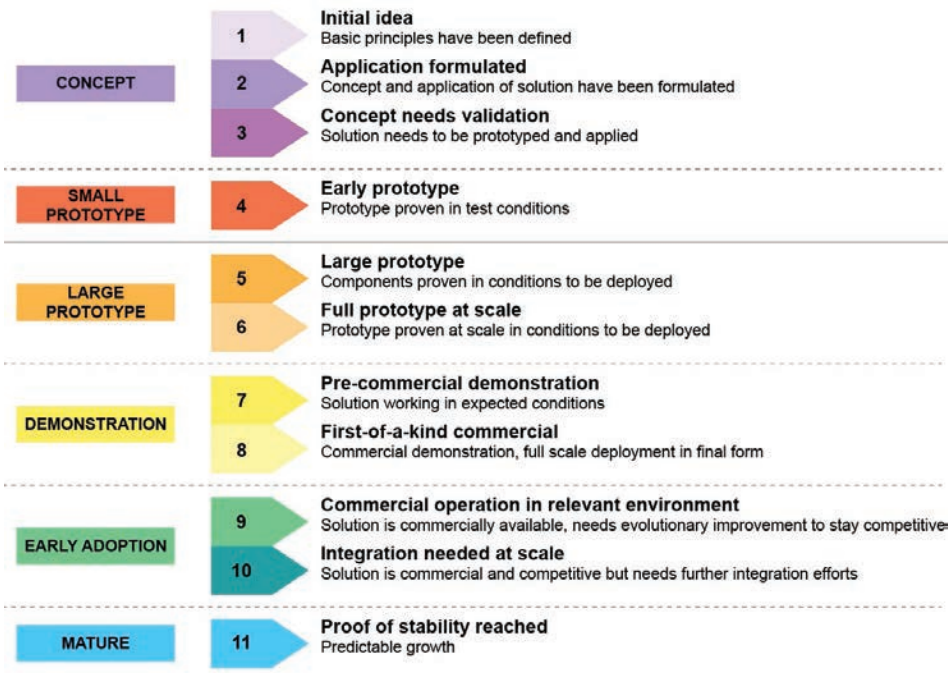
Table 1 details a number of key commercialisation metrics which have been identified across the manufacturers listed in the previous section. These metrics include year founded, installed battery volume (in MWh), number of employees, revenue (in $M USD, if any), annual production volume and total agreed project pipeline (both in MWh).

Some important things to note is that a number of these companies have business interests outside of stationary BESS, so the numbers presented may not necessarily be a direct result of their activities related to BESS. Also, although there may be a significant difference in some values presented when compared to other manufacturers, this does not necessarily mean that they are at different stages of commercialisation, it may simply reflect other market indicators such as market share (i.e. two BESS companies with 200 and 2000 employees may be similarly commercialised within the market. A third company with 20 employees is likely significantly less commercialised). Nevertheless, the metrics presented provide reasonable proxies to indicate a company's stage of commercialisation.

Similarly to the previous section, although identified, some companies associated with the technologies of interest do not provide sufficient commercial information in the public domain to allow for any kind of analytical comparison between products and therefore have not been included. In the majority of cases, each company presented does not detail each and every metric of interest in the public domain, however they do provide enough to make an educated comparison.

Estimates of commercialisation stage may be mapped against the 11-point technology readiness level (TRL) scale presented by the International Energy Agency (see Figure 1).[39]

Figure 1: Technology Readiness Level (IEA)



The range which is relevant to the manufacturers included is estimated to be TRL 7 to TRL 11, pre-commercial demonstration to mature in market:

TRL 11: Mature in market (very large product volumes manufactured, delivered and demonstrated in field i.e. >1GWh, revenue likely >$50M USD)

- CATL
- Corvus Energy
- NGK Insulators
- Rongke Power
- SAFT
- Tesla

TRL 10: Early adoption in market (large product volumes manufactured, delivered and demonstrated in field i.e. 100MWh-1GWh, revenue likely $10M-$50M USD)

- CellCube
- EOS Energy Enterprises
- FZSoNick (acquired by Hitachi Chemical - $5.8B USD revenue in 2021)

TRL 9: Commercial operation (significant product volumes manufactured, delivered and demonstrated in field i.e. 10MWh-100MWh, revenue likely $1M-$10M USD)

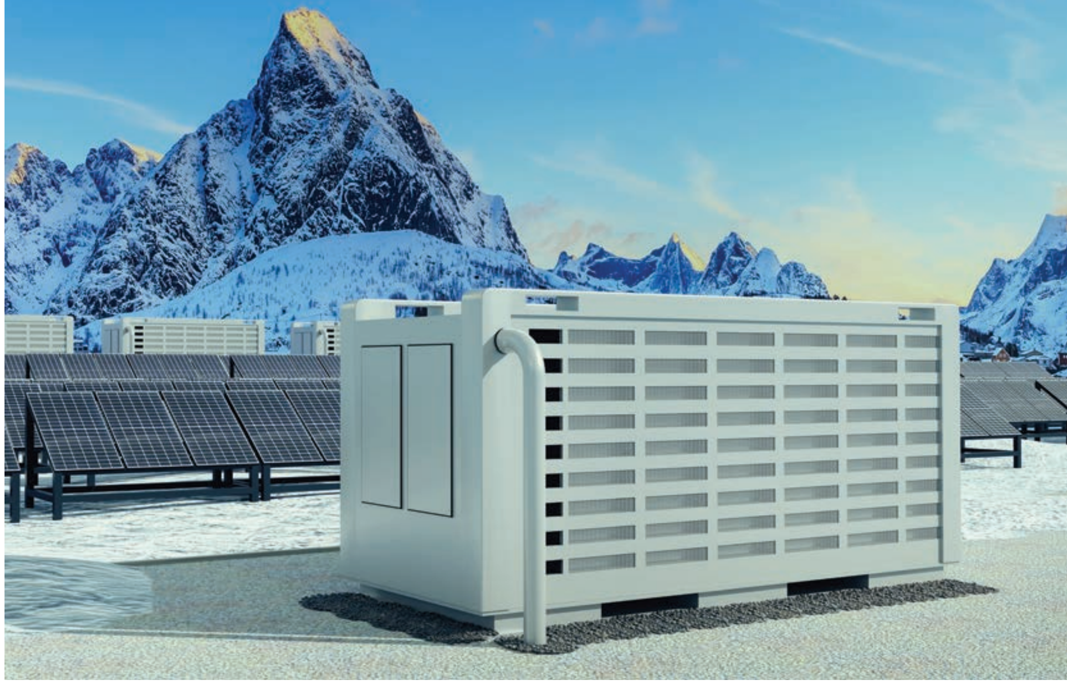
- Invinty Energy Systems
- VRB Energy

TRL 8: Commercial demonstration (small product volumes under demonstration with significant growth in manufacturing i.e. 1MWh-10MWh, revenue likely $100K-$1M USD)

- Ambri
- EnerVenue (globally branded as SLB - $28.1B USD revenue in 2022)
- ESS
- Redflow

TRL 7: Pre-commercial demonstration (only small product volumes manufactured, delivered and demonstrated in field, minimal or pre-revenue)

- Gelion
- PolyJoule
- Zinc8



Some takeaways from this TRL mapping include:

- Older technologies, with fewer recent developments, such as lithium ion, vanadium flow and molten sodium batteries are higher up the TRL scale.
- Of the newer technologies, EOS Energy Enterprises (non-flow zinc-bromide) appears to have a significant commercial advantage over its competitors, generating over $10M USD in revenue in 2022 with at least a 1.8GWh project pipeline.
- Companies lower on the TRL scale (TRL 7-8) will have a significant number of commercialisation barriers (for example, manufacturing and supply chain) to cross before gaining early adoption in the market. This will be significantly more challenging for independent companies when compared to, for example, EnerVenue (nickel-hydrogen), who have backing from global, multibillion dollar engineering company, Schlumberger (now marketed as SLB).

