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Insights on Consumer-based Battery Energy Storage Systems in the Tropical Climate of Malaysia

A Collaboration between
CSIRO Australia & SEDA Malaysia

Final Report

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Foreword

It is with great pleasure that we present this report on Tropical Batteries, a collaborative effort between the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Sustainable Energy Development Authority (SEDA) of Malaysia. This report marks the beginning of a promising relationship between our two organizations, united by a shared vision of advancing sustainable energy solutions.

As Malaysia assumes the role of ASEAN chair for 2025, the country stands at the forefront of Southeast Asia's urgent energy transition. This pivotal position underscores the importance of our collaboration, as we work together to address the pressing challenges of energy sustainability and climate change. The innovative research and development outlined in this report highlight the potential for tropical battery technologies to revolutionize energy storage and distribution in the region.

We are confident that this partnership will not only strengthen the ties between CSIRO and SEDA but also contribute significantly to the broader goals of sustainable development and energy security in Southeast Asia. Together, we can pave the way for a cleaner, greener future, harnessing the power of innovation and cooperation.

We extend our heartfelt gratitude to all those who have contributed to this report and look forward to the continued success of our collaborative efforts.

Dr John K Ward

Research Director - Energy Systems

CSIRO Energy

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Executive Summary

Reliable, safe and cost-effective energy storage is critical to achieving Malaysia's emissions reduction targets

Since the Paris Agreement came into effect in 2016, there has been a widespread drive to limit the global temperature rise to below 2°C above pre-industrial levels, with efforts to cap the increase at 1.5°C.[1] Governments around the world have made public commitments to reduce emissions and to achieve net zero targets, mostly by 2050 or soon thereafter. For example, Australia has a target of emissions 43% below 2005 levels by 2030 and to reach net zero by 2050.

Malaysia is an emerging leader within the Southeast Asian region in the stand against climate change, as highlighted by the World Economic Forum in the Fostering Effective Energy Transition report.[2] This has been demonstrated by delivery of a series of plans and policies aimed at reducing carbon emissions and increasing renewable energy contribution to the electricity system. In particular, Malaysia set an ambitious target of reducing carbon emissions by 45% by 2030, compared to 2005 levels.[3] This is part of the country's National Energy Transition Roadmap, aiming to achieve 70% renewable energy shares by 2050.[4]

Malaysia's strategy to achieve these targets is supported by favourable location, weather and natural resources. Malaysia's equatorial location provides high daily solar radiation, ranging from 4.7-6.5 kWh/m^2 in most areas.[5] This makes solar energy the largest renewable resource potential, estimated at 269 GW. The consistent rainfall and favourable topography also support both small- and large-scale hydroelectric power generation, potentially contributing an additional 16.1 GW of power. The strong agricultural sector produces substantial amount of biomass waste, which can be used for an estimated 3.6 GW of bioenergy resources. Geothermal resources are estimated at 0.23 GW.[6]

The high contribution of solar power in Malaysia's renewable energy mix poses 3 main challenges: intermittency, misalignment between peak generation (midday) and peak demand (evenings) periods, and the risk of grid instability in a decentralised/distributed renewable generation system. Hence, there is a critical need to design and integrate reliable, safe, and cost-effective energy storage systems to strengthen the renewable energy ecosystem.

Battery energy storage systems (BESS) are a versatile pool of options with different characteristics, performance criteria and challenges

Energy storage options function through mechanical (pumped hydro), thermal (concentrated solar thermal), chemical (hydrogen or ammonia), electrochemical (batteries), light (luminescence) or magnetic (superconducting materials) mechanisms. Selection of an optimal energy storage system for a specific application requires balancing performance, cost, and sustainability of the system.

Electrochemical-based systems (led by lithium-ion batteries) are the fastest growing storage options due to steady improvement in performance, sharp decline in cost, a strong global supply chain, and versatility of applications.

Whilst there are a large number of existing and emerging electrochemical energy storage technologies, this report focusses on 6 battery families (12 chemistries) selected for their potential application in consumer-based energy storage systems in Malaysia. Each family or chemistry is discussed in terms of its technical, commercial and sustainable viability.

Technical viability

The technical viability of the selected chemistries is discussed in terms of anatomy, performance criteria, and their strengths and weaknesses. Performances of the selected families/chemistries are compiled in Table ES1.

The cell voltage of the aqueous based systems (lead-acid, nickel-based and redox-flow systems) is lower than those based on organic electrolyte (lithium and sodium-ion batteries) or high temperature molten salt technologies. The power density, whilst affected by the cell voltage, is more sensitive to the rate of the electrochemical processes, the ionic conductivity of the electrolyte, and the nature of the membrane used in the system. The charge and discharge rates, usually referred to as C-rate in technical reports, are presented herein by the time required to charge (lower value of the range) and discharge (upper value of the range) 1 Wh of the system. The durability of the systems is measured by the number of cycles the system can deliver in a specific application.

Table ES1 Summary of the performance criteria of some of the battery families presented in this report

Chemistry[§]	Voltage (V)	Energy Density (Wh/kg)	Power Density (W/kg)	(Dis)Charge Time of 1 Wh	Cycle life (Cycles)
Lead-acid batteries	2.1	30 - 40	180	0.6 s – 100 h	500 - 4,000
Lithium-ion batteries*	2.3 - 3.7	50 - 260	300 - 1,000	12 min - 1 h	1,000 - 20,000
Sodium- ion batteries	3.1	75 - 200	300	20 min	5,000
Nickel-based batteries*	1.2 - 1.3	55 - 140	220 - 1,000	12 min - 12 h	2,100 - 20,000
Redox-flow systems*	1.2 - 1.9	15 - 70	0.02 - 1.4 (W/cm^2)[#]	1 h – 10 h	2,000 - 20,000
Molten salt systems*	2.0 - 2.6	118 - 220	36 - 170	2 h - 6 h	4,500 – 7,300

[§] The table shows the performance of the mature energy storage families. Metal-air systems are also discussed in this report but not presented here, due to the lack of reliable performance criteria.

* These values are for different chemistries in the family, and hence lower and upper values may not be for the same system.

[#] Power density of redox-flow systems is expressed in W/cm^2, driven by the surface of the inert electrodes rather than the mass of active material.

Commercial viability (maturity, scalability and cost)

Maturity - Twelve main chemistries were identified across 4 main categories of emerging (those that promise superior performance but over a long timeline), developing (new entries to the market aimed at niche applications but with potential of further growth), mature (commercially available with strong global supply chain) and declining (likely to exit the market due to competition or sustainability concerns). Their technology readiness level (TRL) and commercial readiness index (CRI) are presented Figure ES1.

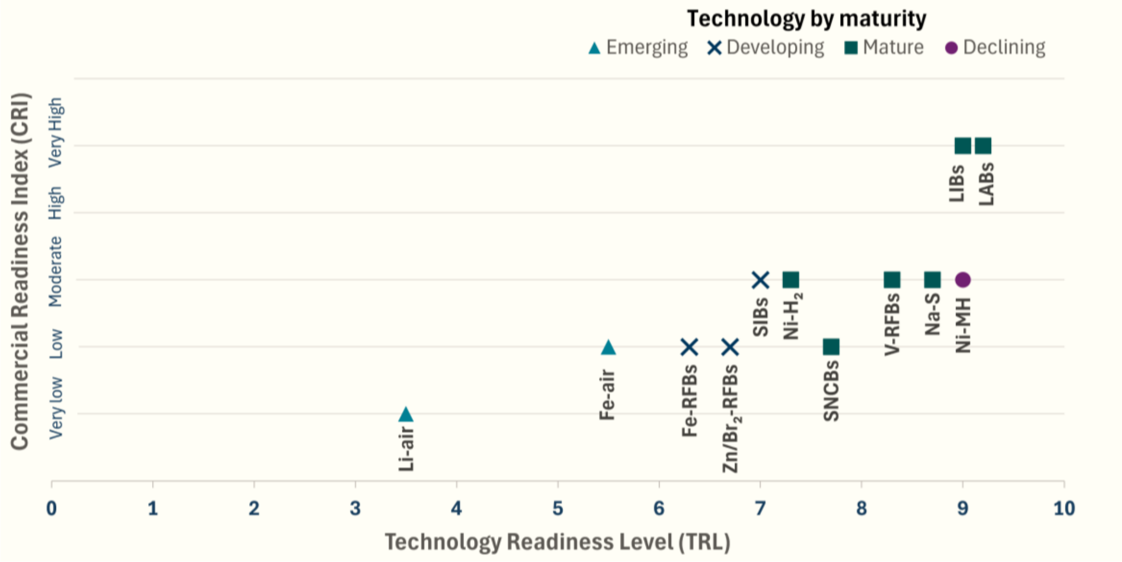

Figure ES1 TRL, CRI and technology level of maturity of the chemistries presented in this report

Scale - The range of applications of the energy storage systems varies from small devices/electronics to mobile equipment and stationary applications. However, for this study the scalability of the selected energy storage systems was assessed based on their potential for stationary applications only.

Four scales of stationary application were considered: residential (single household generating and storing renewable electricity individually, at 5-20 kWh capacity), community (multiple households share a central storage facility, at 50-500 kWh capacity), commercial (a micro-grid system where renewable power is generated and stored at a large-scale central facility and delivered to the community on commercial terms, at a capacity of up to several MWhs) and industrial (large-scale renewable generation and storage facility designed to serve a single industrial user, at a capacity up to tens of MWhs or GWhs). The suitability of different battery chemistries to these applications is illustrated in Table ES2.

Table ES2 Suitability of battery chemistries depending on the scale of stationary application

	10s kW	100s kWh.	MWhs	10s MWhs	100s MWhs
Residential	**Lithium-ion** Sodium-ion				
Community	**Lithium-ion** Vanadium Redox Flow Lead Acid				
Commercial		**Lithium-ion** Vanadium Redox Flow Iron RFBs and Zn/Br RFBs Lead Acid			
Industrial			**Lithium-ion** Vanadium Redox Flow Iron RFBs and Zn/Br RFBs (A mix and match approach)		

Cost - The cost assessment is based on the levelised cost of storage (LCoS) metric, defined as the sum of all costs per unit of energy delivered by a storage system throughout its lifetime. This encapsulates the capital investment required for the storage facility, operating costs associated with its operation (charging, maintenance, etc), storage duration (short, medium, long or multi-day), and the degree of utilisation (number of cycles per year).

The LCoS analysis is highly sensitive to the nature of the application in terms of its location, renewable energy degree of intermittency (utilisation) and market drivers such as cost of capital and labour costs. This sensitivity limits the application of the analysis to more mature technologies (for which all cost drivers are well understood) and hinders the ability to compare costs reported by different reports.

Figure ES2 shows a comparison of the forecasted LCoS of lithium-ion batteries (LIB) and vanadium redox-flow batteries (V-RFBs) under 3 different scenarios: 2-hour storage, 8-hour storage with 'low' utilisation (230 cycles), and 8-hour storage at a higher number of cycles (285 cycles). Whilst the cost of V-RFBs is higher than that of LIBs across all scenarios, the analysis shows that this gap decreases with the higher degree of utilisation (i.e., V-RFBs becomes relatively more competitive).

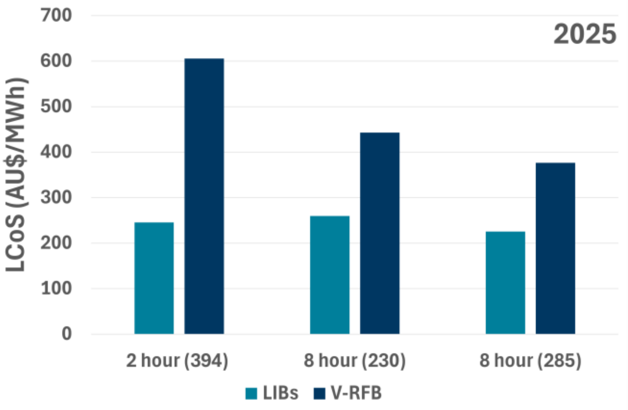

Figure ES2 Forecasted LCoS of LIBs and V-RFBs in 2025

Sustainability (operational risks, environmental impact, and end-of-life management)

Operational risks - There are 4 major risks associated with operating these different energy storage systems:

- **Fire risks** are typically associated with systems that utilise organic electrolytes such as lithium-ion and sodium-ion batteries. The risk is attributed to thermal runaways because of ineffective management of the system.
- **Chemical reagent risks** are associated with aqueous-based technologies such as lead-acid, vanadium redox-flow or nickel-based batteries. Such systems employ either highly acidic or highly alkaline electrolytes, which pose risks to the user and the environment in the event of spillage.
- **High-pressure risks** are associated with both lead-acid batteries and nickel-hydrogen systems. In lead-acid batteries, oxygen and hydrogen gas generation can occur in case of overcharge, resulting in pressure build up inside the case. Nickel-based systems, in particular nickel-

hydrogen, employ hydrogen stored under high pressure (150-200 bar), which is a hazard in case of accidental release or puncture of the cylinder.

- **High temperature risks** are associated with molten salt systems, such as sodium-sulfur and sodium-nickel chloride batteries, which typically operate at temperature higher than 300°C.

Environmental impact - Several environmental impacts are identified throughout the value chain of the battery manufacturing process, from mining to manufacturing and recycling processes. These can be grouped into 5 categories:

- **Impacts on flora and fauna** of mining sites, especially for large-scale open pit mining operations for copper and nickel.
- **Gaseous emissions** including greenhouse gas emissions and sulfur dioxide. Carbon dioxide (CO_2) emissions are associated with the energy intensive mining and smelting processes, while sulfur dioxide is released from metal sulfide smelting.
- **Dust and hazardous particulate matter** from operation like lead mining or smelting.
- **Water resource overconsumption or pollution** large-scale tailing dams, in particular, present a serious threat to the underground water resources and local communities.
- **General chemical contamination** from mineral processing as some of the battery components (organic solvent used as electrolyte, electrode material, etc.), if released, have adverse effects on human life and ecosystems. Fluoro-carbon compounds (PFAS), known as ‘Forever Chemicals’, are high risk pollutants because of their long life in the environment.

End-of-life management - Commercially viable end-of-life management routes are generally limited to batteries dominating the market (lead-acid, lithium-ion and nickel-based batteries). Lead-acid and lithium-ion batteries will be covered herein due to their market size.

Lead-acid battery recycling is the predominant route for treating retired batteries because of the maturity of their supply chains. A combination of pyrometallurgic (smelting) and hydrometallurgical (flotation, leaching and solvent extraction) processes are employed to recover 99% of the battery components including the lead metal, plastics, and the acid. Despite the energy and water intensity of this route, the recycling costs is estimated at US $200-500 per ton, with a 40% reduction in energy consumption when compared to mining new lead.

Lithium-ion battery recycling is an emerging industry driven by the global drive towards greenhouse gas emission reduction and the market premium paid to accredited ‘green’ products. This has incentivised many countries to regulate and promote recycling via Extended Producer Responsibility (EPR) policies. However, the economic feasibility of recycling lithium-based batteries is hindered by unfavourable market and cost drivers such as the fluctuating prices of critical metals like cobalt and lithium, the high capital and operational costs, and falling prices of first-life batteries (approaching US $50/kWh).

Reuse of lithium-ion batteries is an alternative pathway to manage retired batteries. It involves reallocating the retired battery to a less demanding application (second-life use) with lower capacity, efficiency, and charging/discharge rates. The viability of this option is limited to small scale opportunities and may face community, commercial, and regulatory challenges as the market matures and the volume of retiring batteries exceeds the capacity of second life applications.

Malaysia's tropical weather poses additional performance and durability challenges to energy storage systems

Malaysia has a tropical rainforest climate throughout the year, characterised by high rainfalls, moderately high temperatures, high humidity, and high salinity.

The country's average rainfall is between 2,000-4,000 mm over 150-200 rain days. The seasonal and daily temperature changes in the Peninsular Malaysia are consistent and mild, with a temperature range of 22°C (night)-30°C (day) and a seasonal variation of ± 2°C at night and ± 3°C during the daytime. High humidity (>80%) dominates the Peninsula consistently throughout the year, with highest humidity observed in the eastern coastal regions, while the less humid zone is in the high-altitude central parts of the land. Malaysia also has high salinity of the ambient air, due to evaporation of nearby salty water. This is likely to be a critical factor in battery performance, given the fact that 70% of the Malaysian population live in coastal locations.

Temperature tolerance - All chemistries operate within an optimal temperature window, shown in Table ES3. Outside of these ranges they suffer lower performance, shorter life, and potentially fire and/or explosion risks.

The lower performance is caused by increased unwanted side reactions at high temperatures or loss of electrolyte. Shorter life is linked to faster chemical reactions and gas evolution, impacting the mechanical stability of the electrodes and the permeability of the membranes. Side reactions at high temperatures also generate unwanted gases that may pose a fire or explosion risk.

Some battery chemistries (such as redox-flow systems) show higher performance at mildly high temperatures due to increased mobility of ions and hence lower resistance across the cell.

Table ES3 Optimal temperature window of selected chemistries

Temperature Range

	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C
Lead Acid	🟨	🟩	🟩	🟩	🟨	🟫	🟫	🟫	🟫
X-ion	🟨	🟩	🟩	🟩	🟨	🟨	🟨	🟫	🟫
Ni-MH Batteries	🟨	🟩	🟩	🟩	🟨	🟫	🟫	🟫	🟫
Redox Flow Systems	🟨	🟩	🟩	🟩	🟨	🟫	🟫	🟫	🟫

🟩 Optimal 🟨 Tolerable 🟫 Detrimental

Humidity - Elevated humidity affects the performance of batteries by either accelerating the corrosion of external-facing components (such as casings, terminals and connections), impacting the balance of active material in the electrolyte, or interfering with internal electrochemical processes. Humidity control is also required during the manufacturing process and for the electronics supporting the battery management systems.

Closed energy storage systems such as sealed lead-acid, X-ion, and molten salt batteries are less susceptible to loss of performance due to humidity, compared to open systems such as flooded lead-acid and vanadium redox-flow batteries. Some nickel-hydrogen batteries are reported to benefit from a certain degree of increased humidity.

The impact of humidity on the corrosion of the casing of the battery is dependent on the selection of the material. Lead-acid and redox-flow systems are less impacted because of their reliance on polymer-based casings. Lithium-ion and other systems typically use corrosion resistant alloys such as stainless steel or specific aluminium alloys. Molten salt batteries are generally less susceptible to the impacts of humidity. However, prolonged exposure to humidity has been reported to lead to gradual degradation of the ceramic, drastically affecting its ionic conductivity and hence increasing the cell resistance.[7]

Salinity - Salinity is an accelerating factor of corrosion of metal surfaces due to the increased concentration of chloride ions in the atmosphere. The chloride concentration is influenced by various factors, including proximity to the shore, wind strength and direction, wave height, and geographical topographies. In addition to accelerating corrosion, higher salinity increases the potential formation of conductive salt bridges between corroded battery terminals, resulting in accelerated cell self-discharge and a reduced battery life.

Concluding remarks

Malaysia is moving towards greater renewable energy generation, and the transition will require energy storage solutions. This report presents an overview of different battery energy storage systems that may be utilised to enable a higher adoption of intermittent renewable energy sources in the Malaysian consumer-based context. The simple and consistent framework presented here is intended as an additional data point available for SEDA’s internal and external stakeholders as they consider the potential applications of conventional and emerging energy storage options in supporting the transition to renewable energy systems.

Introduction

This report presents an overview of the different battery energy storage systems (BESS) that may be utilised to enable a higher adoption of intermittent renewable energy sources (such as solar and small-scale hydro) in Malaysia. In particular, the report highlights the opportunities and challenges associated with different BESS chemistries in terms of their performance criteria and adaptability to Malaysia's tropical climate.

The purpose of this report is to provide decision makers at Malaysia's Sustainable Energy Development Authority (SEDA) with a simple but consistent framework to assess the conventional and emerging energy storage options available on the market. Hence, it is tailored for an informed reader with an understanding of the challenges and some appreciation of the technical/scientific principles of different energy storage systems, particularly the electrochemical pathways.

Accordingly, the report is structured into 3 main parts, starting with an overview of the broader Malaysian and technical context, followed by a deep dive into the different electrochemical storage platforms. The last section focusses on the specific constraints of tropical climates and their impact on the performance and life of electrochemical energy systems.

The first part, **Setting the Scene**, highlights the role of energy storage systems in Malaysia's national strategy for transitioning to increased levels of renewable power generation. It also provides an overview of the renewable power generation and storage market in Malaysia in terms of current and planned solar power generation projects across the country. This section concludes with a summary of the different energy storage categories (mechanical, electrochemical, chemical, thermal, electromagnetic, and light) that may be considered for specific locations or applications and so are worth further investigation in the future.