Table 1: Commercial metrics of battery manufacturers

Chemistry	Manufacturer	Founded	Dispatched volume	Employees	Revenue*	Production volume	Pipeline volume
		Year	MWh	#	$M USD/year	MWh/year	MWh
Lithium ion	CATL	2011	-	Approx. 33,000	14,364[40]	170,000 (Additional 140,000 per year under construction)	-
	Corvus Energy	2009	400	192	61 (2020)[41]	>1,000	-
	SAFT	1918	-	>4,000	780 (58M for BESS)[42]	170,000 (Total planned production by 2025)	-
	Tesla	2003	>17,000	128,000	81,462 (10,000 non-automotive)[43]	40,000 (Megapack only)	-
Vanadium	CellCube	2008	42.9	61	4.09 (2019)[44]	-	-
	Invinty Energy Systems	2020	28.0	171	3.2[45]	-	66.3
	Rongke Power	2008	992	-	-	300	-
	VRB Energy	2007	>30	65	-	-	>500
Zinc-based	EOS Energy Storage	2008	640	250	18.4	800	>1,800
	Gelion	2015	Pilot scale#	50	0.43[46]	2	-
	Redflow	2005	>2	62	1.12[47]	80	-
	Zinc8	2011	Pilot scale	44	0 (Goal to generate by 2024)[48]	1 (Ambition of 60MWh by 2024)	-
Sodium-based	FZSoNick[49]	2011	400	130	32.2 (2019)[50]	100	-
	NGK Insulators[51]	1919	4,100	20,100	4041	1,000	-
Iron flow	ESS	2011	-	183	0.87[52]	750	>12,000[53]
Calcium-Antimony	Ambri	2010	Commercial pilot#	122	-	200 (200,000 cells by end of 2023)	>1,200[54]
Nickel-Hydrogen	EnerVenue (SLB)	2020	Commercial pilot	110	-	60 (2,200 planned by 2024; 31,000 by 2027)	>5,000[55]
Organic	PolyJoule	2011	Pilot scale	11	-	>1 (10,000 cells)	<1

* Revenue data has been gained from Google Finance Q3 2021 to Q3 2022, unless specified otherwise. Unknown data not available in the public domain has been indicated with a dash.

\# Pilot scale refers to installations less than 1MWh. Commercial pilot refers to installations between 1 – 2MWh.

Analysis

The data presented in this section is either publicly available or has been gained through direct consultation with the manufacturer. For those technologies with multiple players (i.e. lithium ion and vanadium flow), battery data has been aggregated and average values are presented. The raw, non-aggregated data is provided in tables in the Appendix.

Technical comparison

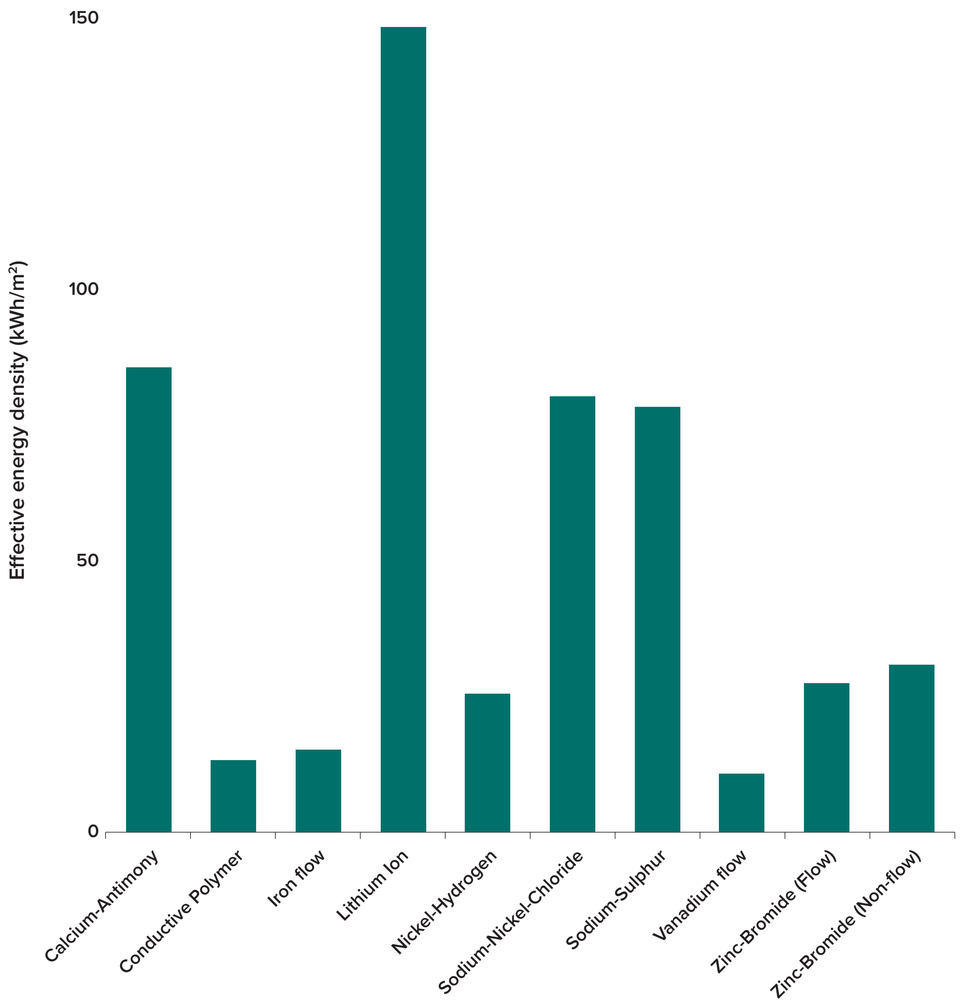
Effective energy density

The energy density of batteries is typically presented in watt-hours per gram (Wh/g or kWh/kg). This provides a reasonable comparison when the useable energy output and weight of the battery is known, however, in the case of containerised energy storage systems, there is significant voidage within the container for the purpose of maintenance, air flow etc. This means that only an effective energy density can be determined using the useable energy output and the weight of the containerised system.

This approach is also challenging as some manufacturers do not provide the weight of the containerised system, however, all provide the area footprint of the system for a given energy output, enabling an effective energy density of kWh/m^2 to be presented in Figure 2. Note that an advantage of containerised systems is that they may be stacked, however, for the purpose of this comparison, the footprint density has only been presented for a system with a single container.

Lithium ion has the highest average energy density of the technologies compared at approximately 145kWh/m^2. This observation is not surprising as lithium ion is known for having a particularly high energy density when compared to other renewable battery technologies.[56] This is then followed by molten-salt batteries (calcium-antimony, sodium-nickel-chloride, sodium-sulphur), which are also known for high energy densities,[57] at approximately 80kWh/m^2. Zinc-bromine technology, in both flow and non-flow battery configurations, has an effective energy density of 30kWh/m^2. This density is similar to nickel-hydrogen (25kWh/m^2), but much higher than other flow chemistries (Vanadium, 10kWh/m^2; Iron, 15kWh/m^2). Due to its early stage of development, the conductive polymer battery has a low energy density of 15kWh/m^2, similar to very large redox flow systems.

Figure 2: Effective energy density of battery technologies



Battery cycling

The lifetime of a battery is measured by the total number of charge/discharge cycles a battery can achieve before:

- The battery can no longer hold a charge; or
- Significant energy capacity degradation has occurred.