Part 2 of the report is dedicated to the technological and commercial viability, as well as the sustainability of 12 electrochemical storage technologies. **Technological Viability** focusses on the battery anatomy, performance criteria and a SWOT[a] analysis of each technology. **Commercial Viability** assessment is based on the maturity of the technologies (i.e., technical and commercial readiness), application scale, and cost constraints. In the **Sustainability** section, different technologies are discussed in terms of operational safety, environmental impact and end-of-life management options. The commercial and sustainability assessments were carried out at high level rather than by specific battery chemistry (e.g., X-ion batteries as a family).

Part 3, **Evolving Energy Storage**, focuses on the impact of Malaysia's weather attributes of high temperature, humidity, salinity and solar radiance on the life and performance of different chemistries. A brief discussion on mitigation strategies is also included where possible. It is worth noting that data on this topic is scarce in the literature, and whilst this report presents a summary of the data readily available, a deeper investigation is required for a better understanding of the risks and cost implications specific to the Malaysian context.

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[a] Strengths, Weaknesses, Opportunities, and Threats

Part 4, **The Way Forward**, compiles a non-exhaustive list of strategies and actions used by Australia, the United States of America and Europe to facilitate the adoption of BESS.

The report closes with a summary of the key takeaways and conclusions of the study. References have been noted in the text with superscript numerals; details of these can be found in the end matter. Appendices are included to provide more details on each system chemistry (chemical reactions, performance details, and SWOT analyses). A glossary is also included.

1 Setting the Scene

1.1 Strategic Alignment of Malaysian National Priorities

1.1.1 World context

The scientific consensus is that climate change poses serious impacts to our ecosystems, biodiversity, economies, and societies. This has compelled governments worldwide to develop strategies for transitioning to clean and renewable energy sources. The Paris Agreement, which came into effect in 2016, is an international treaty aimed at limiting global temperature rise to below 2°C above pre-industrial levels, with efforts to cap the increase at 1.5°C.[1] The European Copernicus Climate Change Service announced that 2024 was the first year to have exceeded the 1.5°C rise limit.[8]

In addition to the Paris Agreement in 2016, a few major reports have been published by international bodies, such as the United Nation's (UN) Sustainable Development Goals (SDGs)[9] and the International Energy Agency's (IEA) *Net Zero by 2050: A Roadmap for the Global Energy Sectors*.[10] The IEA's roadmap outlines the global pathway to net zero emissions by 2050 through the implementation of energy policies. The UN's SDG 13,[11] is dedicated to climate action, under the banner 'Take urgent action to combat climate change and its impact'. In their 2024 report, the United Nations Framework Convention on Climate Change (UNFCCC) established 2023 as the warmest year yet and estimated that nearly $6 trillion is needed for the climate action plan of developing countries by 2030.[12]

1.1.2 The energy transition in Malaysia

Malaysia has positioned itself as an emerging leader within the Southeast Asian region in the context of worldwide climate action, as highlighted by the World Economic Forum in the *Fostering Effective Energy Transition* report.[2] Increased energy consumption and the challenge of high carbon emissions have prompted Malaysia to shift its energy strategy to increase renewable energy contribution to the electricity system. National priorities include targets for reducing carbon emissions and enhancing energy security and reliability, while ensuring sustainable economic growth.

Although Malaysia's power generation mix is still dominated by non-renewable fossil fuels, renewable energies make up about 5% of Malaysia's total energy supply as of 2022 and roughly 20% of the electricity generation.[13] This total renewable energy (RE) consists of solar, hydropower, biogas, biomass and waste-to-energy. Through the Nationally Determined Contribution in 2021, Malaysia increased their 2030 carbon emissions reduction targets by 45% compared to 2005 levels.[3] This will see the country produce more economic output with smaller carbon footprint. These targets are supported by the National Energy Transition Roadmap, which outlines RE generation strategies to achieve 70% renewable energy shares by 2050.[4]

The roadmap details a comprehensive strategy to follow the energy policy recommendations of international bodies such as the UN and IEA, highlighting 6 energy transition levers and 10 flagship catalyst projects (Figure 1). It covers:

- *Governmental policies* to promote energy efficiency in different industrial sectors and encourage the adoption of energy efficient technologies via incentives.
- *A shift to renewable sources of energy* with the promotion of solar energy through programs such as Net Energy Metering and the development of hydropower and bioenergy. This also includes low carbon technologies such as hydrogen economy, or electric vehicles promoting green mobility.
- *A decarbonisation plan* with a carbon capture, utilisation and storage (CCUS) strategy.

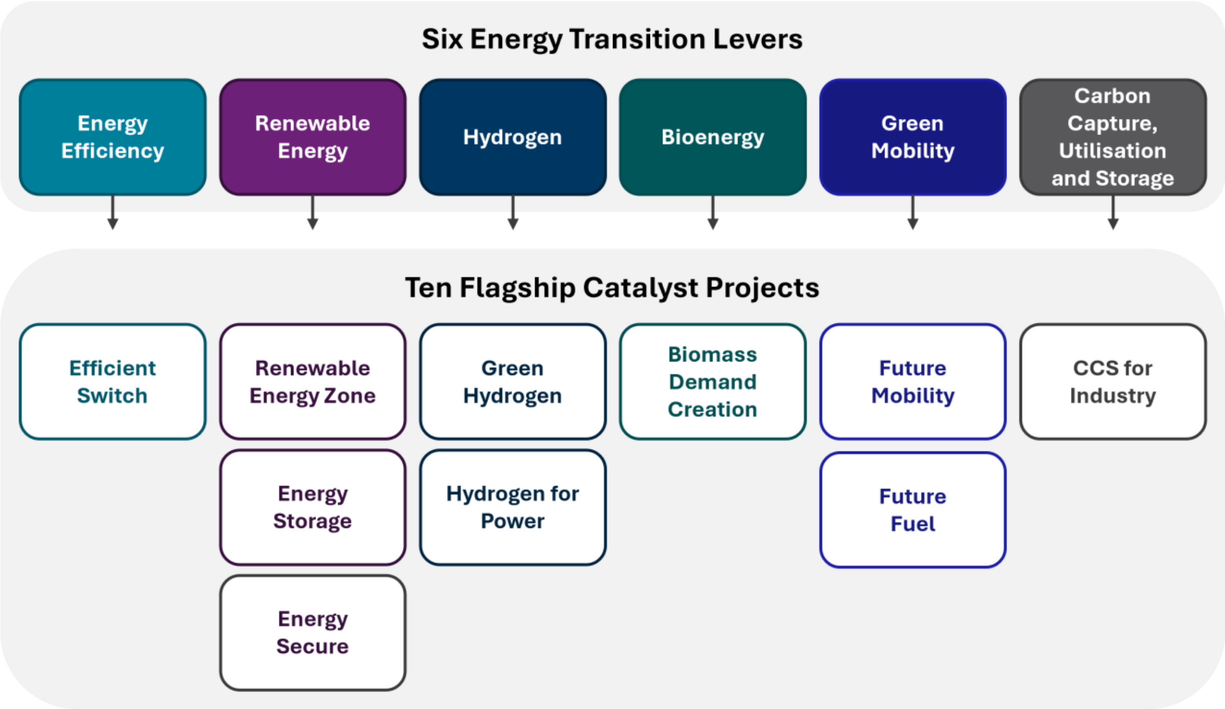

Figure 1 Malaysia's energy transition strategy as described in the 2023 National Energy Transition Roadmap[4]

1.2 The Malaysian Renewable Energy Landscape

1.2.1 The Malaysian renewable energy generation strategy

Geographically, Malaysia is well-positioned to harness abundant RE sources such as solar energy, bioenergy, hydropower, and thermal energy. Malaysia's total RE resource availability is illustrated in Figure 2. Solar energy has the largest renewable resource potential by far, with a total availability of 269 GW. The country benefits from a mean daily solar radiation of 4.7-6.5 kWh/m^2 in most places,[5] making it ideal for solar power generation. Abundant rivers and rainfall create favourable conditions for hydroelectric power generation. Combined large and small hydropower comes second in RE potential at 16.1 GW, followed by bioenergy at 3.6 GW, and lastly geothermal resources, estimated at 0.23 GW.[6] Malaysia also produces millions of tonnes of that could be converted into bioenergy through combustion or gasification processes (Figure 3).

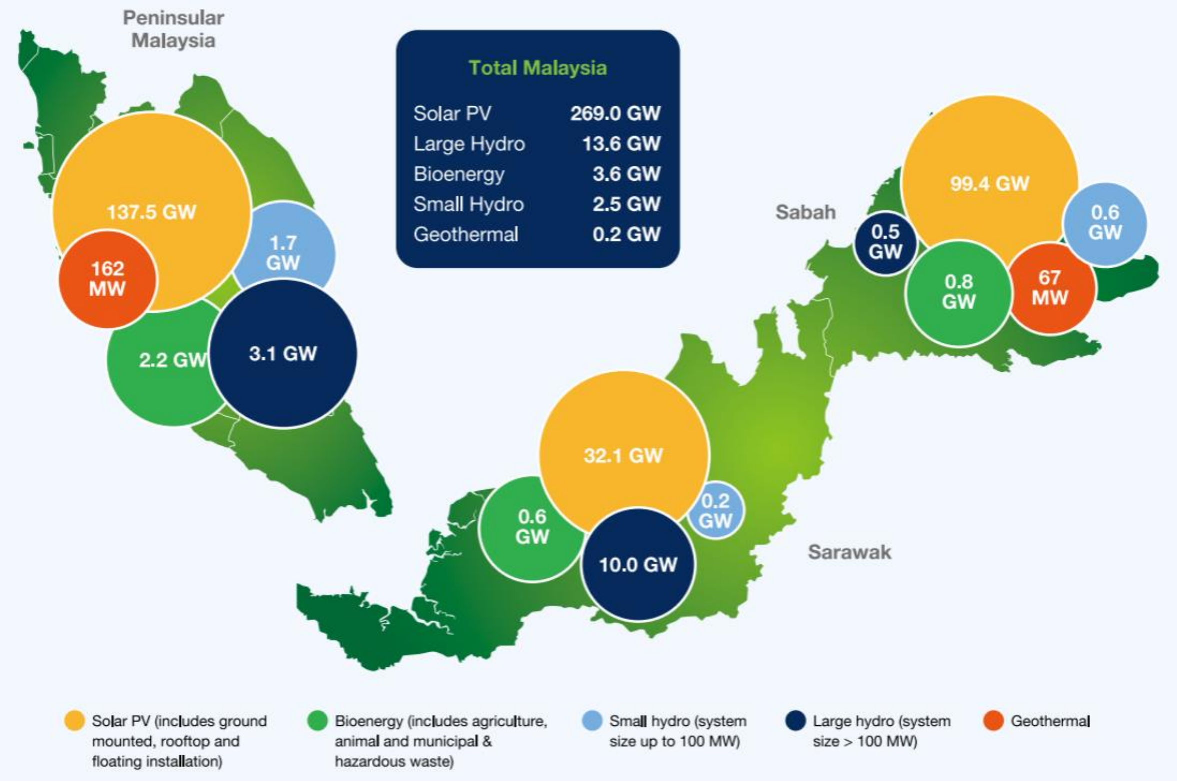

Figure 2 Total renewable energy resource potential in Malaysia

Source: Malaysia Renewable Energy Roadmap, SEDA Malaysia, 2021[6]

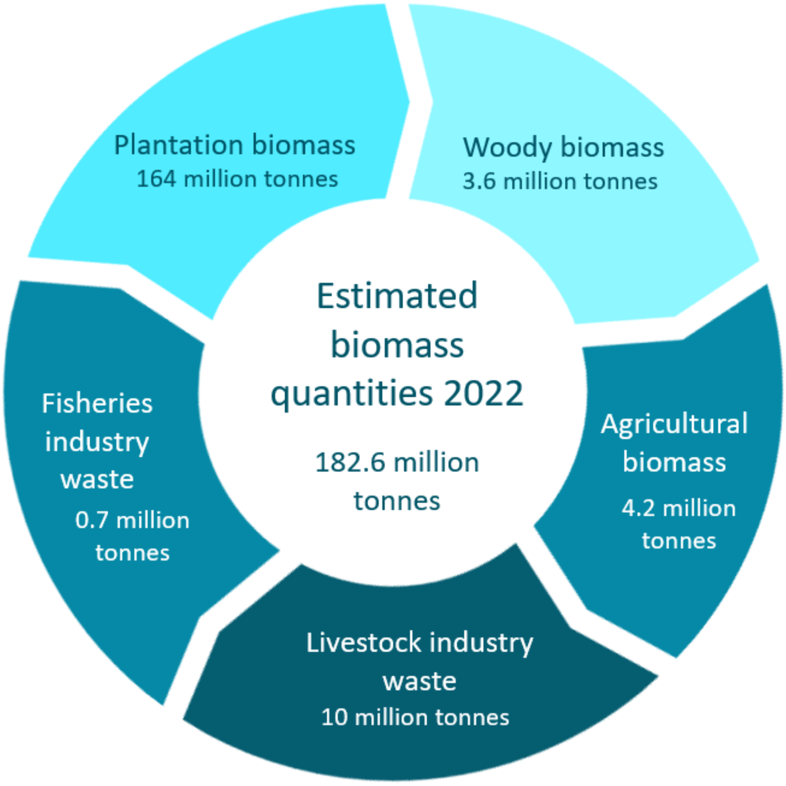

Figure 3 Estimated biomass quantities by industry in Malaysia for 2022

Source: National Biomass Action Plan 2023-2030, Ministry of Plantation and Commodities, 2023

Malaysia's renewable energy integration began in 1999 with the government's plan to diversify the country's energy mix under The Fifth Fuel Policy. Initially, the Small Renewable Energy Power Programme and the Biomass Power Generation Project were established to harness the potential of biomass and hydropower.[14] Solar energy was introduced through the Ninth Malaysia Plan from 2006 to 2010 via the Malaysian Building Integrated Photovoltaic Project (MBIPV), which focused on the market development for such technology, and building the national capacities in 3 major areas: (a) policy and education, (b) technical skill and market implementation, and (c) technology development support.[15] Since then, solar power has become the main focus of the energy generation strategy of the country.

A significant policy framework was introduced in 2010, coupling the newly established National Renewable Energy Policy and Action Plan (NREPAP) with the ratification of the Renewable Energy Act 2011 and the establishment of the Sustainable Energy Development Authority (SEDA) of Malaysia. This framework provided a solid basis for the implementation of RE via incentives, such as a feed in tariff (FiT) scheme, for grid connected RE projects.

Further growth of the solar sector from 2016 to 2020 was boosted by the Eleventh Malaysia Plan. Three main programs were introduced: the Large-Scale Solar (LSS), Net Energy Metering, and Self-Consumption (SELCO) programs. While Malaysia’s renewable energy capacity was only 53 MW (excluding of large hydropower) between 2001 and 2009, it had reached 2.8 GW (or 6.17 GW with the inclusion of all renewable energies) by December 2020, a significant milestone towards Malaysia’s sustainable energy future.

Despite Malaysia’s progress in promoting RE, technical and infrastructure issues remain barriers to its adoption. Challenges include integrating RE into an electricity grid designed for centralised fossil fuel plants and managing intermittent energy from sources like solar and small-scale hydro, which require support from storage systems or a fast-ramping backup system to stabilise the distribution. Fluctuations in RE generation affect grid stability, including frequency and voltage levels, while rural grids often lack the capacity to support increased loads, causing congestion and inefficiencies. Upgrading infrastructures requires substantial investments in smart grids and advanced management systems to ensure stability, share backup power storage, and fully utilise renewable energy for industries and end-users. By adopting these changes, Malaysia is poised to become a leader in sustainable energy development.

1.2.2 The challenges of solar-generated power

Solar power systems, while a promising RE source, present several challenges. One is the intermittent nature of solar photo-voltaic (PV), which is variable by time of day and cloud cover. Although seasonal variations in solar radiation impact output in certain regions of the world, this challenge is less critical in Malaysia because of the relatively consistent amount of daylight throughout the year. A second challenge is the mismatch between solar energy generation and peak electricity demand. As solar power generation is highest during the middle of the day, it does not align with morning and evening peak demand periods. This discrepancy can result in excess energy generation that may not be efficiently consumed or integrated into the grid, as well as the inability to provide solar-generated electricity during peak demand. The integration of solar photovoltaic (PV) technologies into the grid also creates stability issues. The intermittency of solar PV can cause voltage and frequency fluctuations, potentially impacting grid reliability and security.

Energy storage technologies play a vital role in mitigating such challenges. By storing excess solar energy generated during periods of high irradiance, such systems allow for a shift in power use to periods of low or no solar generation, such as nighttime or cloudy days. This helps balance energy supply and demand, ensuring a consistent and reliable power supply. Moreover, energy storage systems can enhance grid stability by providing a buffer against fluctuations in solar power generation. They can quickly discharge and improve grid reliability. For residential and commercial solar PV users, energy storage systems can encourage self-consumption, reduce reliance on the grid, and lead to significant savings on electricity bills.

1.3 Energy Storage Systems (ESS)

1.3.1 Energy storage mechanisms

An ESS is a technology capable of capturing and keeping energy for later use, often at a different place or time than its original generation. Although it is often thought of as electrochemical energy storage, such as batteries, there are several mechanisms to store energy, which can be grouped into 6 main categories (Figure 3).

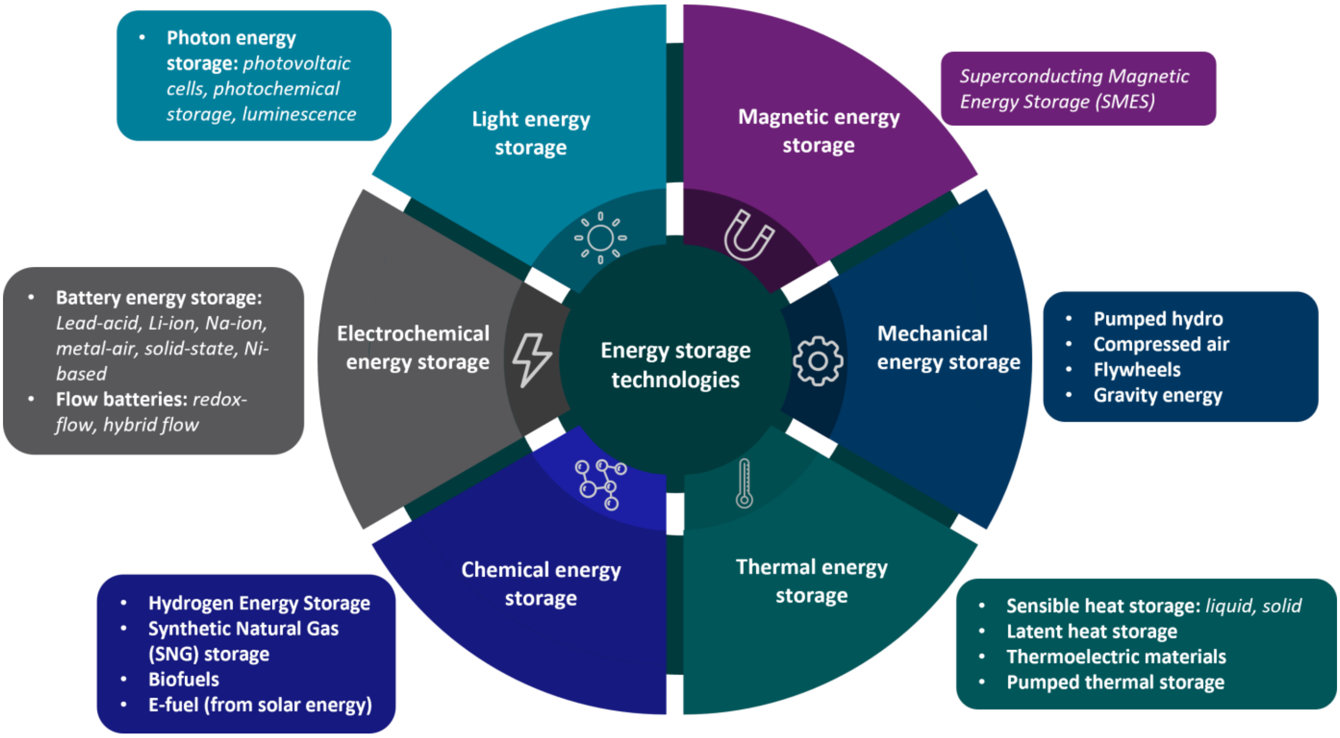

Figure 4 Energy storage mechanisms

Each method offers unique advantages and challenges, and their suitability for the intended application depends on factors such as the amount of energy they can store, how fast they can release it, cost, and environmental impact. Interest in different storage method varies across regions and countries, influenced by local resources, geographical constraints, and energy policies. Understanding these different storage mechanisms is essential for developing fit for purpose, efficient, and sustainable energy systems.

Electrochemical energy storage systems

Storing energy in chemical reactions where electrons are exchanged (redox reactions)

In a redox reaction, one substance undergoes oxidation (loses electrons) while another undergoes reduction (gains electrons). This electron transfer allows the conversion of chemical energy into electrical energy and vice versa. For example, during discharging a lead-acid battery, electrons from the anode, where the lead metal is oxidised to form lead sulfate, travel through the electric circuit to the cathode, where lead dioxide is reduced to form lead sulfate. The electron flow direction is reversed during the charging process to restore the lead metal and the lead dioxide starting materials at each electrode.