Of the battery technologies investigated (see Figure 3), nickel-hydrogen is capable of achieving at least 30,000 cycles in its lifetime. This is followed by vanadium and iron redox flow batteries with lifetimes of approximately 20,000 cycles. All other technologies have a theoretical lifetime less than 12,000 cycles, with the majority less than 7,000 cycles.

For this research, it is of particular interest to understand which battery technology is suitable for multiple cycles on a given day. Some battery manufacturers state that their technology is capable of an unlimited number of daily cycles despite stating a very long lifetime in years (which does not align with the theoretical cycle lifetime). As a result, some battery technologies capable of multiple cycling per day are only able to do so by significantly decreasing the years of useable battery life.

To conduct a fair comparison, the annual cycles of a given technology has been determined by dividing the theoretical cycle life of the battery by the design lifetime, in years. As shown on Figure 3, due to its design life of 30 years, nickel-hydrogen technology is again dominant with a design of 1000 cycles per year (or approximately three cycles per day). Similarly, large redox flow systems (vanadium and iron) are capable of approximately 800 cycles per year, followed by conductive polymer at 600 cycles per year (approximately two cycles per day). All other battery technologies, based upon their theoretical cycle and yearly lifetimes, are capable of one cycle per day.

Specific energy output

The total specific energy output of each battery technology, on both an annual and lifetime basis, can be determined through combining the effective energy density with the number of theoretical annual and lifetime charge/discharge cycles (see Figure 4).

When accounting for lifetime degradation, nickel-hydrogen has the highest specific energy output over its lifetime (720MWh/m^2-lifetime) when compared to the aggregated lithium ion lifetime output (710MWh/m^2-lifetime) and the output of the other high energy density technologies (600MWh/m^2-lifetime, calcium-antimony). This is due to the technology's very high cycle lifetime and low degradation rate (0.2%/year compared to 2%+ for lithium ion). It is notable however that two of the six lithium ion products analysed (CATL and Tesla) have lifetime energy outputs exceeding that of the nickel-hydrogen technology (>1000MWh/m^2-lifetime) whilst the four remaining lithium ion products have outputs of less than 650MWh/m^2-lifetime.

On an annual basis, due to having high energy densities, lithium ion has the highest energy output (43MWh/m^2-year, aggregated; 76MWh/m2-year, Tesla), followed by the molten salt calcium-antimony battery (30MWh/m^2-year). Interestingly, despite having a relatively low energy density, nickel-hydrogen has the third highest output of 24MWh/m^2-year (joint with sodium-nickel-chloride molten salt technology) due to the technology's capability to cycle three times per day.

Other technologies have specific energy outputs generally less than 350MWh/m^2-lifetime and 20MWh/m^2-year.

C-rating

The C-rating or charge/discharge rate is a measure of the speed to fully charge or discharge a battery.

This is an important measurement when considering battery technologies for IRES, as long duration energy storage is of particular interest due to the potential to meet peak demand over extended periods using stored renewable power rather than fossil fuels.[58]

The definition of long duration energy storage or LDES varies by source. Typically, it is energy storage for greater than four hours (i.e. C/4).[59] This extends to greater than 10 hours (C/10) as per the definition set by the US Department of Energy.[60]

Figure 5 presents the inverse C-rating, i.e. the charge/discharge duration, for each battery technology. All technologies except lithium ion have a charge/discharge rate much greater than four hours. This is consistent when increasing the charge/discharge rate to 10 hours, with only sodium-nickel-chloride (and lithium ion) falling below this level.

Ambient temperature range

Figure 6 presents the operating ambient temperature range of each battery technology. All technologies can operate within New Zealand's mean temperature range and at extreme maximum temperatures.[61] Only calcium-antimony, nickel-hydrogen, sodium-nickel-chloride and conductive polymer chemistries can operate at NZ's extreme minimum temperatures.

Importantly, irrespective of ambient temperature, the majority of lithium ion battery systems require cooling systems to prevent thermal runaway.