It is worth noting that primary (non-rechargeable) batteries rely on irreversible reactions that allow only for the discharge reaction to occur.

Chemical energy storage systems

Storing energy in chemical bonds that can be broken and reformed

The amount of energy stored in a chemical bond depends on the strength of the bond, which in turn depends on the atoms involved. Chemical energy storage is the underlying principle of internal combustion engines, where burning gasoline (petrol) releases the energy stored in the bonds of the fuel. Hydrogen, bioenergy (biomass derived from living matter such as plants and animal waste products), and e-fuel (e.g. using solar energy to transform carbon dioxide (CO_2) to methanol) are other forms of chemical storage.

Mechanical energy storage systems

Storing potential or kinetic energy into a mechanical form for delayed release

A mechanical energy storage system uses RE when it is available to create motion (for instance, conversion from solar energy to kinetic energy) or lift a mass (conversion from solar energy to potential/gravitational energy). Such systems store energy that can be released on demand by letting the system go back to a stable equilibrium. Examples include pumped hydro (pumping water uphill to a reservoir for later release, when a turbine is activated to generate electricity), compressed fluid systems (compressing air or carbon dioxide (CO_2) at high pressure to drive turbines), or flywheels (rotating systems).

Thermal energy storage systems

Storing energy as heat

There are 3 forms of thermal energy storage:

- *Sensible energy storage* involves heating a material, such as water or rocks, to store thermal energy.
- *Latent energy storage* uses materials capable of absorbing or releasing heat as they change phase between solid and liquid states.
- *Thermoelectric generators* are based on materials generating electricity upon application of a temperature gradient.

Sources of thermal energy include Concentrated Solar Thermal (CST), in which mirrors are used to concentrate sunlight onto a receiver to convert the light into heat, and waste heat from high-temperature industries such as computing centres.

Electromagnetic energy storage systems

Storing energy in an electromagnetic field

Magnetic energy storage systems exploit the properties of superconducting materials to efficiently store and release electrical energy. At extremely low temperatures, coils exhibit zero electrical resistance, hence allowing a flow of direct current without energy loss. A strong magnetic field is therefore generated, storing energy in the form of electromagnetic potential energy. When discharged, a decrease of current in the coil yields to the magnetic field collapsing, creating a current in the opposite direction and inducing a voltage. The stored electromagnetic energy is therefore converted back to electrical energy.

Light energy storage systems

Storing energy in a material's ability to absorb and release photons

This approach involves exploiting the interaction between photons and the electronic structure of specific materials to induce an energetic 'excited' state. This excited state can persist for varying durations, ranging from femtoseconds in experimental quantum batteries to hours in commercial luminescent paints. Energy is then recovered as light (emission of photons) when the system transitions back to a lower energy (or 'ground') state. Materials with short-lived excited states are suitable for applications requiring a rapid energy release, while those with longer-lived states are better suited for prolonged energy delivery.

1.3.2 ESS in the Malaysian context

Malaysia's ideal geographic location and diverse energy resources offer significant potential for a versatile mix of energy storage solutions. Situated at the equator, Malaysia benefits from abundant solar radiation throughout the year, making solar energy technologies ideal candidates for clean energy generation. Electrochemical energy storage systems (batteries) are an obvious solution to store energy generated from photovoltaic solar devices. Moreover, concentrated solar thermal power plants, coupled with appropriate thermal energy storage systems such as molten salt devices, can efficiently harness solar energy and store it for later use.[16]

The topological diversity, including mountain regions and abundant rain falls and water resources, presents opportunities for small or large-scale pumped hydro energy storage.

In addition to the advantageous geographic location, Malaysia's strong agricultural sector, including its palm oil industry, generates substantial biomass waste. This biomass can be converted into biofuels, offering a sustainable source of energy integrating well within the economic profile of the country.

1.4 Battery Energy Storage Systems (BESS) in Malaysia's Energy Transition

The intermittent nature of solar power requires effective energy storage solutions and BESS has emerged as the most immediate and viable choice, as evidenced by Tenaga Nasional Berhad's (TNB) recent 400 MW installation. BESS plays a critical role in supporting intermittent renewable energy generation systems at 3 levels:

- **Grid:** Modern grid configurations aim to integrate increased proportions of renewable energy generation systems. BESS can enhance the efficiency, reliability, and sustainability of modern grids. They are a proven solution to provide a rapid response to fluctuations in supply and demand, ensuring grid stability and preventing outages. For example, in August 2020, a heat wave in California triggered a 46.8 GW peak demand, which in turn, triggered blackouts. During a similar situation 2 years later, despite a significantly higher 51.4 GW peak demand, 3.4 GW of new BESS systems helped prevent a similar blackout.[17]
- **Industry:** BESS provides stability and assurance to high-energy intensity industries. BESS mitigates reliance on the grid, ensuring uninterrupted operations and potentially lowering costs during high-tariff hours.
- **Community:** At the residential or community levels, consumers can tailor their energy solutions to their personal consumption, reducing electricity bills. BESS can also create revenue streams by allowing users to sell their stored energy back into the grid.

2 Technological Aspects of Batteries

2.1 Technological Viability

2.1.1 Lead-acid batteries

Lead-acid batteries (LABs) are often described as the cornerstone of energy storage technologies as they are the oldest battery chemistry currently commercialised, having been used for over a century in various forms. The first LAB was commercialised in 1859 by French physicist Gaston Planté and was also the first rechargeable battery in commercial use. Robust design and reliable performance have made them the battery of choice for various applications. Although, increasingly, they may now be an expensive option for some applications such as stationary ESS when compared to other more recent technologies such as lithium-ion or sodium-ion batteries.[18]

Structure and materials – A LAB cell comprises a cathode and anode separated by an ion conductive barrier and immersed in an aqueous electrolyte, as shown in Figure 5. Materials of each of the components are described below:

Cathode	A porous layer of lead (IV) oxide, PbO_2 ,[19] pasted onto a current collector made of lead or lead alloys.[20] The current collector must be highly corrosion-resistant, as this is the primary factor limiting the battery's lifespan. Hence, additives such as antimony or calcium are used to improve corrosion resistance, tin to increase the mechanical strength, or silver in small quantities to improve both aspects.
Anode	Metallic lead (Pb), [21] also known as 'sponge lead', is comprised of a porous, high surface area form of elemental lead. The anode current collector is lead alloy with tin additives to enhance mechanical properties.[20]
Electrolyte	Aqueous sulfuric acid, providing the sulfate ions and protons consumed or produced during the charging and discharging processes.[22]
Separator	Microporous polymers, ensuring the separation of the 2 electrodes, preventing short circuits.[23]

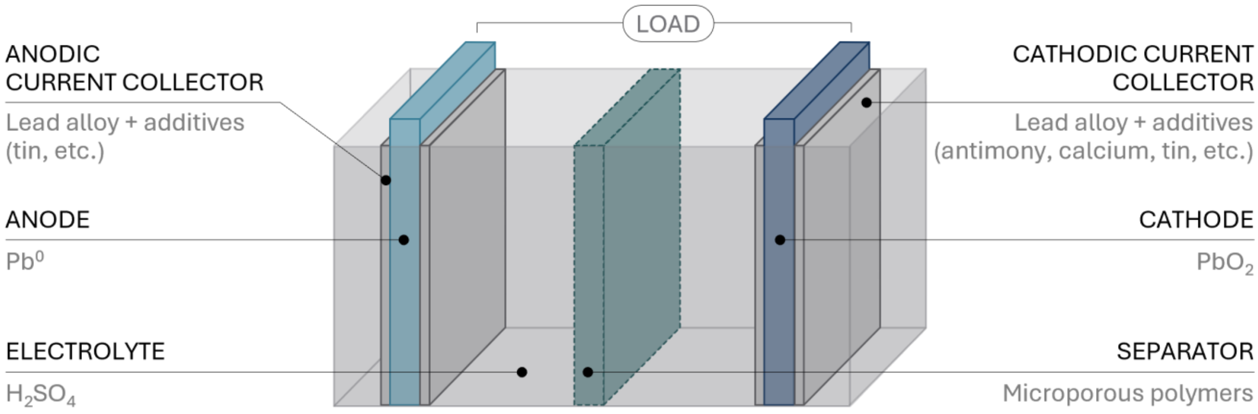

Figure 5 Schematic representation of the internal structure of a LAB and materials used

Redox couples – LABs rely on the reversible reaction of Pb^{4+} in lead (IV) oxide (PbO_2) and lead (Pb^0) with sulfuric acid as illustrated in Figure 6. When fully charged, the cathode and anode active materials are Pb^{4+} in lead dioxide (PbO_2) and lead metal (Pb^0), respectively. During discharge, Pb^0 loses 2 electrons to form Pb^{2+} in lead sulfate ($PbSO_4$) on the anode side. The 2 electrons travel through the external circuit to the cathode, converting Pb^{4+} in lead dioxide (PbO_2) to Pb^{2+} in lead sulfate ($PbSO_4$). This process is reversed during the charging process. Meanwhile, protons and sulfate ions move between the anode and cathode compartments to maintain charge balance.

These chemical reactions are detailed in Appendix A.1, Equations 1-3.

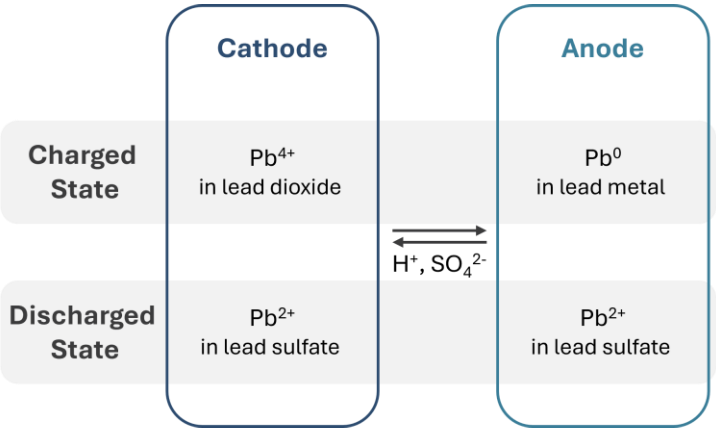

Figure 6 Redox couples involved in the charge and discharge states of LAB electrodes

Form factors and battery types – Depending on the primary application, LABs can have one of 2 variations: flooded cells or sealed LABs, also known as valve-regulated lead-acid (VRLA) batteries. Flooded cells are the most common, and are widely used in the automotive industry, where the sulfuric acid electrolyte is present in an aqueous form. They require regular maintenance such as the addition of distilled water to compensate for evaporation. Flooded cells usually cost less and provide higher discharge rates. However, they can spill easily and need to be handled with care. Sealed cells, or VRLA cells, on the other hand, are designed to be maintenance free. In this case, the electrolyte is either in a gel form or absorbed into microfibrous glass mats, both of which prevent spills. By slightly over-building the negative electrode, only oxygen is evolved during charging and this reacts at the negative electrode to form water, thereby removing the need for water maintenance. Sealed batteries are more compact and are commonly used in hot areas (where water evaporation is a challenge), motorcycles, or solar power applications.

Performance – LABs offer a reliable performance profile (Figure 7), making them suitable for a wide range of applications. Each cell typically delivers a voltage of 2.1 V. While their energy density[b] (30-40 Wh/kg) is relatively low compared to newer technologies, they present a power density of up to 180 W/kg, allowing for high discharge rates. LABs are capable of fast discharge within 0.6 seconds in vehicle ignition, while large batteries are suitable for slow discharge applications and can take up to 100 hours to charge in stationary energy storage. They also perform at low temperatures, operating down to -60°C, while their upper temperature limit of +40°C is primarily constrained by water loss, degradation and corrosion issues. Optimal performance is achieved within the -10°C to +30°C temperature range. Lifespan varies significantly based on application and depth of discharge, typically ranging from 500 to 4000 cycles for an 80% depth of discharge.

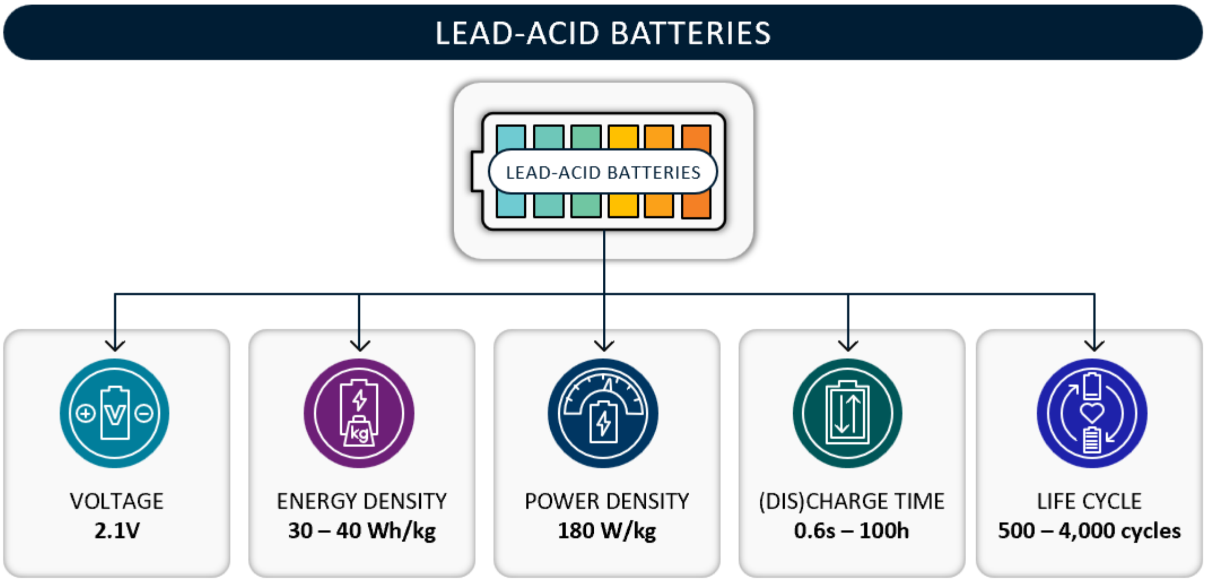

Figure 7 Key Performance Indicators of LABs

SWOT analysis – Figure 8 presents a summary of LAB strengths, weaknesses, potential threats, and opportunities in the future. A detailed discussion of these aspects is presented in Appendix B.1. The main strength of LABs is their maturity and familiar aspect, relying on a strong supply chain from mining and manufacturing to distribution, services and recycling, and safety against fire risks. They are also capable of providing high surge currents.

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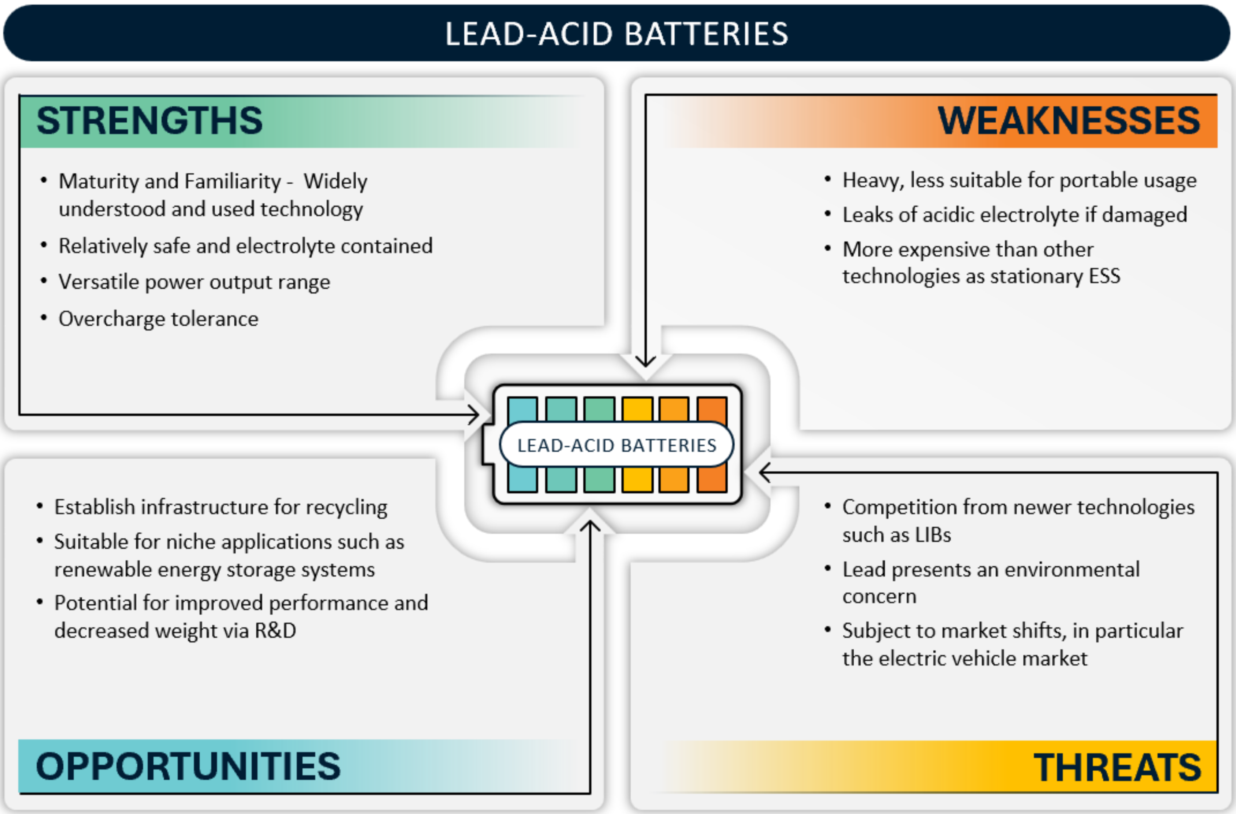
[b] Usually referred to as specific energy in scientific literature



STRENGTHS

- Maturity and Familiarity - Widely understood and used technology
- Relatively safe and electrolyte contained
- Versatile power output range
- Overcharge tolerance

WEAKNESSES

- Heavy, less suitable for portable usage
- Leaks of acidic electrolyte if damaged
- More expensive than other technologies as stationary ESS

- Establish infrastructure for recycling
- Suitable for niche applications such as renewable energy storage systems
- Potential for improved performance and decreased weight via R&D

OPPORTUNITIES

- Competition from newer technologies such as LIBs
- Lead presents an environmental concern
- Subject to market shifts, in particular the electric vehicle market

THREATS

Figure 8 SWOT analysis of LABs

2.1.2 X-ion batteries

The X-ion batteries include a family of chemistries where X can be lithium (Li), sodium (Na), potassium (K), aluminium (Al), magnesium (Mg) or zinc (Zn). Two have emerged as promising technologies for energy storage: lithium-ion (LIBs) and sodium-ion batteries (SIBs). With high energy density, long cycling life and rapid charging capability, these have revolutionised the field of energy storage for various applications, from portable electronics to electric vehicles and stationary storage solutions.

Lithium-ion batteries (LIBs)

Since their first commercialisation in 1991 by Sony, lithium-ion batteries have come to be the technology dominating a fast-growing market. They have marked a significant milestone in the development of rechargeable batteries, facilitating the adoption of portable devices and, more recently, electric vehicles. They are increasingly used in stationary storage due to their ability to be scaled at various sizes, allowing for tailored solutions.

Structure and materials – A schematic representation of a LIB is presented in Figure 9. Commercialised LIBs include multiple cathode and anode chemistries, with 6 types dominating the market. Five of these share a common anode material but differ in their cathode composition: NMC, NCA, LFP, LMO, and LCO. The sixth, LTO, is distinguished by employing a different anode material.

The materials making up the cell components of the first 5 chemistries are:

Cathode	• ***NMC*** uses lithium nickel manganese cobalt oxide ($LiNi_xMn_yCo_zO_2$, where x+y+z=1). • ***NCA*** uses lithium nickel cobalt aluminium oxide ($LiNi_xCo_yAl_zO_2$, where x+y+z=1). • ***LFP*** uses lithium iron phosphate ($LiFePO_4$). • ***LMO*** uses lithium manganese oxide ($LiMn_2O_4$). • ***LCO*** uses lithium cobalt oxide ($LiCoO_2$). The cathodic current collector is typically an aluminium sheet.
Anode	Graphite-based anodes. The anodic current collector is typically a copper sheet.
Electrolyte	A carbonate-based solvent with lithium hexafluorophosphate ($LiPF_6$) or other lithium salts as lithium-ion source.
Separator	Polyethylene (PE) or polypropylene (PP) derivatives membranes.