Figure 3: Lifetime and annual cycling of battery technologies

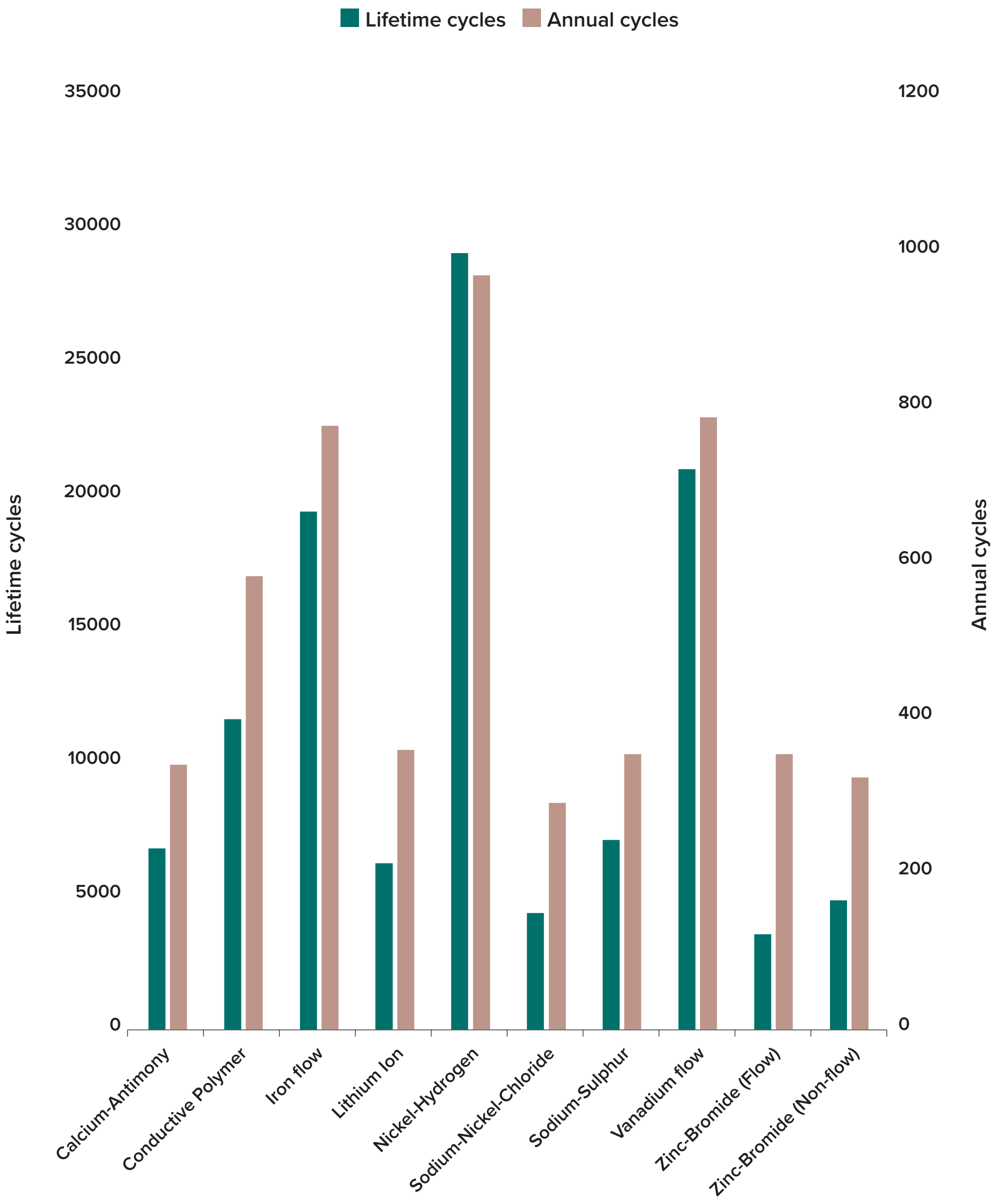


Figure 4: Annual and lifetime specific energy output of battery technologies

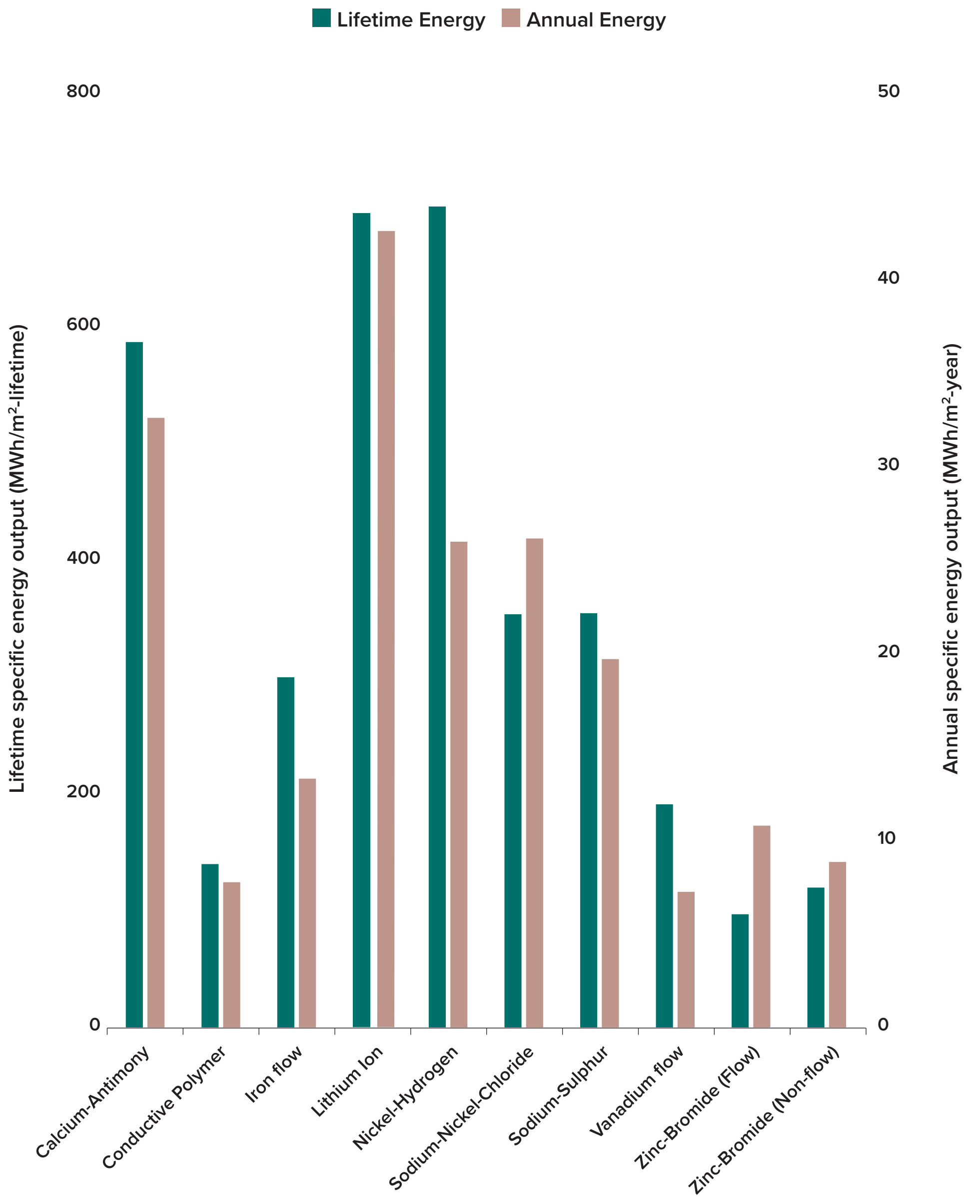


Figure 5: Charge/discharge duration of battery technologies

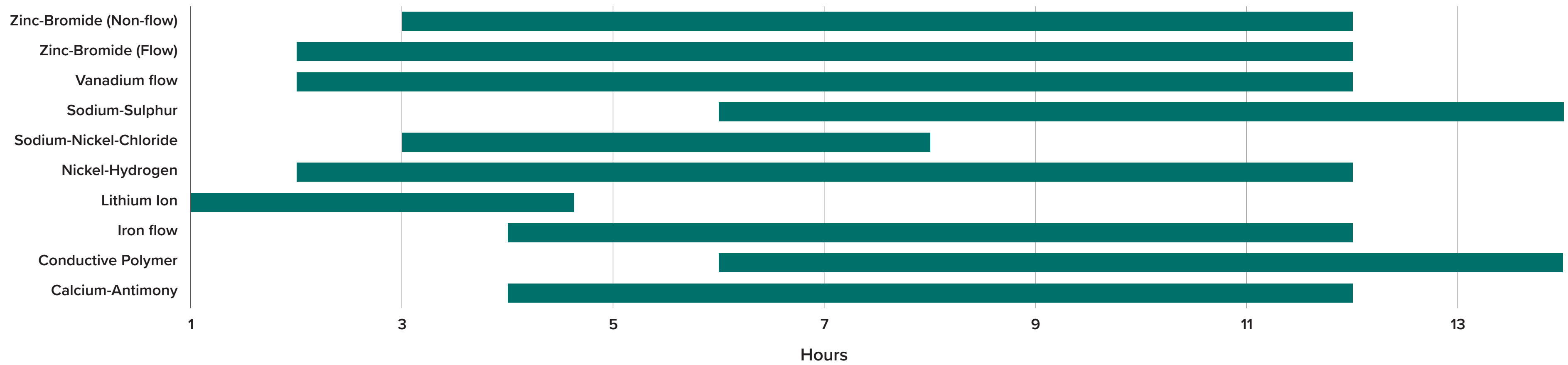
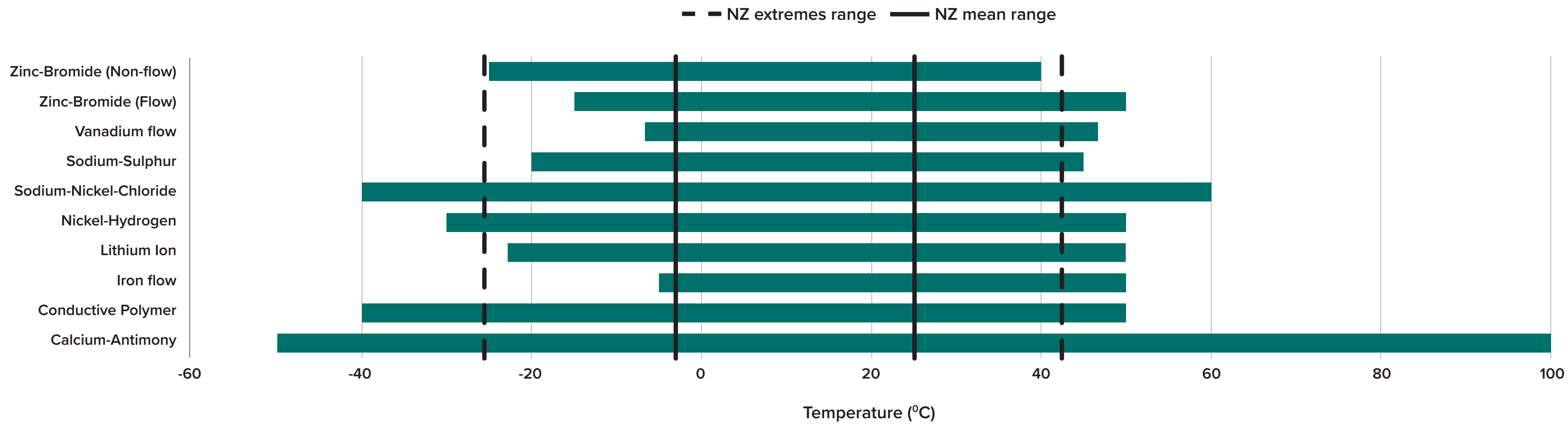


Figure 6: Operating ambient temperatures of battery technologies



Commercial comparison

Levelised cost of storage

Of the manufacturers within this analysis, few provide numerical insight into the cost of their energy storage systems beyond presenting only favourable data from a marketing perspective.

In order to effectively compare the cost of energy storage systems, a calculation known as the levelised cost of storage (LCOS) is utilised to quantify the discounted cost per unit of discharged energy for a specific storage technology, accounting for all technical and economic parameters affecting the lifetime cost of discharging energy stored in a battery.[62] The equation for LCOS is presented as,

$$\text{LCOS}\left(\frac{\$}{\text{MWh}}\right) = \frac{\text{Investment cost} + \sum_{n}^{N} \frac{\text{O\&M cost}}{(1+\boldsymbol{r})^{\boldsymbol{n}}} + \sum_{n}^{N} \frac{\text{Charging cost}}{(1+\boldsymbol{r})^{\boldsymbol{n}}} + \sum_{n}^{N} \frac{\text{End of life cost}}{(1+\boldsymbol{r})^{\boldsymbol{n}}}}{\sum_{n}^{N} \frac{\text{Electricity discharged}}{(1+\boldsymbol{r})^{\boldsymbol{n}}}},$$

where $\boldsymbol{n}$ is the year, $\boldsymbol{N}$ is the system lifetime (in years) and $\boldsymbol{r}$ is the discount rate (set as 8%). Charging cost and construction time (which influences the value of $\boldsymbol{n}$) have been left consistent for each technology and have been set at the default values of $50USD/MWh and 1 year.

This methodology, along with the calculation of each individual component, is detailed in Schmidt et al. (2019). A dashboard for this calculation is available at EnergyStorage.ninja, pre-populated with 2021 data for a variety of battery technologies.

Costing data utilised for lithium ion, sodium-sulphur, vanadium and zinc-bromide batteries was gained from the aggregated data available in Schmidt et al. (2019); as well as from Lazard, an international financial advisory and asset management firm who are specialists in LCOS calculations;[63, 64] and Sandia National Laboratories, a multimission R&D centre working under the US Department of Energy.[65]

Data for calcium-antimony, iron flow and nickel-hydrogen were gained through either direct consultation with the manufacturer or was back calculated from cost data available on their websites.[66, 67] Despite having consulted with the manufacturer to gain access to the cost data, the conductive polymer battery is not presented here as, at present, the technology is simply not cost competitive.

Figure 7 details the LCOS for battery systems against total storage duration, assuming 300 and 600 cycles per year (approximately one and two cycles per day).

Insights from the figures are summarised below:

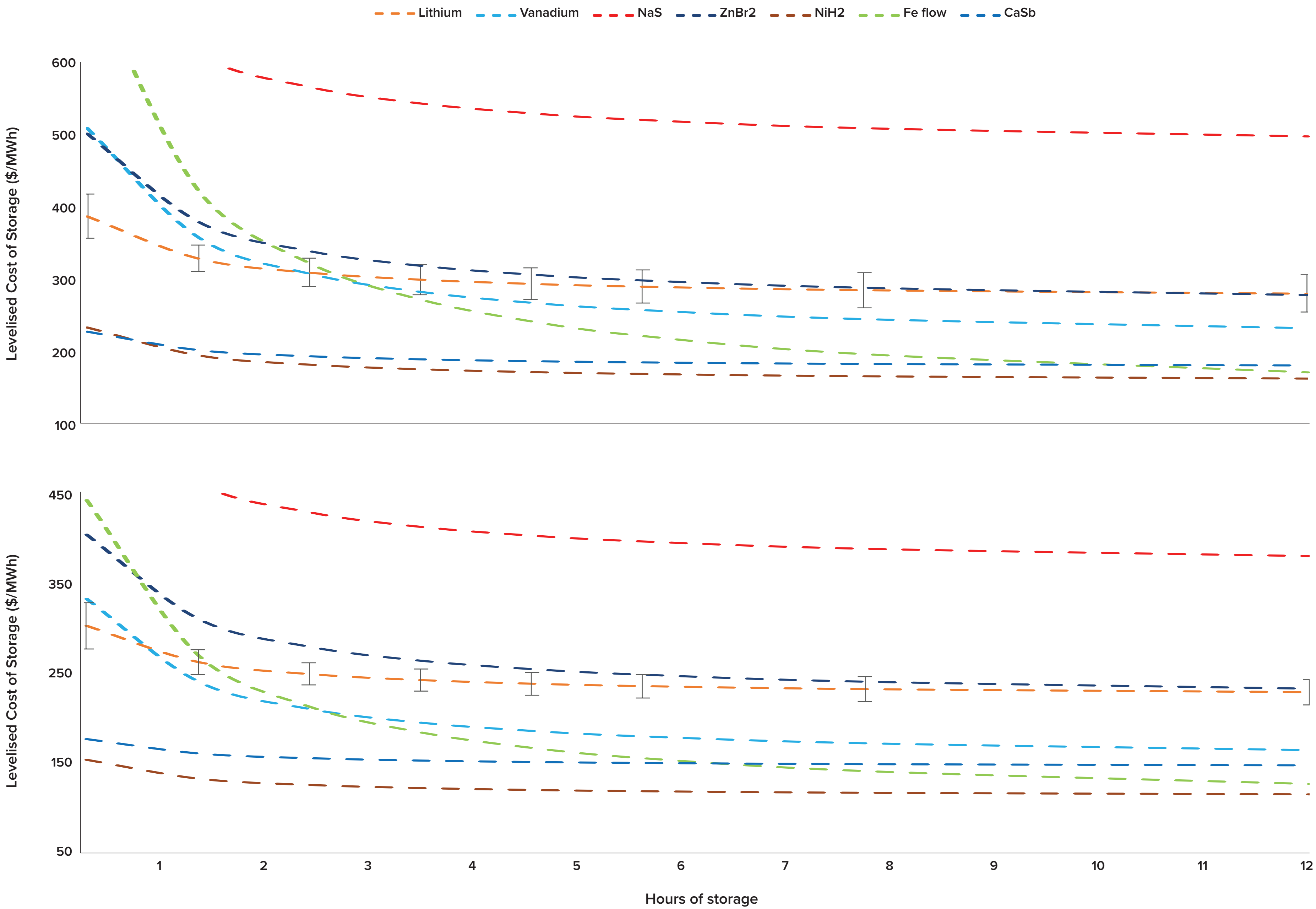
One cycle per day:

- Lithium ion batteries, operating at one cycle per day, start at approximately $400(±40)/MWh for one hour of storage, reducing to $280(±20)/MWh for 4-12 hours of storage.
- The majority of other technologies do not become more cost effective than lithium ion (<$280/MWh) until reaching storage durations exceeding four hours.
- However, both calcium-antimony and nickel-hydrogen outcompete the other technologies, including lithium ion, between 1 and 11 hours with LCOS values between $180-225/MWh and $160-230/MWh, due to having similar capital costs to lithium ion, but significantly greater cycle lives, enabling them to produce energy for more years on a per MWh basis.
- At 12 hours, iron flow is on the trajectory to become the most cost effective (<$160/MWh) due to having a minor marginal energy cost with growing energy capacity.