The materials in LTO cells are:

Cathode	***NMC*** (lithium nickel manganese cobalt oxide) or ***LFP*** (lithium Iron Phosphate). The cathodic current collector is typically an aluminium sheet.
Anode	Lithium titanate oxide ($Li_4Ti_5O_{12}$). The anodic current collector is typically an aluminium sheet.
Electrolyte	A carbonate-based solvent with lithium hexafluorophosphate ($LiPF_6$) or other lithium salts as lithium-ion source, as per the other 5 chemistries.
Separator	Polyethylene (PE) or polypropylene (PP) derivatives membranes, as per the other 5 chemistries.

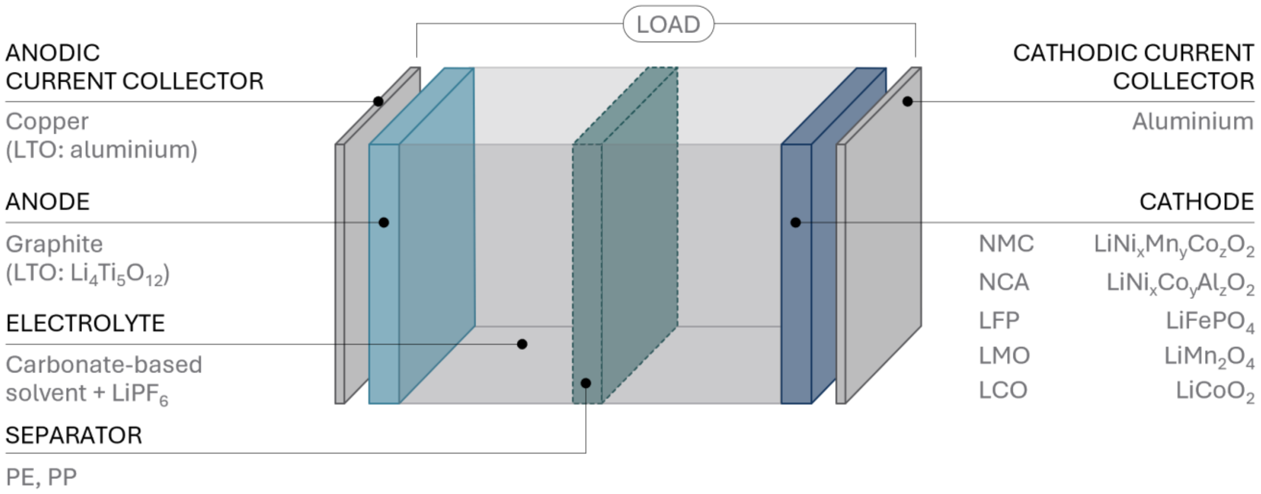


Figure 9 Schematic representation of the internal structure of a LIB and materials used

Redox couples – LIBs rely on the reversible reaction of lithium-ions with the anode (graphite) and cathode (metal oxides) materials following an intercalation mechanism as illustrated in Figure 10. When fully charged, the active materials are a partially lithiated metal oxide (Li_{1-x}-MO) on the cathode side and lithiated graphite at the anode side. In lithiated graphite, the carbon matrix hosts partially reduced lithium-ions between the graphite layers. During discharge, partially reduced lithium-ions lose their electrons and are released from the carbon lattice into the electrolyte solution. The electrons travel through the external circuit to the cathode to reduce lithium-ions from the electrolyte, resulting in the formation of more stable fully lithiated metal oxide material (Li-MO). The reversed reaction occurs during the charging process. The charge balance of the cell is maintained through the transport of lithium cations (Li^+) between the anode and cathode compartments.

The detailed chemical reactions for each chemistry presented herein are outlined in Equations 4-10 in Appendix A.2.

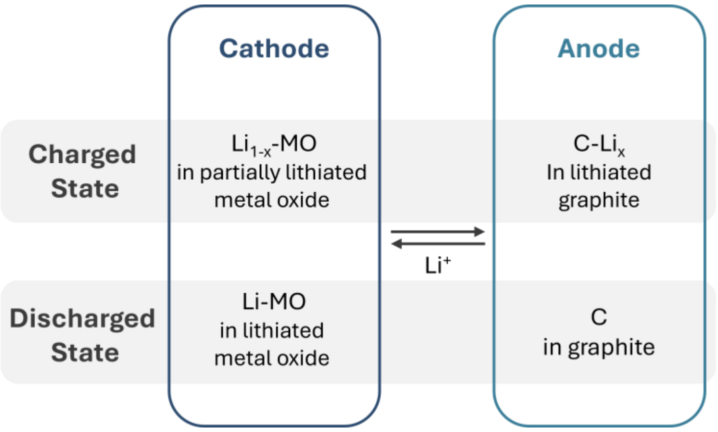


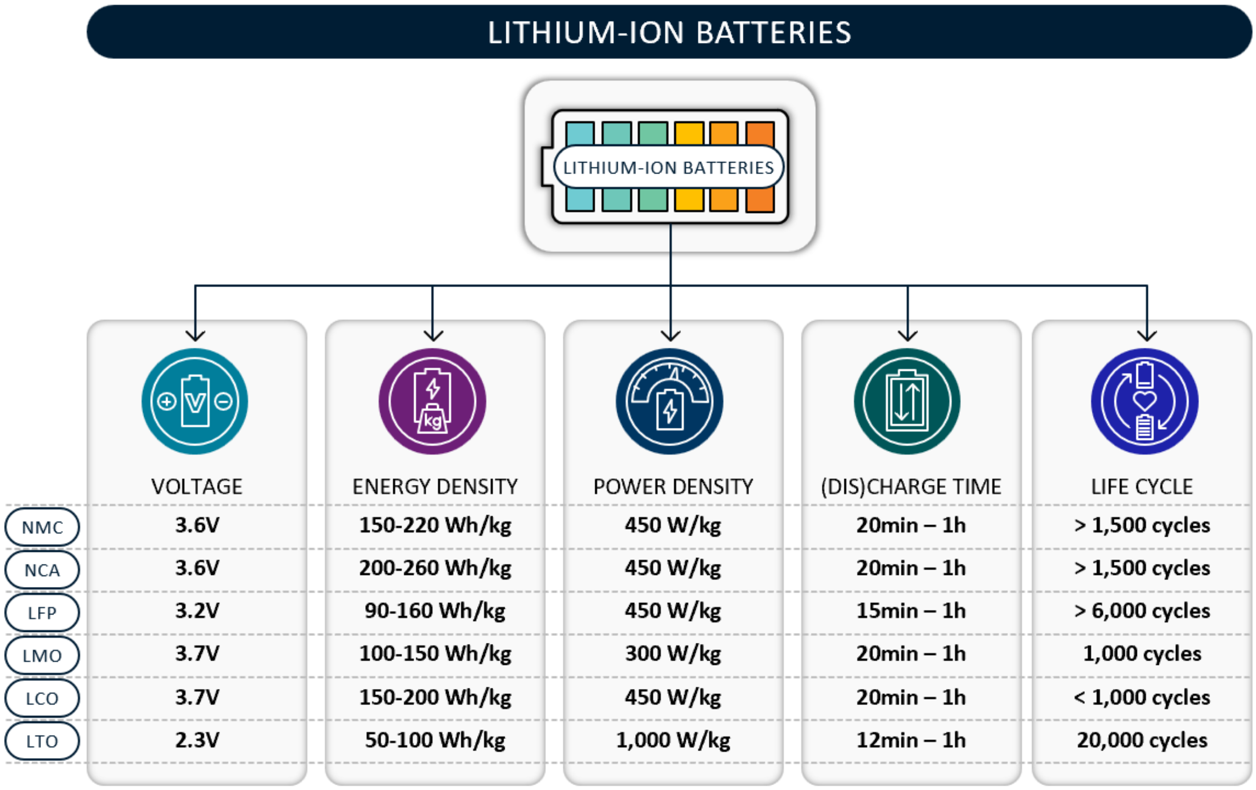
Figure 10 Redox couples involved in the charge and discharge states of LIB electrodes

Form Factors – LIBs are available in 4 form factors: coin, cylindrical, prismatic, and pouch cells. The choice of form factor is primarily driven by a balance between the device's size and shape constraints, its energy and power requirements, and the specific application's thermal management needs, ensuring both optimal performance and safe operation. All forms contain the same components but are packaged differently, tailored to specific requirements of applications (Table 1).

Table 1 Typical applications, capacity range, and pros and cons of different LIB form factors

FORM	APPLICATIONS	CAPACITY	PROS	CONS
Coin Cells	Compact size and shape make them ideal for small, low-power devices such as watches, calculators, hearing aids, or remote controls.	0.01 - 1 Ah	• Simple design and low material requirements • Low self-discharge	• Limited capacity and low current output • Often non-rechargeable
Cylindrical Cells	Commonly used in portable electronics, power tools, laptops and electric vehicles.	1 - 5 Ah	• Mechanical strength • Standardised and easy to manufacture • Excellent thermal management • Long cycle life	• Low packing density in stacks due to space inefficiencies between cylindrical cells in an assembly • Rigid shape, which limits the design flexibility
Pouch Cells	Flexible design ideal for space-constrained applications. Found in smartphones, tablets, and wearable devices, where manufacturers need to prioritise thinness and pliability.	5 - 100 Ah	• Lightweight • High energy density • Flexible design • Efficient space usage	• Mechanically fragile, they require careful handling to prevent punctures • Complex manufacturing process • Prone to swelling, requiring external protection
Prismatic Cells	Well-suited for larger-scale applications like electric vehicles and stationary energy storage systems.	5 – 300 Ah	• Rectangular shape making them space-efficient in customisable design • Good volumetric energy density (good packing in stacks)	• Prone to swelling, requiring external protection • Complex manufacturing process

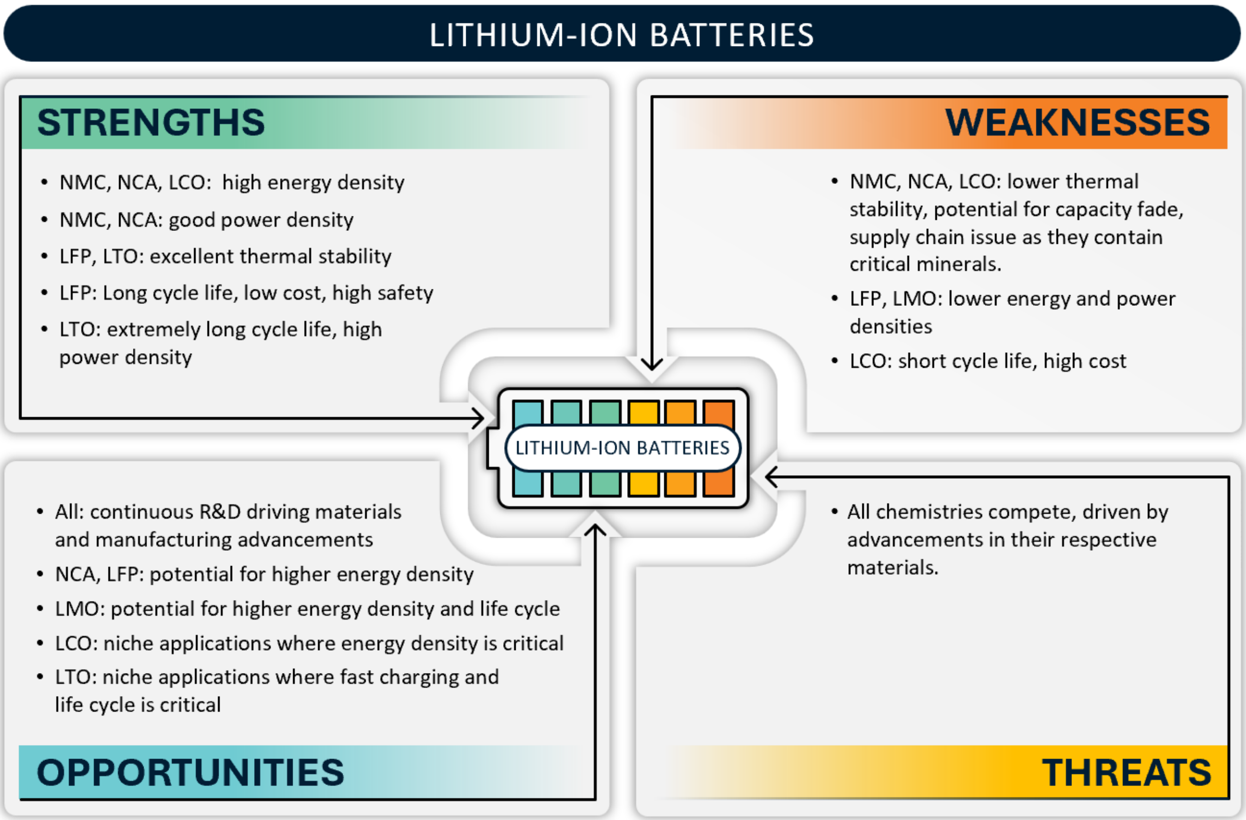
Performance – The LIB chemistries present differences in performance that make them suitable for a wide range of applications. For example, with energy and power densities of 150 - 220 Wh/kg and 450 W/kg, respectively, NMC batteries present a good balance, making them the chemistry of choice for electric vehicles and power tools. NCA batteries, while offering an energy density of up to 260 Wh/kg, can be less stable and require careful thermal management. This is the case of LCO batteries as well – once dominant in mobile devices, they have been largely replaced due to lower thermal stability and environmental and cost concerns associated with cobalt. Meanwhile, safety is prioritised in LFP batteries as they present a crystal structure of the cathode material that is more temperature tolerant, making them one of the preferred chemistries for stationary energy storage systems and electric vehicles that prioritise range over performance. LTO, though lower in energy density, exhibits a high power density of up to 1,000 W/kg, in addition to higher cycle life and low-temperature performance, making them ideal for applications requiring frequent charging and discharging in cold environments. A comparison of the Key Performance Indicators (KPIs) is shown in Figure 11.



	VOLTAGE	ENERGY DENSITY	POWER DENSITY	(DIS)CHARGE TIME	LIFE CYCLE
NMC	3.6V	150-220 Wh/kg	450 W/kg	20min – 1h	> 1,500 cycles
NCA	3.6V	200-260 Wh/kg	450 W/kg	20min – 1h	> 1,500 cycles
LFP	3.2V	90-160 Wh/kg	450 W/kg	15min – 1h	> 6,000 cycles
LMO	3.7V	100-150 Wh/kg	300 W/kg	20min – 1h	1,000 cycles
LCO	3.7V	150-200 Wh/kg	450 W/kg	20min – 1h	< 1,000 cycles
LTO	2.3V	50-100 Wh/kg	1,000 W/kg	12min – 1h	20,000 cycles

Figure 11 Key Performance Indicators of 6 chemistries of LIBs

SWOT analysis – Figure 12 presents a summary of LIB strengths, weaknesses, potential threats, and opportunities in the future, while Appendix B.2 provides more details of these aspects. LIBs are predominantly valued for their high energy density and versatility of applications.



STRENGTHS

- NMC, NCA, LCO: high energy density
- NMC, NCA: good power density
- LFP, LTO: excellent thermal stability
- LFP: Long cycle life, low cost, high safety
- LTO: extremely long cycle life, high power density

WEAKNESSES

- NMC, NCA, LCO: lower thermal stability, potential for capacity fade, supply chain issue as they contain critical minerals.
- LFP, LMO: lower energy and power densities
- LCO: short cycle life, high cost

OPPORTUNITIES

- All: continuous R&D driving materials and manufacturing advancements
- NCA, LFP: potential for higher energy density
- LMO: potential for higher energy density and life cycle
- LCO: niche applications where energy density is critical
- LTO: niche applications where fast charging and life cycle is critical

THREATS

- All chemistries compete, driven by advancements in their respective materials.

Figure 12 SWOT analysis of LIBs

Sodium-ion batteries (SIBs)

Sodium-ion batteries (SIBs) are emerging as a promising alternative to LIBs due to their cost effectiveness and the abundance of sodium resources.[24]

Structure and Materials – SIBs have a similar structure to LIBs (Figure 12), employing analogous mechanisms for energy storage and delivery. Larger sodium-ions, compared to lithium-ions, prevent them from easily mixing with the metal oxides used for LIBs. Although this requires a reengineering of the materials composing the battery, it allows for the use of more affordable materials in SIBs.

Cathode	Layered transition metal oxide such as $Na_{0.66}Mn_{0.66}Ni_{0.33}O_2$. Polyanions or Prussian Blue analogues such as $Na_3V_2(PO_4)_2F_3$ and $Na_2MnFe(CN)_6$, respectively, are also reported. They show a stronger structural stability but offer a lower energy density. The cathodic current collector is an aluminium sheet.
Anode	Hard carbon, a non-graphitising form of carbon that offers high capacity, low cost and favourable voltage. It also facilitates efficient adsorption in a reversible way, making it the leading candidate for commercialisation.[25] The performance of hard carbon anodes is comparable to that of graphite in LIBs. The anodic current collector is an aluminium sheet.
Electrolyte	An organic carbonate-based solvent with sodium hexafluorophosphate ($NaPF_6$) used as the electrolyte salt, as it offers a high solubility for charge carriers and anodic stability.[26] However, the larger ionic radius of sodium-ions requires higher salt concentrations to achieve comparable

	conductivity levels to LIBs.[27] Performance can also be enhanced by using carbonate, sulfur-containing or silicon-containing additives.[28]
Separator	Polyethylene (PE) and polypropylene (PP). Glass fibre,[29] cellulose-based,[30] and woven fabric[31] are also explored for better porosity, sustainability and better performance, respectively.

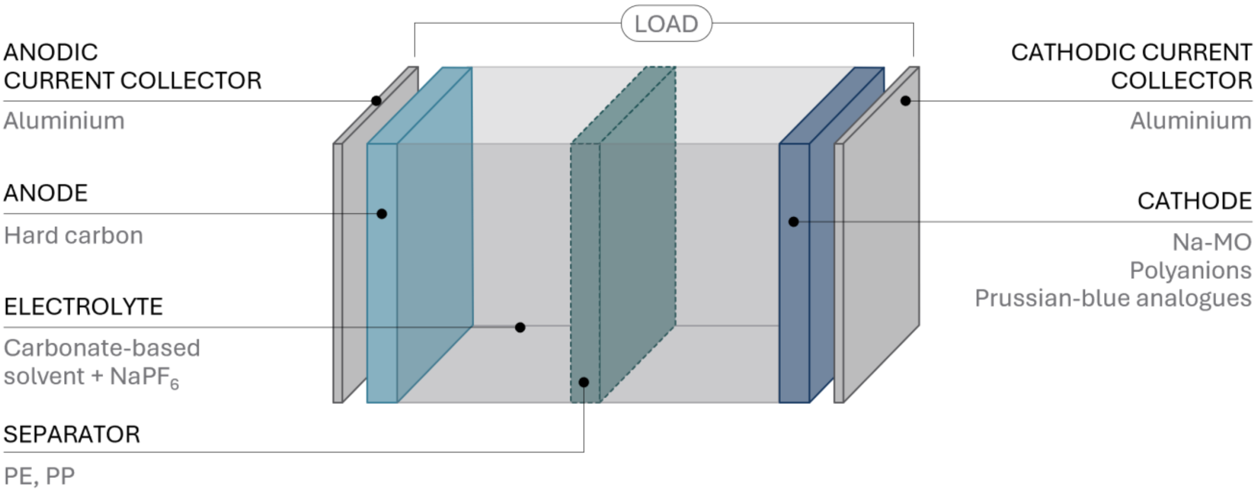


Figure 13 Schematic representation of the internal structure of a SIB and materials used

Redox Couples – The working principle of SIBs is similar to that of LIBs. The main difference lies in the redox species involved, as sodium-ions serve as the charge carrier, as illustrated in Figure 14. When fully charged, the active materials are the partially sodiated metal oxides (Na_{1-x}-MO) on the cathode side and sodiated carbon anode where the carbon material hosts partially reduced sodium cations within its lattice. During discharge, partially reduced sodium-ions lose their electrons and are released from the carbon lattice into the electrolyte solution. The electrons travel through the external circuit to the cathode to reduce sodium-ions from the electrolyte, resulting in the formation of fully sodiated metal oxides (Na-MO) cathode material. The reverse reaction occurs during the charging process. The charge balance of the cell is maintained through the transport of sodium-ions between the anode and cathode compartments.