Two cycles per day:

- Lithium ion batteries, operating at two cycles per day, start at approximately $300(±25)/MWh for one hour of storage, reducing to $230(±15)/MWh for 4-12 hours of storage.
- Vanadium and iron flow batteries quickly become more cost effective than lithium ion, after two hours for vanadium and three hours for iron flow.
- Similarly to one cycle per day, calcium-antimony and nickel-hydrogen are the two most cost effective energy storage technologies, however this is only the case for six hours of storage or less. Above six hours, iron flow overtakes calcium-antimony as the second most cost effective battery.
- Of the technologies compared, nickel-hydrogen is the most cost effective across the 1-12 hour range when operating at two cycles per day with an LCOS between $115-150/MWh due to its long cycle life.

Figure 7: Levelised cost of storage of battery technologies, operating at top) 300 cycles per year; and bottom) 600 cycles per year.



Environmental comparison

In addition to technical and costing aspects, environmental impact of each battery technology is of interest given that it is only worthwhile utilising energy storage to reduce the use of fossil fuels if the actual production of the batteries is sustainable, with minimal use of natural resources and a low global warming potential.

Global warming potential (GWP) allows the global warming impacts of different gases to be measured. Specifically, it is a measure of how much energy the emissions of 1 tonne of a gas will absorb over a given period of time, relative to the emissions of 1 tonne of carbon dioxide (CO_2).[68] The units for this measure are typically kgCO_2e/kg.

In life cycle analysis of various products, GWP is utilised to understand the warming impact based upon the gases released during production. This can be extended to a per kWh basis for batteries, when the battery composition and fossil fuel energy demand is known. Other environmental measures include the total production energy demand and water use required to produce the battery, both measured on a lifetime basis.

Boundless Impact Research and Analytics is an environmental impact analysis firm who have conducted cradle-to-grave environment assessments on a number of the technologies included in this report.[69] The majority of data presented in Figure 9, Figure 10 and Figure 11 are based off the reports produced by this firm, with additional supporting data from He et al. (2020) for the zinc-bromide flow battery.[70] No environment data is currently available for the nickel-hydrogen technology, however estimates could be made using the battery composition[71] and environmental data from the Nickel Institute and Cobolt Institute.[72, 73] Typical production and disposal environmental data for steel shipping containers was also included in the calculation, as was a safety factor of two to capture additional impacts such as converting raw material into battery form.[74]

Figure 8 shows the estimated global warming potential of each battery technology over a period of 100 years on a lifetime energy basis (i.e. kWh released over the battery's lifetime). Of the batteries studied, lithium ion has the highest GWP per kWh compared to other technologies by a significant margin (approximately 200% higher than sodium-sulphur and vanadium flow). Due to the lifecycle capabilities of iron flow and nickel-hydrogen batteries, they have the lowest GWP per kWh.

In Figure 9, the energy demand to produce the batteries is estimated. Vanadium flow and lithium ion dominate, both requiring over 1MJ/kWh-lifetime (more than double the energy demand of sodium-sulphur and both zinc-bromide technologies). Again, iron flow and nickel-hydrogen have the lowest estimated energy demands, requiring less than 0.1MJ/kWh-lifetime, again likely due to high cycle life.

In terms of water use (Figure 10), this is negligible for all technologies studied apart from lithium ion.

Figure 8: Estimated 100 year global warming potential of battery technologies

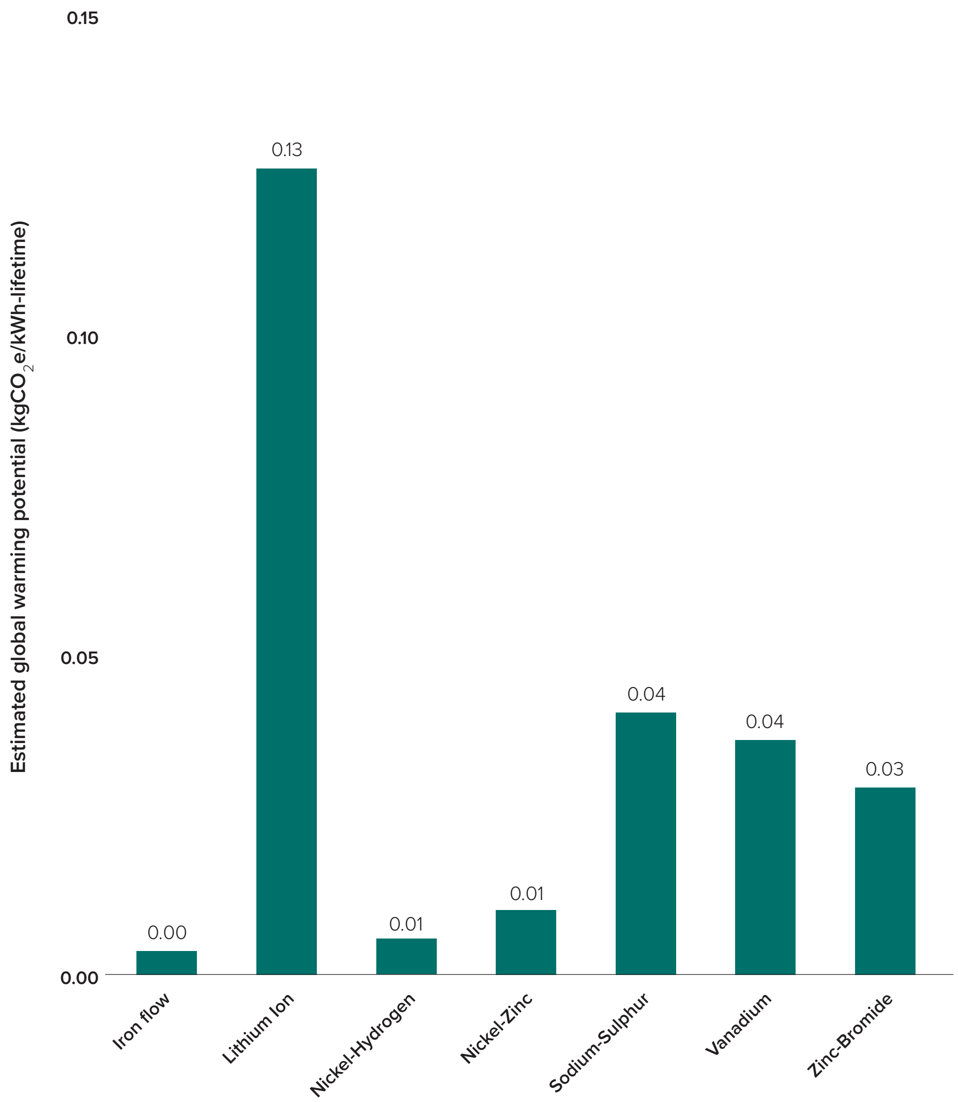


Figure 9: Estimated energy demand of battery technologies

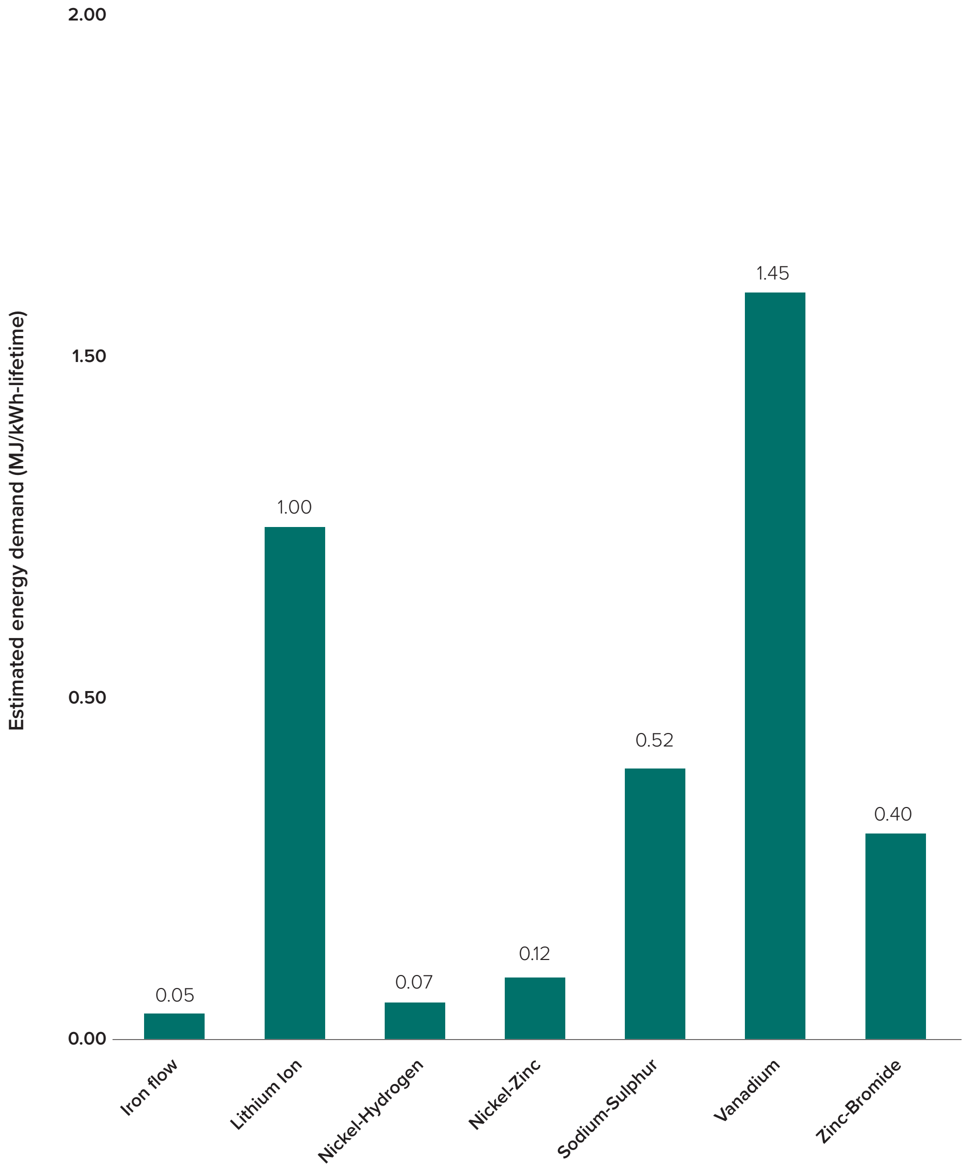
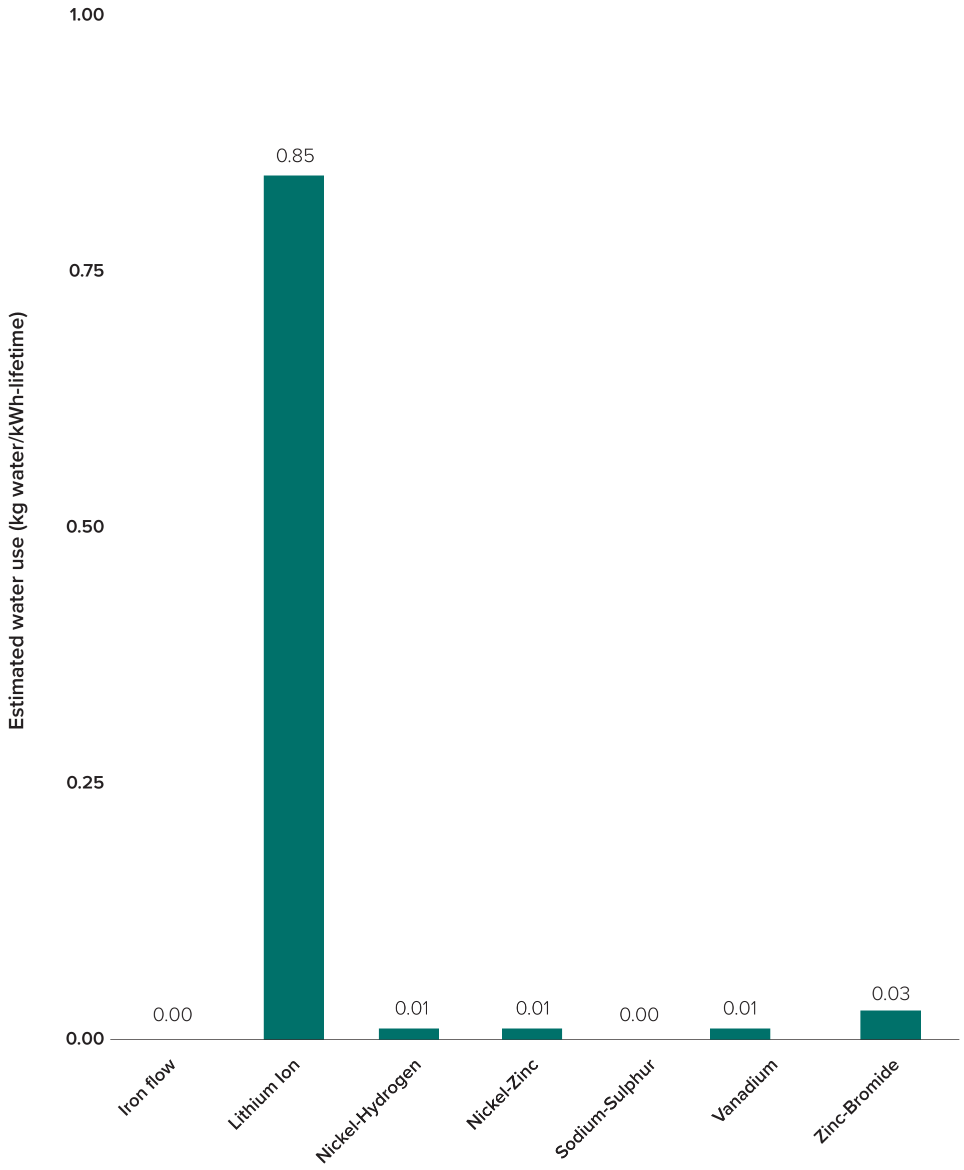


Figure 10: Estimated water use of battery technologies



Safety comparison

Irrespective of technical and commercial strength, battery technology needs to be safe. A number of standards exist in New Zealand for on-grid BESS including:

- AS/NZS 4777.1:2016 Grid connection of energy systems via inverters - Part 1: Installation requirements
- AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements
- IEC 61427-2:2015 Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 2: On-grid applications

Note: AS/NZS 5139:2019 Electrical installations - Safety of battery systems for use with power conversion equipment has not been listed here due to only covering batteries with rated capacities below 200kWh.

Although on-grid battery systems for renewable energy storage in New Zealand need to meet the above standards, the manufacturers studied in this report are all offshore, hence do not report specific compliance with these standards.