Detailed chemical reactions are outlined in Equation 11-13 in Appendix A.3

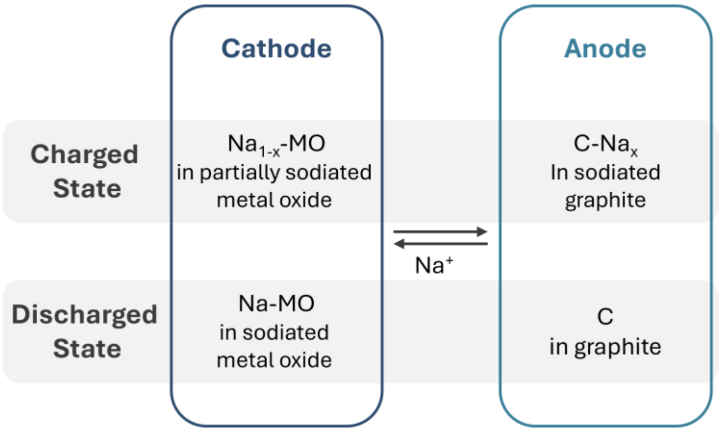


Figure 14 Redox couples involved in the charge and discharge states of SIB electrodes

Form Factors – Form factors of SIBs are similar to LIBs. They involves cylindrical, prismatic and pouch cells.[32]

Performance – SIBs offer promising performance characteristics (Figure 15), though they generally exhibit lower energy densities than LIBs. Despite this, SIBs can deliver power densities up to 300 W/kg in commercial systems, enabling rapid charging and discharging cycles. They typically operate within a wide temperature range, from -20°C to +60°C, and can sustain up to 5,000 charge-discharge cycles. With a nominal voltage of 3.1 V and a wide range of capacities, SIBs are well-suited for various applications, from stationary energy storage to electric vehicles. Research and development efforts continue to improve the energy density and cycle life of these batteries, making them a viable alternative to LIBs.

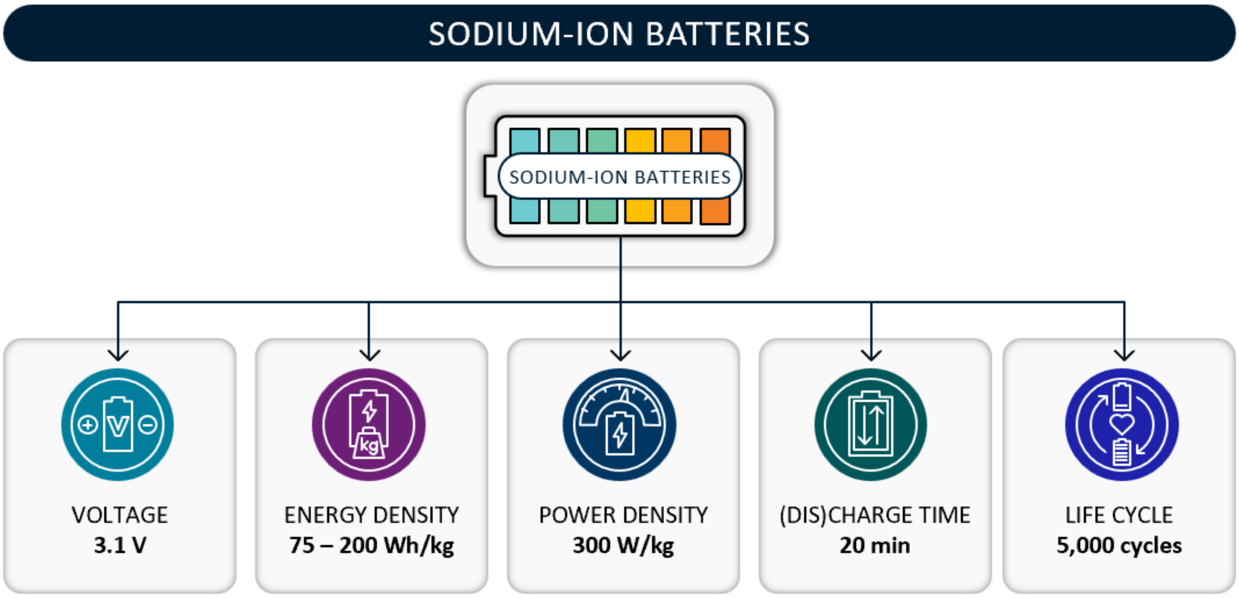


Figure 15 Key Performance Indicators of SIBs

SWOT analysis – Figure 16 presents a summary of SIB's strengths, weaknesses, potential threats, and opportunities in the future. These aspects are discussed in Appendix B.3. However, it is worth noting the main competitive advantage of SIBs compared to LIBs is in the cathode material being less dependent on critical minerals like lithium, nickel or cobalt.

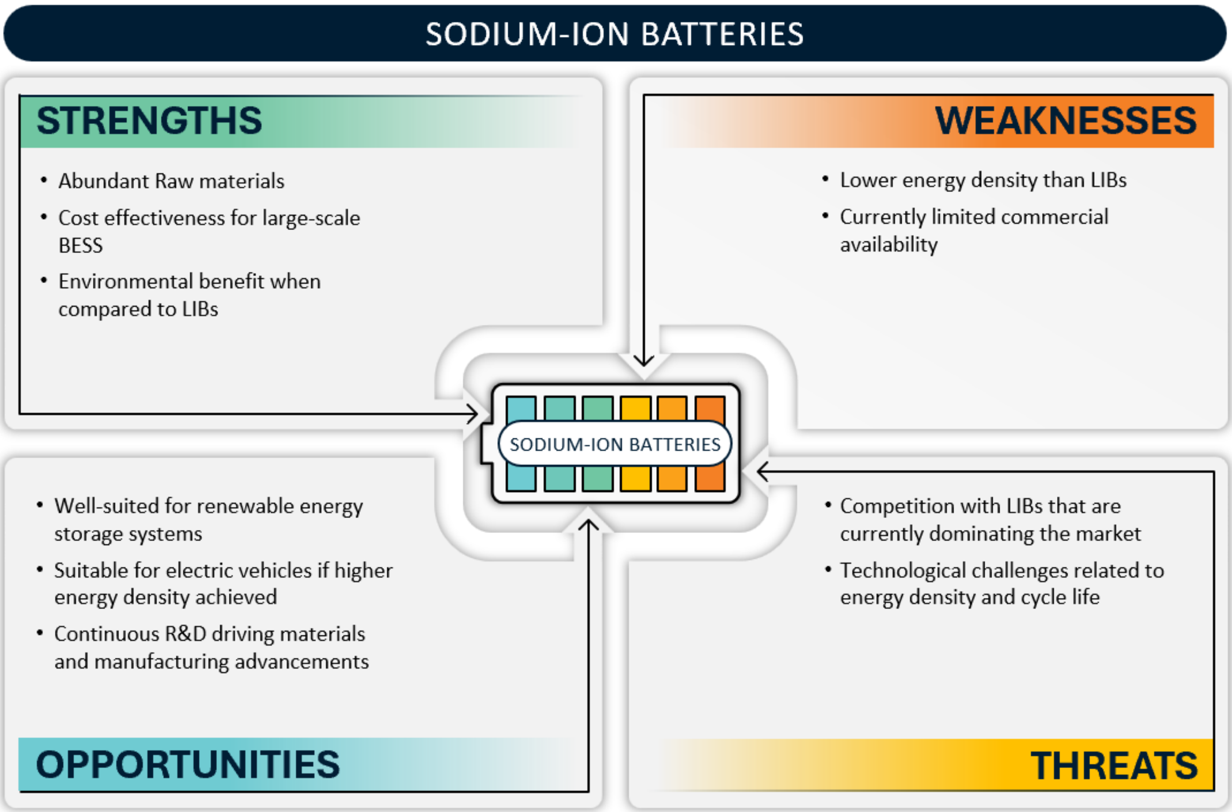


Figure 16 SWOT analysis of SIBs

2.1.3 Nickel-based batteries

Nickel-based batteries are a popular type of secondary battery known for their durability and versatility. They are commonly found in power tools, portable electronics, and hybrid electric vehicles. They are also used in stationary energy storage systems such as backup power for critical systems, as they are well suited for applications requiring high discharge rates. Nickel-based batteries come in various chemistries, including nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) and the less common nickel-hydrogen (Ni-H_2) batteries. Each of those commercially available batteries show different drawbacks – poor environmental impact for Ni-Cd, poor cycle stability for Ni-MH, and high cost for Ni-H_2.

It should be noted that due to the environmental toxicity of cadmium, Ni-Cd batteries are now banned for most applications. Exemptions from The European Union Battery Directive include medical devices, alarm systems, emergency lighting, and portable power tools. As these applications are beyond the scope of this report, Ni-Cd batteries will not be detailed in this report.

Nickel metal hydride (Ni-MH) batteries

Nickel-metal hydride (Ni-MH) batteries are a type of secondary battery that have a lower environmental impact and are largely free from the 'memory effect', a phenomenon observed in Ni-Cd batteries where partial charge and discharge cycles leads to a reduction of the overall capacity overtime. While Ni-MH batteries are much less susceptible to this effect, it is still advised to avoid overcharging them, which would result in gassing. They offer a safety advantage over Ni-H_2 by eliminating the risks associated with storing high-pressure hydrogen gas. Ni-MH batteries are found in various applications, including uninterruptible power supplies (UPS, backup power during outages) or in combination with solar energy generating systems.

Structure and materials – A schematic representation of the internal structure of a Ni-MH battery is presented in Figure 17, along with the materials composing the main components of the system.

Cathode	Nickel hydroxide.[33] The current collector is nickel-plated steel.[34]
Anode	The anode can consist of different hydrogen-absorbing alloys: • AB5, where 'A' is a mixture of rare-earth metals like lanthanum, cerium, neodymium, and praseodymium and 'B' contains nickel, cobalt, manganese or aluminium (Ex: $LaNi_5$, $CeNi_5$). • AB2, used for higher capacity, where 'A' is titanium or vanadium, and 'B' is zirconium or nickel. • Other alloys are also available, including AB (HfNi, FeTi), A2B (Hf2Fe, Mg_2Ni), A2B7 (Pr_2Ni_7, Ce_2Co_7), or AB3 ($NdCo_3$, $GdFe_3$). The current collector is nickel-plated steel.
Electrolyte	An aqueous alkaline solution of potassium hydroxide (KOH) at a concentration of roughly 30 wt%.
Separator	Porous materials like polyolefins, a non-woven polyamide, or a mixture of both.[35]

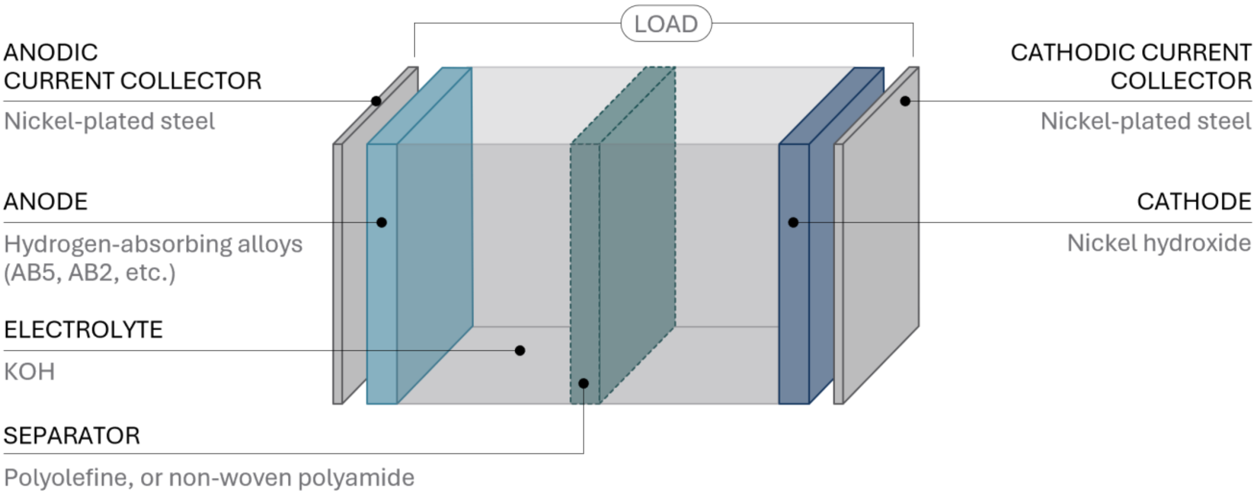


Figure 17 Schematic representation of the internal structure of a Ni-MH battery and materials used

Redox couples – Ni-MH batteries operate through the reversible oxidation-reduction of nickel compounds using hydrogen H_2 (Figure 18). When fully charged, active materials are Ni^{3+} in nickel oxohydroxide (NiO(OH)) at the cathode side, and hydrogen (H_2^0) stored in the form of a metal hydride ($M-H_2$) at the anode side. During discharge, hydrogen atoms lose their electrons to form protons (H^+) which are released to the electrolyte solution and react with the excess hydroxide (OH^-) to form water (H_2O). The electrons travel through the external circuit to the cathode to reduce the Ni^{3+} in nickel oxohydroxide (NiO(OH)) to Ni^{2+} in nickel hydroxide ($Ni(OH)_2$). This process is reversed during the charging phase. Meanwhile, hydroxide ions move between the anode and cathode compartments to maintain charge balance.

The detailed chemical reactions are outlined in Equations 14-16 in Appendix A.4.

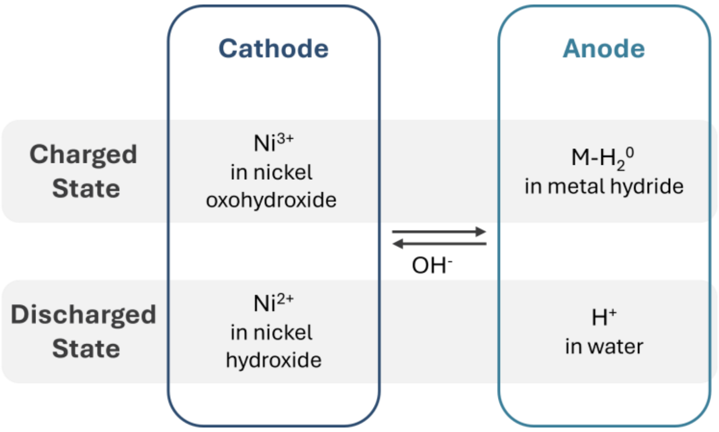


Figure 18 Redox couples involved in the charge and discharge states of Ni-MH battery electrodes

Form factors and battery types – Generally, Ni-MH batteries can be found as cylindrical, prismatic or button cell sealed designs with a safety vent built into the top. In overcharge events, side reactions occur where oxygen and hydrogen gas (O_2 and H_2) are produced. The vent avoids gas buildup and ensures the internal pressure is constant.

Ni-MH batteries are also used in large-scale ESS. In this case, Ni-MH cells can be assembled in 40 stack, such as Kawasaki Heavy Industries Gigacells. Such batteries have applications in battery power systems for railways or as stabilization of the power grid.

Performance – The performance of Ni-MH batteries is presented in Figure 19. They offer a nominal voltage of 1.2 V, an energy density of up to 140 Wh/kg, and a power density of up to 1,000 W/kg, making them suitable for various applications. Ni-MH batteries exhibit performance across a wide range of temperatures, operating efficiently from -20°C to 50°C, with an optimum temperature range of 10-30°C. Their long cycle life, exceeding 2,100 cycles, ensures durability and longevity. Their environmentally friendly materials and robustness makes them good candidates for stationary energy storage systems in cold and/or remote locations.

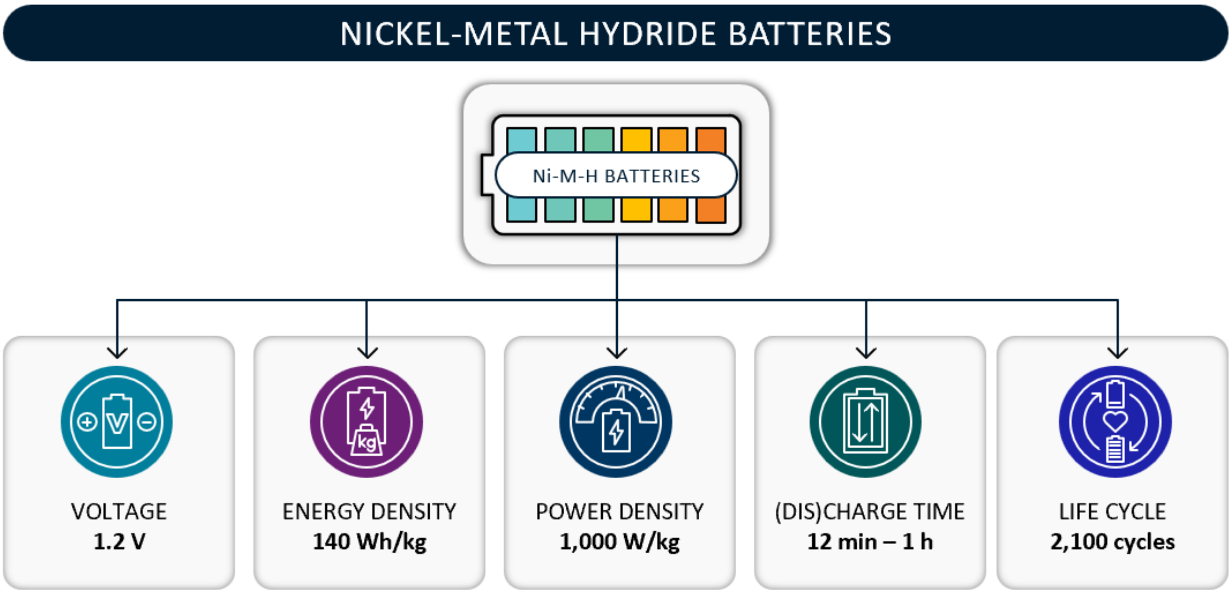


Figure 19 Key Performance Indicators of Ni-MH batteries

SWOT analysis – A summary of Ni-MH battery strengths, weaknesses, potential threats, and opportunities is presented in Figure 20, while Appendix B.4 contains more details on these aspects. The main strength of Ni-MH batteries resides in its low environmental impact chemistry and lower cost than LIBs.

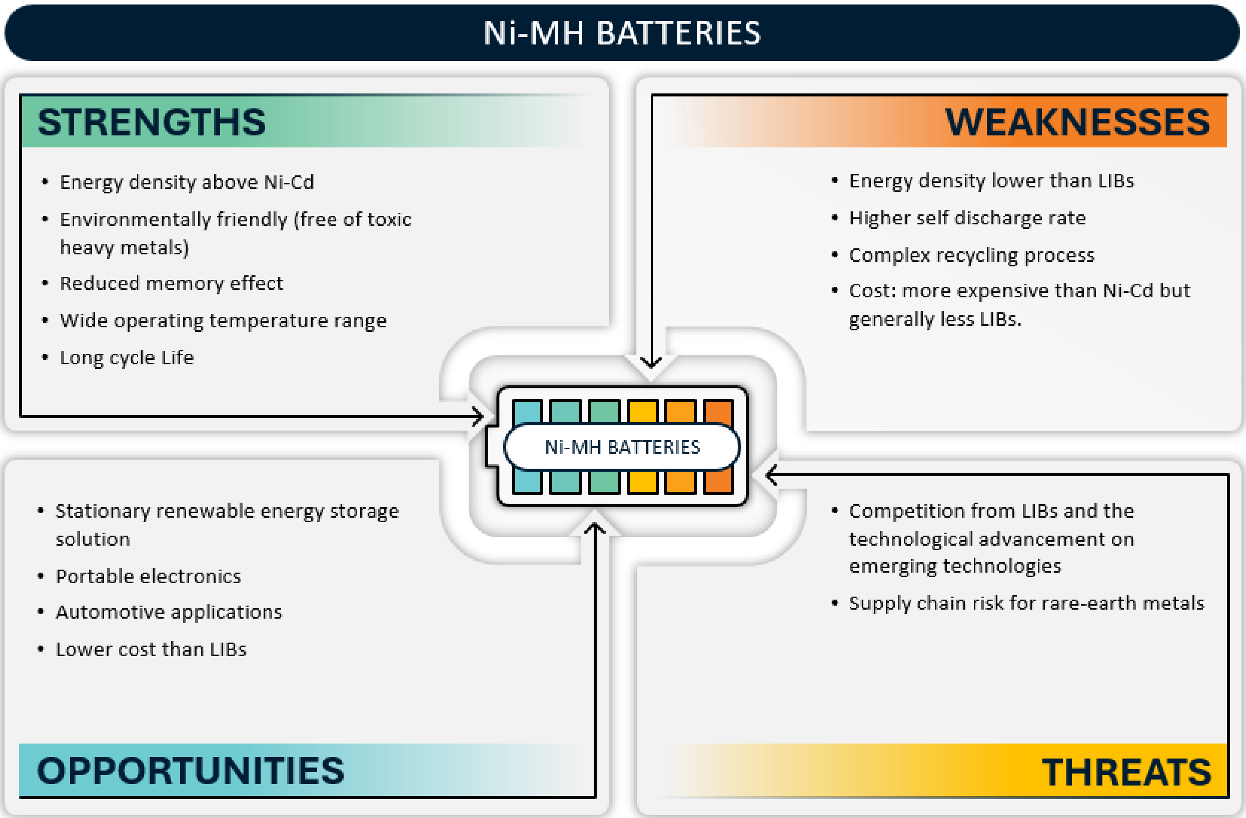


Figure 20 SWOT analysis of Ni-MH batteries

Nickel-hydrogen (Ni-H_2) batteries

Nickel-hydrogen (Ni-H_2) batteries are rechargeable batteries that store energy using nickel and pressurised hydrogen gas. Initially developed in the Soviet Union in the 1970s for space applications, Ni-H_2 batteries offer high energy density and a long lifespan. Their reliability and longevity have made them a popular choice for powering satellites, the International Space Station, and the Hubble Space Telescope.