Instead, they report compliance with a number of key standards and tests conducted by Underwriters Laboratories (UL), an internationally recognised organisation for safety testing and certification of battery technology. In fact, Standards NZ have signed an agreement with UL to enhance standardisation and safety across New Zealand in a variety of industries including energy storage.[75]

These UL standards associated with stationary energy storage systems include:

- **UL 1973: Batteries for Use in Stationary and Motive Auxiliary Power Applications**
  The safety standard detailing the requirements a battery system must meet to be used as an energy storage system for stationary applications. This standard evaluates the battery system's ability to safely withstand simulated abuse conditions, evaluated at the manufacturer's specified charge and discharge parameters.[76]
- **UL 9540: Standard for Energy Storage Systems and Equipment**
  The standard for safety of energy storage systems, which includes electrical, electrochemical, mechanical and other types of energy storage technologies for systems intended to supply electrical energy covering charging and discharging, protection, control, communication between devices, fluids movement and other aspects. UL 9540 provides a basis for safety of energy storage systems that includes reference to critical technology safety standards and codes, such as UL 1973.[77]
- **UL 9540A: Evaluation of Thermal Runaway Fire Propagation in Batteries and Energy Storage Systems**
  A comprehensive test method to evaluate the risk of fire propagation from BESS.[78]

Table 2 details the technologies which meet each standard (or are currently being tested/due to receive certification). The two standouts here are calcium-antimony and lithium ion, which do not meet UL 9540A: Evaluation of Thermal Runaway Fire Propagation in Batteries and Energy Storage Systems, the test for fire safety.

The manufacturer of the calcium-antimony technology states that they have engaged Underwriters Laboratories to develop an appropriate set of safety tests for the certification of their cells, and the technology has subsequently passed these tests.

Lithium ion batteries are known for thermal runaway and very few manufacturers have addressed this. Of those studied here, only a single manufacturer of containerised lithium ion batteries, EVLO, has passed the thermal runaway tests set by UL 9540A.[79]

Table 2: Safety standards of various battery technologies

	UL 1973	UL 9540	UL 9540A
Calcium-Antimony	X	X	-*
Conductive Polymer	X	X	X
Iron flow	X	X	X
Lithium ion	X	X	-#
Nickel-Hydrogen	X	X	X
Sodium ion	X	X	X
Sodium-Nickel-Chloride	X	X	X
Sodium-Sulphur	X	X	X
Vanadium flow	X	X	X
Zinc-Bromide (Flow)	X	X	X
Zinc-Bromide (Non-flow)	X	X	X

* Ambri have passed thermal runaway tests set by UL despite not testing to UL 9540A.
# Only one in the six lithium ion manufacturers has passed the UL 9540A thermal runaway tests.

Conclusion and recommendations

A study was conducted on battery energy storage with regards to potential applications to intermittent renewable energy systems to enable intraday shifting, more effective embedded generation and lower reliance on fossil fuels to meet peak load and network constraints.

Of the more than 10 containerised BESS studied, nickel-hydrogen (NiH_2) is a standout chemistry for storage of 12 hours or less when considering all aspects due to a useable lifetime of 30 years and 30,000 charge/discharge cycles.

- On a footprint basis, nickel-hydrogen is competitive in terms of useable annual energy output with higher energy density lithium ion and molten salt battery chemistries. On a lifetime basis, nickel-hydrogen has among the highest energy output of all technologies studied, beating all manufacturers, but two lithium ion offerings (CATL and Tesla).
- Nickel-hydrogen is designed for up to three charge/discharge cycles per day, yet is also capable of discharge rates varying between 2 and 12 hours. Competitors have similar charge/discharge rates, but are only designed for a maximum of one to two cycles per day before significantly impacting battery lifetime.
- From a cost perspective, nickel-hydrogen is the best value for 12 hours or less of storage when comparing the levelised cost of storage (LCOS) of the technologies, a measure of the total cost of an energy storage system against the energy discharged over the battery's lifetime.
- The estimated environmental impact of the battery is comparable to a number of competitors, but significantly lower than lithium ion.
- The nickel-hydrogen technology has passed all relevant battery safety standards, including the UL 9540A test for thermal runaway. Many new battery technologies have passed this test, however, few lithium ion manufacturers have with only a single containerised lithium ion battery manufacturer in the UL 9540 database (EVLO).
- The manufacturer, EnerVenue, has been backed by multibillion dollar engineering company, Schlumberger (marketed as SLB), who will support large-scale deployment of nickel-hydrogen battery technology across selected global markets. Current production volume is 60MWh/year, however planned facilities soon to be under construction will result in exceeding 2GWh/year by the end of 2024.

Another battery technology which could be of interest is calcium-antimony, given its high energy output and low LCOS similar to nickel-hydrogen. Although no environmental data is available for this technology, considering all other aspects, it could be an interesting technology for similar applications.

Appendix

Table A 1: Technical details of battery technologies

	Footprint (m^2)	Rated power output (kW)	Rated Energy Capacity (kWh)	Depth of discharge (%)	Round trip efficiency (%)	Expected lifetime (cycles/lifetime)	Expected lifetime (years/lifetime)	Lifetime degradation (% decay/lifetime)
Calcium-Antimony	9.3	250	1000	100%	80%	7000	20	0%
Conductive Polymer	14.6	35	210	100%	93%	12000	20	10%
Iron flow	29.3	75	600	100%	75%	20000	25	4%
Lithium ion (aggregated)	15.2(±0.6)	1899(±934)	2438(±1079)	90%	90.8(±3.5)%	5900(±1310)	17.5(±4)	20(±5)%
CATL	14.6	3720	3720	90%	90%	8000	20	19%
Corvus Energy	14.8	1492	1492	90%	90%	4000	20	26%
Eaton	14.8	2000	2000	90%	85%	5000	10	14%
EVLO	16.2	1000	1000	90%	90%	7000	20	20%
SAFT	16.1	2200	2500	90%	96%	6000	20	26%
Tesla	15.1	979	3916	90%	93.7%	5400	15	16%
Nickel-Hydrogen	14.6	175	440	100%	85%	30000	30	6%
Sodium-Nickel-Chloride	14.8	400	1400	80%	85%	4500	15	0%
Sodium-Sulphur	14.8	250	1450	100%	80%	7300	20	37%
Vanadium flow (aggregated)	47.4(±32.6)	164(±86)	610(±390)	100%	80(±5)%	21667(±2357)	27.5(±2.5)	6(±6)%
CellCube	90.3	530	2400	100%	90%	20000	25	-
Invinty energy systems	14.8	78	220	100%	75%	20000	25	12%
VRB energy	80.0	250	1000	100%	85%	25000	30	0%
Zinc-Bromide (Flow)	5.9	50	200	100%	80%	3650	10	0%
Zinc-Bromide (Non-flow)	14.6	150	600	100%	75%	5000	15	20%

Table A 2: Commercial details of battery technologies for LCOS calculation

	Capital cost – power ($/kW)	Capital cost – energy ($/kWh)	Fixed operation and maintenance cost (% capital cost/kW)	Variable operation and maintenance cost (% capital cost/kWh)	End-of-life cost ($/kW)	End-of-life cost ($/kWh)
Calcium-Antimony*	$250	$270	1.0%	<0.1%	$20	$0
Conductive Polymer	$1000-2000#	$2000-4000	1.0%	<0.1%	$0	$0
Iron flow	$580-2800	$0-320	1.0%	<0.1%	$0	$0
Lithium ion	$33-250	$265-358	2.0-4.0%	<0.1%	$0	$20
Nickel-Hydrogen	$165#	$330	0.5%	<0.1%	$0	$0
Sodium-Sulphur	$300	$500	1.7%	<0.1%	$20	$0
Vanadium flow	$0-819	$371-819	0.8-1.4%	<0.1%	$20	-$100
Zinc-Bromide (Flow)	$0-890	$335-456	1.4-1.7%	<0.1%	$0	$0

* Values based upon Ambri cells projections to be priced less than lithium-ion cells in 2022. 1% OPEX assumed due to no cooling required.

\# Values are currently unavailable and have been set at half the energy capital cost. The impact of increasing this power to energy capital cost ratio from the baseline of 0.5:1 to 1:1 increases the LCOS by 7%, 4% and 3% for storage durations of 4, 8 and 12 hours respectively (22%, 12% and 8% for 2:1).

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