Structure and materials – Ni-H_2 systems combine the functioning principles of a battery on the cathode side and fuel cell on the anode side, which dictates its structure, presented in Figure 21.

Cathode	Nickel hydroxide cathode $Ni(OH)_2$, which reversibly oxidises to nickel oxohydroxide (NiO(OH)). The cathodic current collector is typically made of nickel-plated steel.
Anode	Similar to a fuel cell, incorporating a catalyst (usually platinum) supported on carbon-based material,[36] and gas diffusion elements for the hydrogen stored under pressure, typically up to 1,200 psi (82.7 bar). Some anodes use a nickel-molybdenum-cobalt (NiMoCo) material, a porous structure aiding the reduction of hydrogen gas.[37] While Ni-Pt systems present a shorter cycle life (*ca.* 800), due to the release of platinum from the anode carbonaceous structure, NiMoCo, have shown remarkable retention of the initial capacity. The anodic current collector is nickel-plated steel.
Electrolyte	A potassium hydroxide solution (30 wt%).[38]
Separator	A porous material, such as polyethylene (PE) or polypropylene (PP).[39]

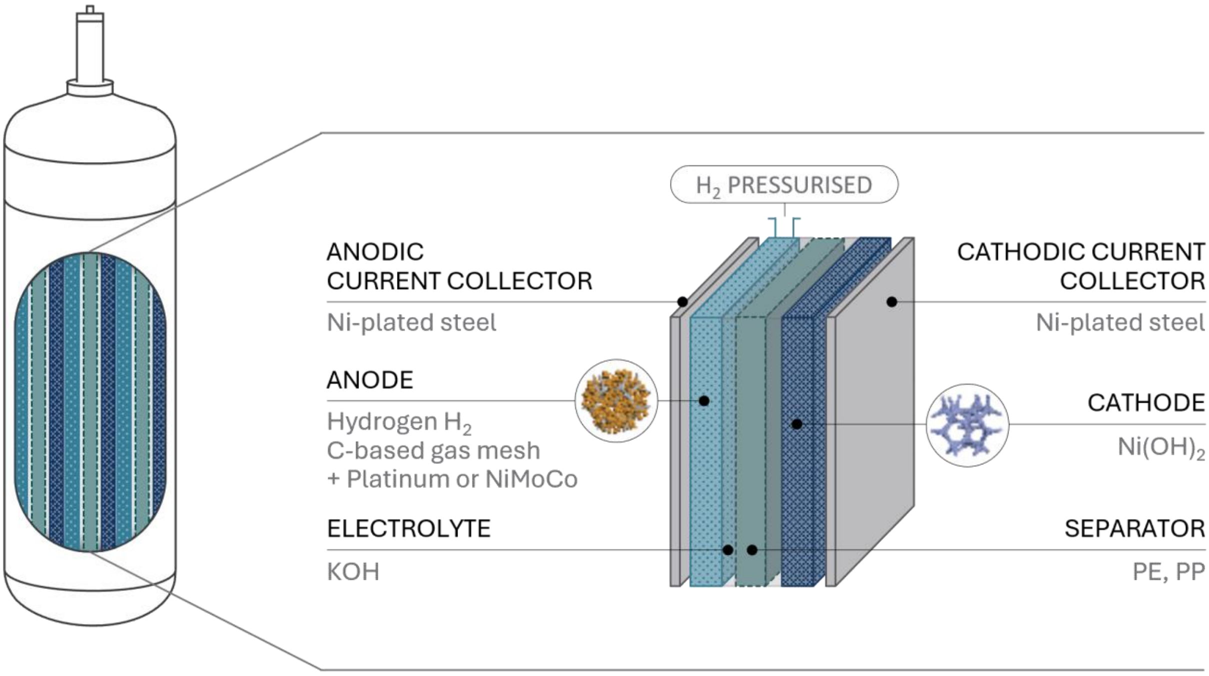
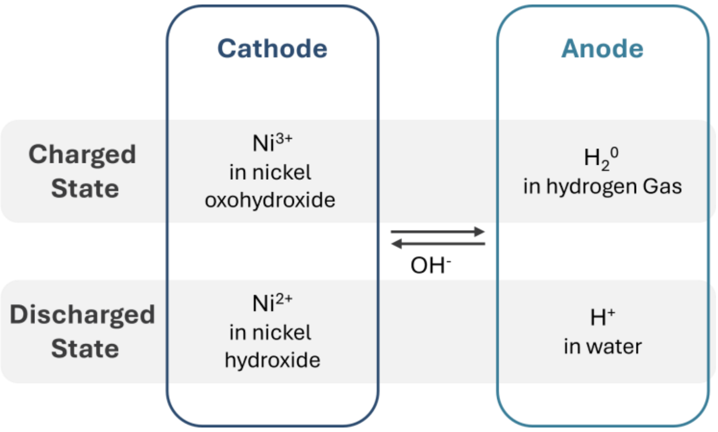


Figure 21 Schematic representation of the internal structure of a Ni-H_2 battery and materials used

Redox couples – The redox species in Ni-H_2 batteries are similar to those in Ni-MH batteries, the main difference arising from the medium in which the hydrogen is stored. As depicted in Figure 22, when fully charged, active materials are Ni^{3+} in nickel oxohydroxide (NiO(OH)) at the cathode side and hydrogen gas (H_2^0) stored in a compressed tank on the anode side. During discharge, hydrogen gas loses electrons to form protons (H^+) which are released to the electrolyte solution to react with the excess hydroxide to form water. The electrons travel through the external circuit to the cathode to reduce the Ni^{3+} in nickel oxohydroxide (NiO(OH)) to Ni^{2+} in nickel hydroxide ($Ni(OH)_2$). This process is reversed during the charging phase. Meanwhile, hydroxide ions (OH^-) move between the anode and cathode compartments to maintain charge balance.

The detailed chemical reactions are outlined in Equation 17-19 in Appendix A.5.



	Cathode	Anode
Charged State	Ni^{3+} in nickel oxohydroxide	H_2^0 in hydrogen Gas
Discharged State	Ni^{2+} in nickel hydroxide	H^+ in water

Figure 22 Redox couples involved in the charge and discharge states of Ni-H_2 battery electrodes

Form factors and battery types – The form factors of Ni-H_2 batteries are tailored to meet their current use in spacecraft and satellites. Common configurations include cylindrical and prismatic cells, which can be stacked or arranged in modules to achieve the desired capacity and voltage. Cylindrical cells are often used in smaller applications, while prismatic cells are more suitable for larger, high-power systems. These designs prioritise efficient volume and robust construction to withstand the rigors of space environments, such as launch vibrations, temperature fluctuations, and radiation exposure.[40]

Performance – Ni-H_2 batteries deliver a voltage of 1.3 V, enabling efficient energy storage and output. Their energy density, ranging from 55 to 75 Wh/kg, provides balance between energy storage capacity and weight, while their power density of 220 W/kg ensures charge and discharge capabilities. Ni-H_2 batteries have a long cycle life, with over 20,000 cycles achievable, and some designs surpassing 40,000 cycles at 40% depth of discharge. This longevity, coupled with their ability to withstand a wide operating temperature range of -20°C to +60°C, makes them highly reliable and adaptable to various environmental conditions. Their performance is optimum around 25°C, where they exhibit maximum efficiency and lifespan.

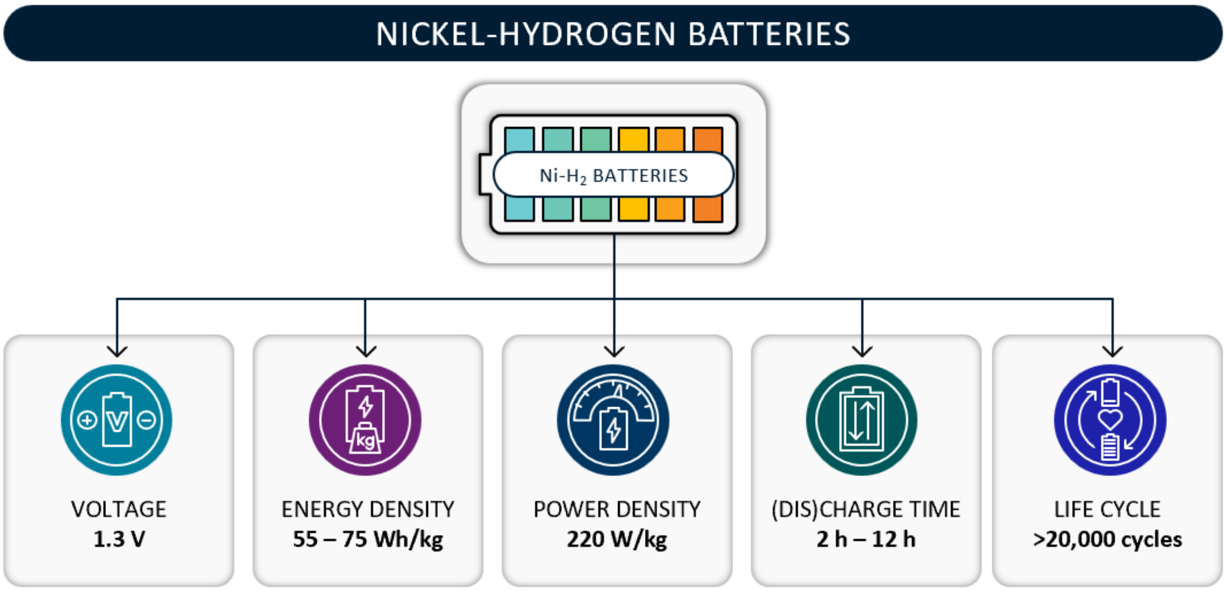
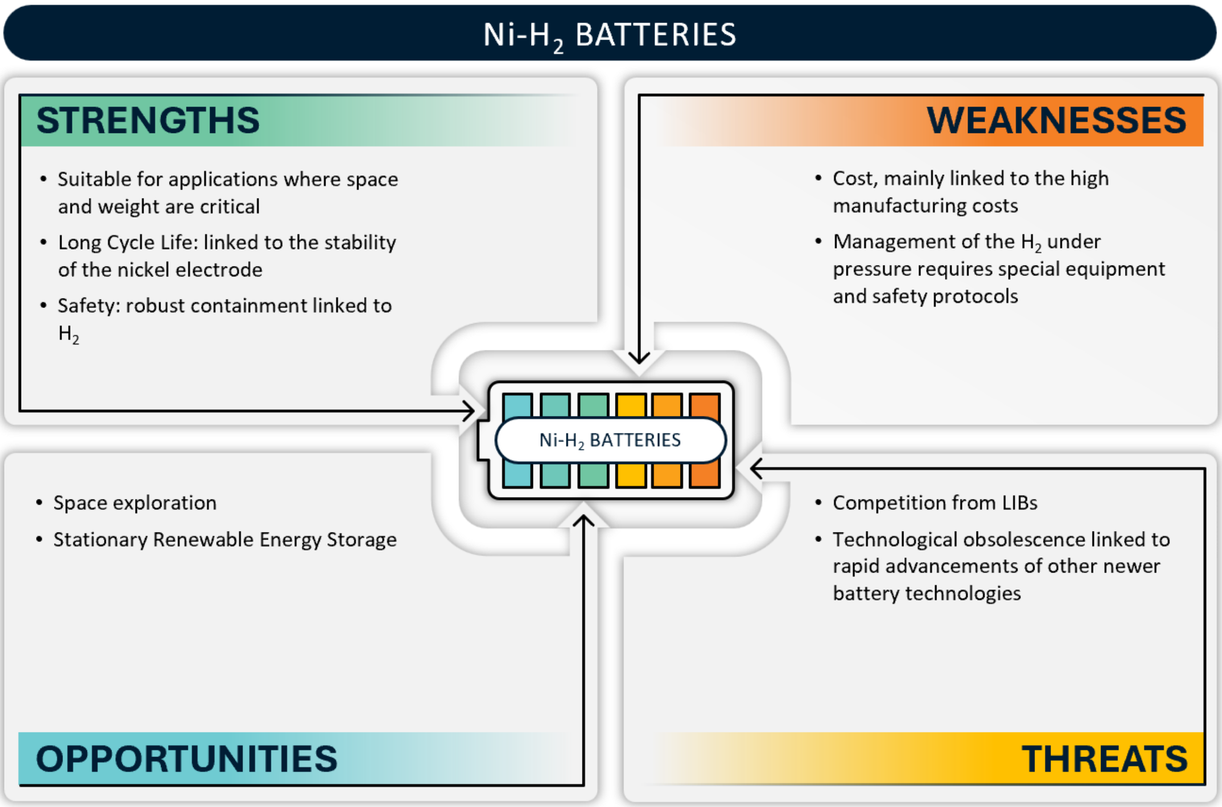


Figure 23 Key Performance Indicators of Ni-H_2 batteries

SWOT analysis – A summary of Ni-H_2 batteries' strengths, weaknesses, potential threats, and opportunities is presented in Figure 24, with Appendix B.5 containing more details on these aspects. The main strength of Ni-H_2 batteries is in their extensive cycle life.



STRENGTHS

- Suitable for applications where space and weight are critical
- Long Cycle Life: linked to the stability of the nickel electrode
- Safety: robust containment linked to H_2

WEAKNESSES

- Cost, mainly linked to the high manufacturing costs
- Management of the H_2 under pressure requires special equipment and safety protocols

OPPORTUNITIES

- Space exploration
- Stationary Renewable Energy Storage

THREATS

- Competition from LIBs
- Technological obsolescence linked to rapid advancements of other newer battery technologies

Figure 24 SWOT analysis of Ni-H_2 batteries

2.1.4 Redox-flow batteries

Unlike the solid-state electrodes of conventional batteries, standard redox-flow batteries (RFBs), such as the vanadium (V-RFBs) analogue presented in this report, store energy in liquid electrolytes, a key distinguishing feature of this technology. Hence, there are no formal cathode, anode, or electrolyte. Instead, they have a *catholyte*, the electrolyte containing the redox species circulating near the positive electrode, and an *anolyte*, the electrolyte containing the redox species circulating near the negative electrode. As energy is stored in a liquid phase, the energy density is usually expressed volumetrically in Wh/L instead of Wh/kg for conventional batteries. In a similar way, RFBs focus on the surface of the inert electrodes for their power output, instead of the mass of material involved, in conventional batteries. Hence, power density in RFBs is usually expressed in W/cm^2 instead of W/kg, which is used for conventional batteries.

Since the energy is stored outside the electrochemical cell, independent scaling of power rating and energy storage is possible, making RFBs an attractive option for long-term energy storage. Energy density is governed by the electrolyte volume, the concentration of active species and the cell voltage, while power rating is determined by the kinetic behaviour of the redox species, the size of the electrodes and the number of cells in a stack.

A variation of standard RFBs is hybrid RFBs, in which one of the electroactive materials is deposited as a solid layer on an electrode. These analogues combine features of conventional batteries (with solid electrodes) and RFBs (with flowing electrolyte). This is the case of all-iron (Fe-RFBs) and zinc-bromine analogues (Zn/Br$_2$-RFBs) covered in this report. For hybrid RFBs, the energy density is expressed in Wh/kg, while the power density remains expressed in W/cm^2. Although hybrid RFBs may present a higher energy density than standard RFBs, they can also reduce the ability to independently scale energy and power densities.

Vanadium redox-flow batteries (V-RFBs)

Vanadium redox-flow batteries (V-RFBs) leverage the multiple accessible oxidation states of vanadium for both the catholyte and anolyte. This unique feature eliminates cross-contamination issues common in other flow battery chemistries.

Structure and materials – A schematic representation of the internal structure of a V-RFB is presented in Figure 25. The materials composing the components of the system are described below.[41]

Inert Electrodes	Carbon-based materials, used as anode and cathode electrodes due to their good conductivity, low cost, higher overpotential for gas evolution and excellent chemical resistance. They also offer high permeability and surface area to support fast kinetics and reaction rates. Hence, thermally treated/activated carbon felt, carbon cloth and carbon paper are the most used electrode materials.
Current Collectors	Copper plates.
Catholyte & Anolyte	Aqueous acidic solutions containing the vanadium species. The typical concentration of vanadium species is around 1.5 - 1.8 M in 2.0 - 2.4 M of free sulfuric acid (Total sulfates in the range of 3.8 - 4.5 M).

Separator	Cation exchange membranes (perfluorinated membranes like NAFION); anion exchange membranes are also being considered. The separators should minimise the cross-mixing of redox species and water to maintain the electrolyte balance and energy storage capacity for extended periods.

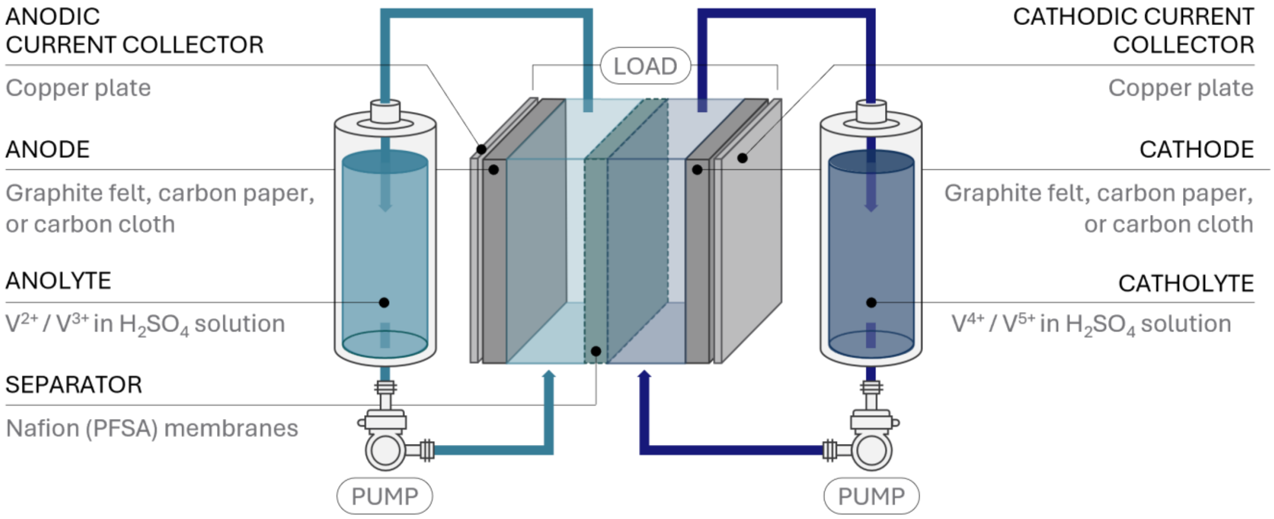


Figure 25 Schematic representation of the structure of a V-RFB and materials used

Redox couples – V-RFBs operate through the reversible oxidation/reduction of vanadium species in the electrolytes. As summarised in Figure 26, when fully charged, active chemical species are V^{5+} in vanadium (V) sulfate (in the form of $(VO_2)_2SO_4$) and V^{2+} vanadium (II) sulfate (VSO_4) in the catholyte and anolyte, respectively. During discharge, V^{2+} loses an electron to form V^{3+}species, and release a proton to the solution. The electron travels through the external circuit to the cathode to reduce the V^{5+} to the lower oxidation state V^{4+}. This consumes a proton from the electrolyte. This process is reversed during the charging process. Meanwhile, protons and sulfate ions move between the anode and cathode compartments to maintain charge balance. Note that V^{2+} are easily oxidised by the oxygen in the air, so oxygen-free conditions must be maintained for V-RFBs. Detailed chemical reactions are presented in Equations 20-22 in Appendix A.6.

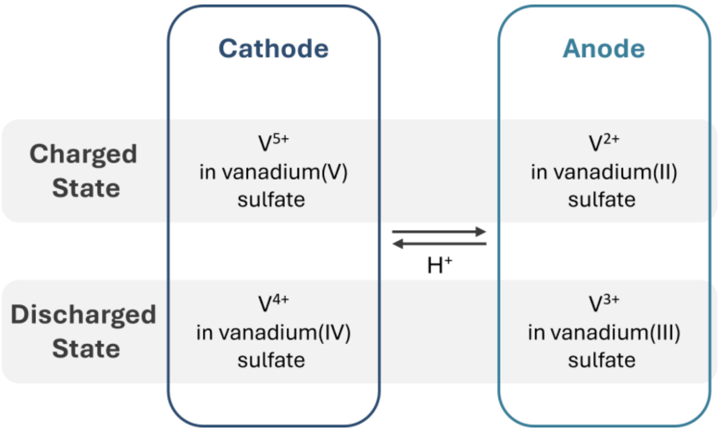
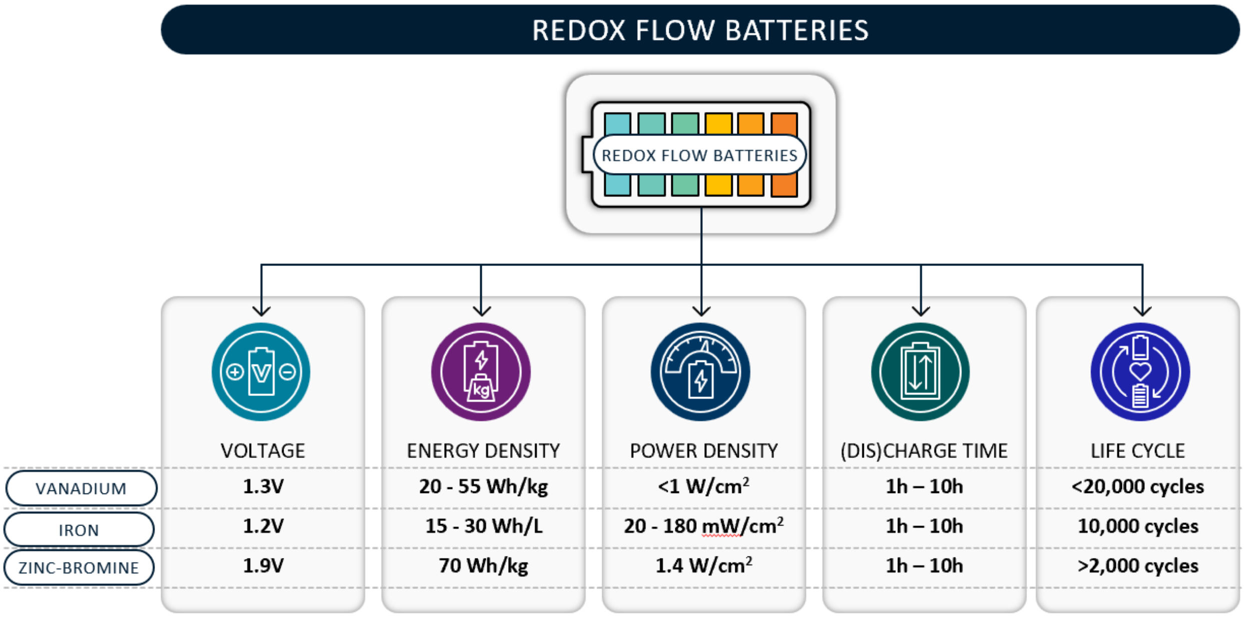


Figure 26 Redox couples involved in the charge and discharge states of V-RFB electrodes

Form factors and battery types – V-RFBs typically feature a modular and scalable form factor. This includes 2 large electrolyte tanks storing vanadium ions in different oxidation states, a cell stack where electrochemical reactions occur, a pump system circulating the electrolytes between tanks and stack, and a proton-, cation-, or anion-exchange membrane separating the electrolyte solutions while allowing ion transfer. For grid-scale use, V-RFBs are often housed in standardised shipping containers for easy transport and installation. This modular design enables scaling to meet varying energy storage needs, making them ideal for applications requiring large capacities and long-durations, such as grid energy storage.

Performance – V-RFBs offer a performance profile (Figure 27) for large-scale energy storage. With a nominal voltage of 1.3 V, they exhibit an energy density ranging from 20 to 55 Wh/L while their power density is often reported as less than 1 W/cm^2. V-RFBs operate efficiently within a temperature range of 10-40°C, with optimal performance anywhere within this range. They present an exceptional cycle life exceeding 20,000 cycles, ensuring long-term reliability and reducing maintenance costs.

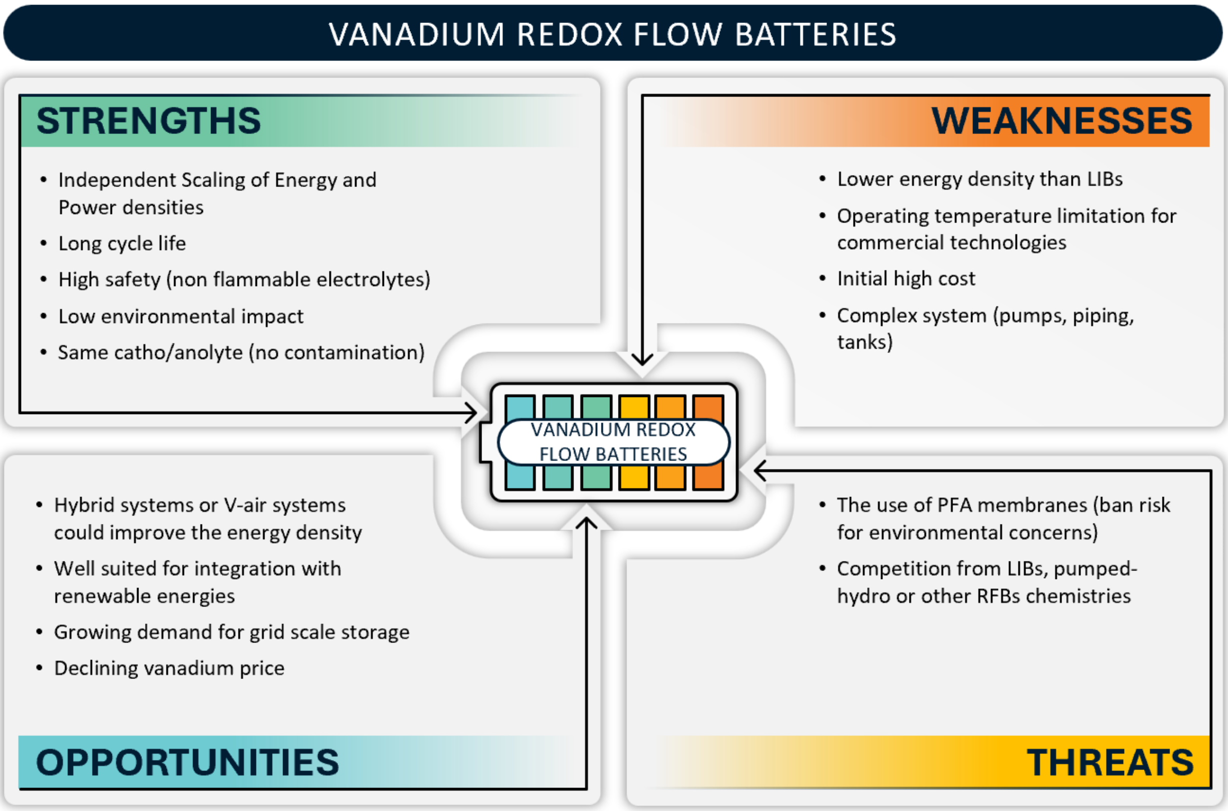


REDOX FLOW BATTERIES

	VOLTAGE	ENERGY DENSITY	POWER DENSITY	(DIS)CHARGE TIME	LIFE CYCLE
VANADIUM	**1.3V**	**20 - 55 Wh/kg**	**<1 W/cm^2**	**1h – 10h**	**<20,000 cycles**
IRON	**1.2V**	**15 - 30 Wh/L**	**20 - 180 mW/cm^2**	**1h – 10h**	**10,000 cycles**
ZINC-BROMINE	**1.9V**	**70 Wh/kg**	**1.4 W/cm^2**	**1h – 10h**	**>2,000 cycles**

Figure 27 Key Performance Indicators of Vanadium, Iron, and Zine-Bromine RFBs

SWOT analysis – A summary of V-RFB strengths, weaknesses, potential threats, and opportunities is presented in Figure 28. A detailed discussion of these aspects is presented in Appendix B.6. The main strength of V-RFBs is the scalability and independence of energy and power densities.



VANADIUM REDOX FLOW BATTERIES

STRENGTHS

- Independent Scaling of Energy and Power densities
- Long cycle life
- High safety (non flammable electrolytes)
- Low environmental impact
- Same catho/anolyte (no contamination)

WEAKNESSES

- Lower energy density than LIBs
- Operating temperature limitation for commercial technologies
- Initial high cost
- Complex system (pumps, piping, tanks)

- Hybrid systems or V-air systems could improve the energy density
- Well suited for integration with renewable energies
- Growing demand for grid scale storage
- Declining vanadium price

OPPORTUNITIES

- The use of PFA membranes (ban risk for environmental concerns)
- Competition from LIBs, pumped-hydro or other RFBs chemistries

THREATS

Figure 28 SWOT analysis of V-RFBs

Iron redox-flow batteries (Fe-RFBs)

First introduced by R. Zito in 1978 and prototyped by Hruska and Savinell in 1981, all-iron redox-flow batteries (Fe-RFBs) are attractive for long-term energy storage due to low cost and modularity of design. Fe-RFBs are hybrid flow batteries, which involves one of the 2 redox couples in solid form.

Structure and materials – A schematic representation of the structure of a Fe-RFB is presented in Figure 29, along with the materials composing the main components of the system described below.[41]

Electrodes	Activated graphite felts due to their higher surface area and lower cost. Carbon-based materials, such as graphite felt or plates, or carbon paper are used as cathode and anode current collectors.
Catholyte	$FeCl_2$/$FeCl_3$ mixtures dissolved in hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) solution with some additives.
Anolyte	Iron (II) chloride ($FeCl_2$) or iron (II) sulfate ($FeSO_4$) (1-2M) dissolved in hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) (1-3M). Additives such as NaCl or organic ligands can be added to enhance the kinetics and the stability of Fe^{2+}.
Separator	Anion exchange membranes. However, they suffer from poor stability, poor conductivity and lose their ionic conductivity in $FeCl_3$/$FeCl_2$ solutions. Composite membranes consisting of microporous separators (e.g. Daramic) coated with non-porous coatings (e.g. hydrogel or Nafion) are the current state-of-the-art in Fe-RFBs.

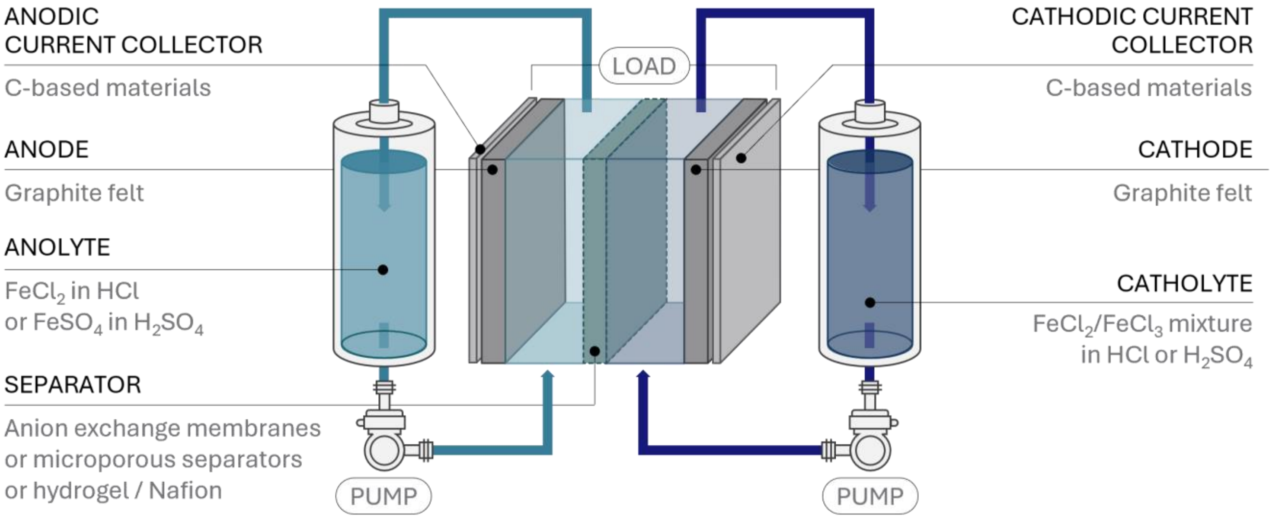


Figure 29 Schematic representation of a Fe-RFB and materials used

Redox couples – In a similar way to V-RFBs, Fe-RFBs operate through the reversible oxidation/reduction of iron species in the electrolytes. As summarised in Figure 30, when fully charged, active materials comprise Fe^{3+} in iron (III) chloride ($FeCl_3$) solution in the catholyte and iron metal (Fe^0) plating the anode. During discharge, the iron metal loses electrons to form Fe^{2+} in ferrous chloride ($FeCl_2$). The electrons travel through the external circuit to the cathode to reduce the Fe^{3+} in ferric chloride ($FeCl_3$) to the lower oxidation state Fe^{2+} in iron (II) ($FeCl_2$). This process is reversed during the charging process. Meanwhile, chloride ions (Cl^-) move between the anode and cathode compartments to maintain charge balance.

The detailed chemical reactions are provided in Equations 23-25 in Appendix A.7.

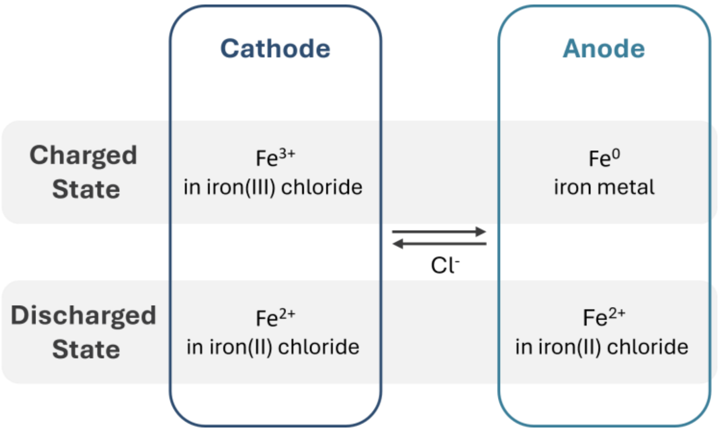


Figure 30 Redox couples involved in the charge and discharge states of Fe-RFB electrodes

Form factors and battery types – Fe-RFBs, like their vanadium equivalent, are designed for large-scale energy storage and share a similar modular and scalable form factor. They also utilise electrolyte tanks for storing iron ions in various oxidation states, a cell stack for electrochemical reactions, and a pump system for electrolyte circulation between the tanks and stack. However, a key difference lies in the membrane separating the electrolyte solutions. This modular design, similar to V-RFBs, enables scaling to meet varying energy storage needs, making them suitable for applications requiring large capacities and long-durations, such as grid energy storage.

Performance – On top of using more abundant iron, Fe-RFBs offer a promising performance profile for stationary energy storage (Figure 27). They operate at a cell voltage of 1.2 V and achieve an energy density of 15-30 Wh/kg, while their power density ranges from 20 to 180 mW/cm^2. Fe-RFBs present a wide operating temperature range of 5°C to 60°C, maintaining optimal performance throughout. Notably, they exhibit a cycle life up to 10,000 cycles, making them suitable for long-duration applications.

SWOT analysis – A summary of Fe-RFBs' strengths, weaknesses, potential threats, and opportunities is presented in Figure 31. A detailed discussion of these aspects is presented in Appendix B.7. The main strength of Fe-RFBs is their sustainability and low cost.

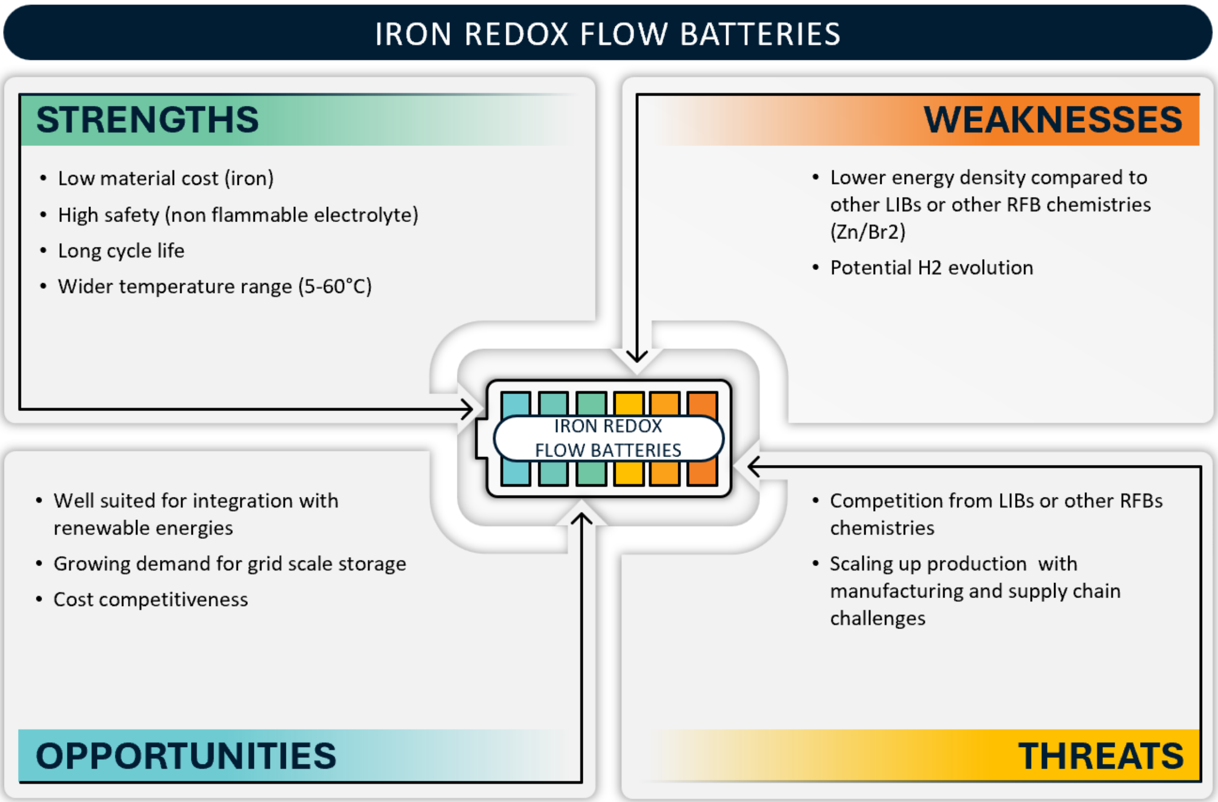


Figure 31 SWOT analysis of Fe-RFBs

Zinc/bromine redox-flow batteries (Zn/Br_2-RFBs)

Originally developed by Exxon in the early 1970s, zinc bromine batteries (Zn/Br_2-RFB) are classified as hybrid flow battery systems, whereby metallic zinc is plated on an anode during the charging step.

Structure and materials – A schematic representation of the structure of a Zn/Br_2-RFB is presented in Figure 32, along with the materials composing the main components of the system described below.[42]

Cathode	Carbon-based materials, such as graphite felt or carbon-polymer composites. The current collector is graphite, carbon-polymer composite or titanium platinised or coated with corrosion-resistant oxides.
Anode	Carbon-based material such as carbon-plastic composite, or carbon felt. Titanium mesh can also be found. The current collector is either titanium or carbon-based composite such as carbon-loaded polyethylene.
Electrolyte	$ZnBr_2$ at a concentration of 1-4 M, shared between the 2 compartments for ionic balance. In the catholyte, bromine complexing agents consisting of different quaternary ammonium bromides are also added to stabilise the bromine. In the anolyte, surfactants are added to decrease the formation of zinc dendrites during plating as well as complexing agents to improve the solubility of Zn^{2+} ions.

Separator	PE/PP-based microporous or ion exchange membranes optimised for Br^- transport and Br_2 blocking. Microporous membranes, while inexpensive, suffer from high ion crossover, leading to increased contamination between the anolyte and catholyte. Ion exchange membranes offer superior performance in this regard but are significantly more expensive.

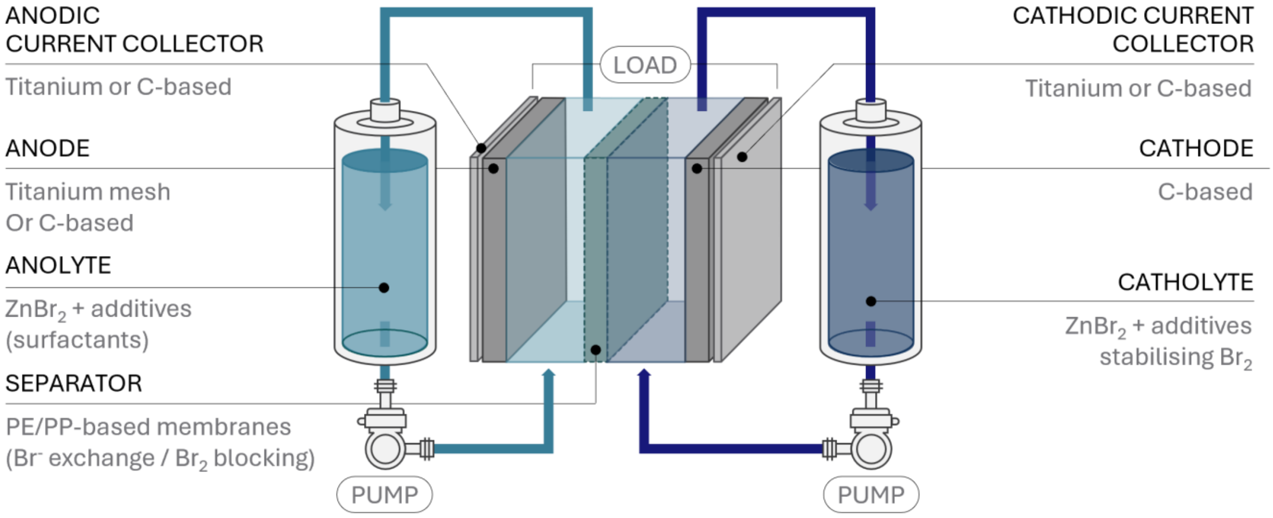


Figure 32 Schematic representation of a Zn/Br_2-RFB and materials used

Redox couples – Zn/Br_2-RFBs use the reversible reaction between zinc metal and bromine. When fully charged, the active materials at the cathode side are a bromine (Br_2) solution, stored as polybromide complexes (Br_3^-, Br_5^-) which helps reducing bromine's volatility and reactivity. On the anode side, zinc metal (Zn^0) is plated on the electrode. During discharge, the zinc metal loses 2 electrons to form zinc ions (Zn^{2+}). The electrons travel through the external circuit to the cathode to reduce the Br_2 molecules to bromine ions (Br^-). The charge balance of the cell is maintained via the migration of bromine ions (Br^-) to the catholyte compartment to maintain the charge balance. This process is reversed during the charging process.

The detailed chemical reactions are in Equations 26-28, Appendix A.8.

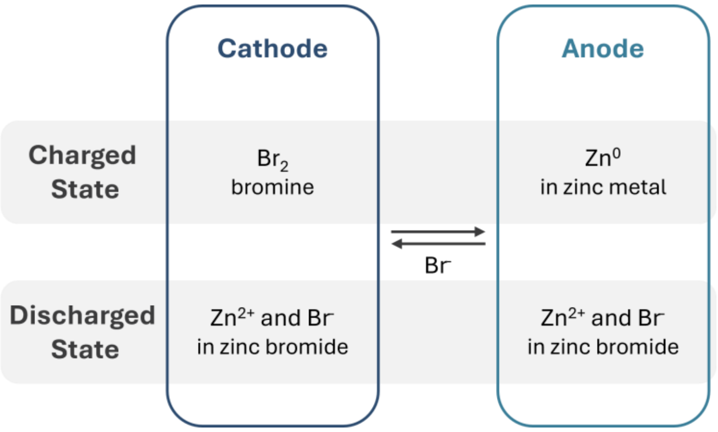
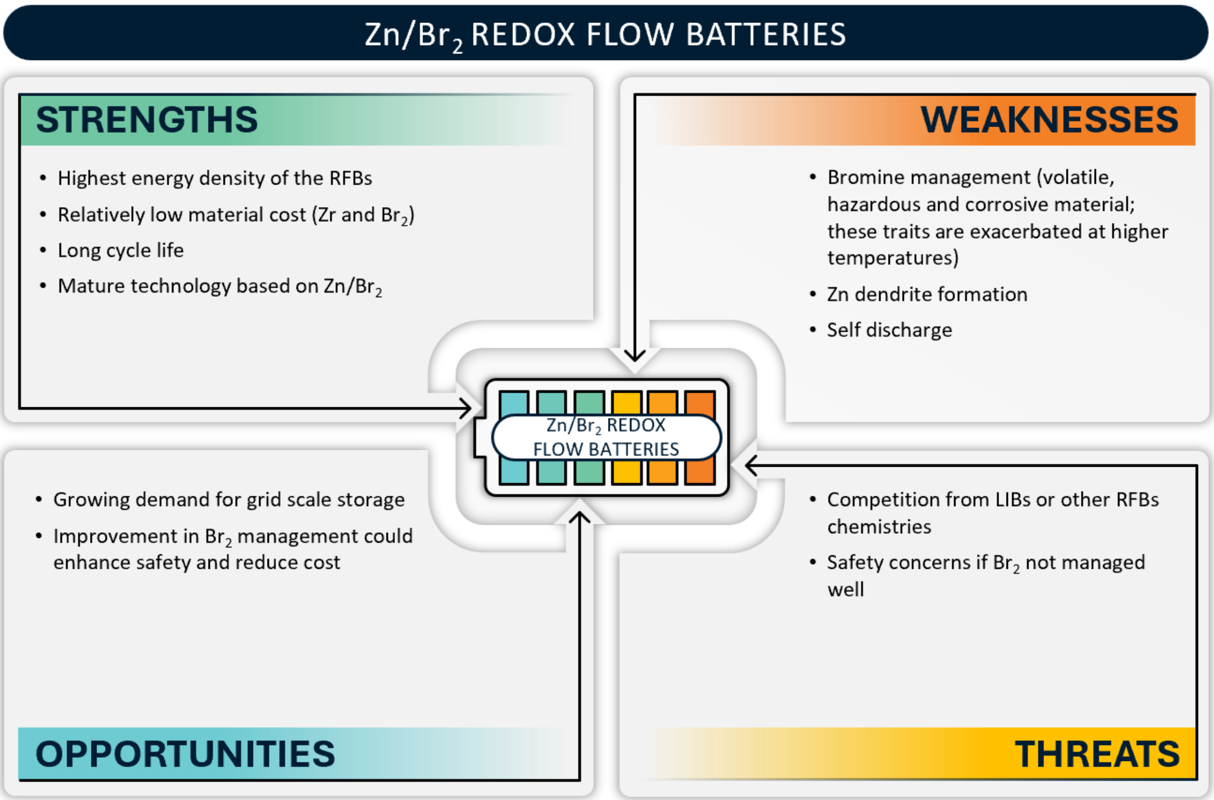


Figure 33 Redox couples involved in the charge and discharge states of Zn/Br_2-RFB electrodes

Form factors and battery types – Flow batteries and hybrid flow types present similar form factors: 2 electrolyte tanks, pumps used to transport electrolyte solutions from the tanks to the cells, and cell stacks consisting of multiple cells where electrochemical reactions occur. These are available in containerised systems housed in scalable and easy-to-transport standard shipping containers.

Performance – Zn/Br_2-RFBs offer the highest energy density of all the commercialised RFB presented in this report, around 70 Wh/kg (Figure 27).[43] This higher energy density stems from the electrochemical process involving zinc metal deposition. Zn/Br_2-RFBs generally operate with a cell voltage around 1.9 V. While specific power densities can vary, they are generally considered moderate. These batteries can achieve a cycle life of a few thousand cycles, not as extensive as V-RFBs. Zn/Br_2-RFBs present a viable option for applications prioritizing higher energy density within the RFB landscape.

SWOT analysis – A summary of Zn/Br_2-RFBs' strengths, weaknesses, potential threats, and opportunities is presented in Figure 34. A detailed discussion of these aspects is presented in Appendix B.8. The main strength of Zn/Br_2-RFBs is the highest energy density among the RFBs for long-duration storage.



Zn/Br_2 REDOX FLOW BATTERIES

STRENGTHS

- Highest energy density of the RFBs
- Relatively low material cost (Zr and Br_2)
- Long cycle life
- Mature technology based on Zn/Br_2

WEAKNESSES

- Bromine management (volatile, hazardous and corrosive material; these traits are exacerbated at higher temperatures)
- Zn dendrite formation
- Self discharge

OPPORTUNITIES

- Growing demand for grid scale storage
- Improvement in Br_2 management could enhance safety and reduce cost

THREATS

- Competition from LIBs or other RFBs chemistries
- Safety concerns if Br_2 not managed well

Figure 34 SWOT analysis of Zn/Br_2-RFBs

2.1.5 Molten-salt batteries

Molten salt batteries are a class of rechargeable batteries based on molten salts as their electrolyte. Unlike the other battery technologies described in this report, molten salt batteries operate at high temperatures, typically between 100°C and 500°C. This high operating temperature allows for the use of electrode materials and chemical reactions that would be impractical or impossible at room temperature. The molten salt electrolyte provides high ionic conductivity, facilitating rapid charge and discharge rates.

Na-$NiCl_2$ batteries (SNCBs)

The first type of molten batteries described here are sodium-nickel chloride batteries (SNCBs), also known as Zebra batteries. First introduced in 1978 in South Africa, ZEBRA stands for Zeolite Battery Research Africa Project. These now have been used commercially for more than 25 years, showing good performance and reliability while being considered safe despite the high operating temperatures. Applications include uninterrupted power supply (UPS) and stationary energy storage.

Structure and materials – A schematic structure of a SNCBs is presented in Figure 35. Materials composing the main components of the system are described below.[44]

Cathode	Nickel chloride ($NiCl_2$). The current collector employs nickel plating over a copper core wire, offering good conductivity and corrosion resistance at the operating temperature.
Anode	Molten sodium metal Na^0. The current collector is made of nickel-coated stainless steel, providing a chemically compatible interface with the molten sodium.
Electrolyte	Sodium tetrachloroaluminate ($NaAlCl_4$), which has a melting point of 157°C and influences the optimal performance of battery, between 270 and 350°C, where it presents its higher conductivity, as well as minimal side reactions during operation.
Separator	A solid beta-alumina membrane, which acts as a selective sodium-ion conductor.

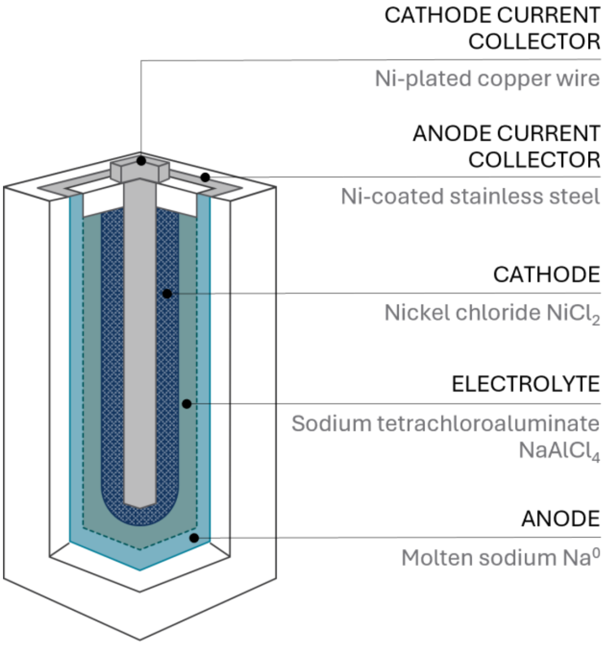


Figure 35 Schematic representation of the internal structure of a SNCB and materials used

Redox couples – SNCBs function through the reversible electrochemical reactions of sodium and nickel metals (Figure 36). They are assembled discharged, using nickel powder and sodium chloride to form, upon the first charge, the battery's active material nickel chloride ($NiCl_2$) at the cathode and sodium metal (Na^0) at the anode. During discharge, the sodium metal loses its electron to form a sodium cation (Na^+) that combines with a chloride ion from the molten bath. The electron travels through the external circuit to the cathode, reducing the nickel cation (Ni^{2+}) to plate a porous nickel (Ni^0) on the cathode. The charge balance of the cell is maintained by the migration of the sodium cations through membrane to the catholyte compartment. This process is reversed during the charging process.

The detailed chemical reactions are outlined in Equations 29-31 in Appendix A.9.

Redox-active additives such as Aluminium powder or iron sulfide can enhance the performance and longevity of SNCBs. Examples are given in Appendix A.9.

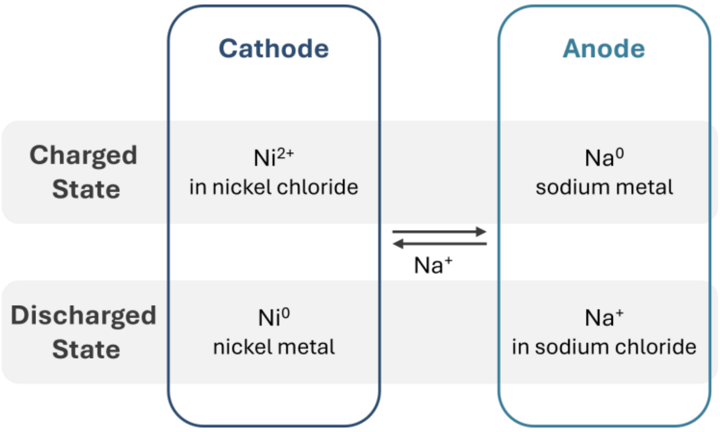


Figure 36 Redox couples involved in the charge and discharge states of SNCB electrodes

Form factors and battery types – SNCB cells are mainly found in prismatic shapes. Prismatic cells are well suited for modular assemblies as they allow for easy stacking. The modular arrangement of SNCB cells can be done in series or parallel to achieve the desired voltage and capacity of specific applications. SNCBs demonstrate resilience to overcharging and discharging with minimal impact on the cycle life. Therefore, if a cell within a parallel string fails, the remaining operational cells in that string can be overcharged to reach the desired voltage, effectively mitigating the impact of the failed cell. As chains typically incorporate 100-200 cells, the voltage loss associated with a single cell failure (approximately 2.6 V) can be compensated. The battery can maintain an effective operation even with 10% of cells failing.[44]

An internal heating system, usually electric, warms the battery to operating temperature. These systems maintain the batteries in a molten state, as reaching operating temperature from a solid state can take 12 to 24 hours.

Performance – SNCBs offer a performance profile, detailed in Figure 37, for grid-scale energy storage and other stationary applications. A single cell offers a nominal voltage of 2.6 V. Meanwhile, commercial assemblies can deliver in the range of 26-550 V.[45] While a cell energy density reaches 118 Wh/kg per cell, commercial systems include the weight of the battery management system (BMS) and peripheral equipment, lowering the value to 80-100 Wh/kg.[46] These batteries present a power density of 150-170 W/kg, highlighting the versatility of such BESS. They operate effectively within a wide ambient temperature range (-40°C to +70°C), with the internal optimum temperature ranging from 270°C to 350°C. SNCBs also demonstrate longevity, exceeding 4500 cycles (approximately 15 years of service).[47]

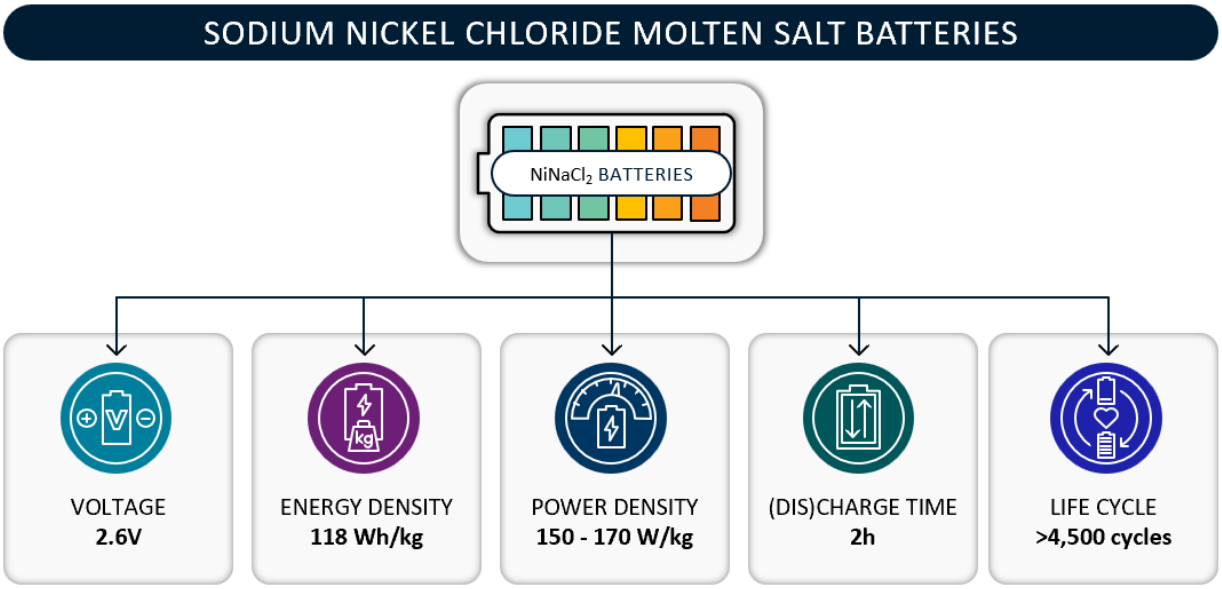


Figure 37 Key Performance Indicators of SNCBs

SWOT analysis – A summary of SNCB's strengths, weaknesses, potential threats, and opportunities is presented in Figure 38. A detailed discussion of these aspects is presented in Appendix B.9. The main strength of SNCBs is their longevity and robustness while containing abundant and relatively inexpensive materials.

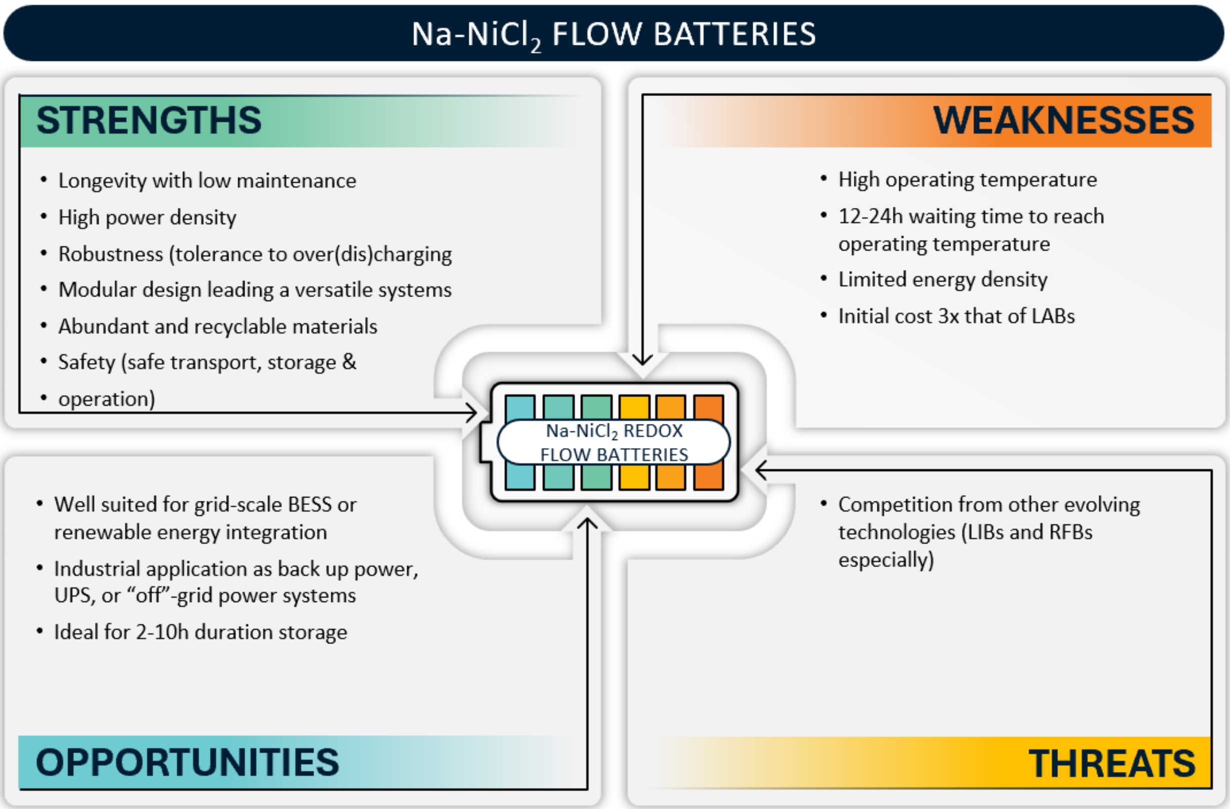


Figure 38 SWOT analysis of SNCBs

Sodium-sulfur batteries (Na-S)

Sodium-sulfur (Na-S) batteries are another type of high-temperature molten salt battery. Initially developed by the Ford Motor Company in the 1960s, Na-S batteries have been deployed commercially for decades, demonstrating high energy density and long cycle life. High operating temperatures make them well-suited for large-scale stationary applications such as grid energy storage, helping to balance supply and demand of electricity.

Structure and materials – A schematic structure of a Na-S batteries is presented in Figure 39, along with the materials composing the main components of the system described below.[48]

Cathode	Molten sulfur, often contained within a porous carbon or graphite matrix to enhance electrical conductivity and provide space for volume changes during charge/discharge. The current collector is usually made of materials like graphite or molybdenum.
Anode	Molten sodium. The current collector is usually made of materials like graphite or molybdenum.
Separator	A solid beta-alumina ceramic electrolyte selectively conducts sodium-ions. This ceramic material is essential for preventing the direct mixing of the highly reactive sodium and sulfur.

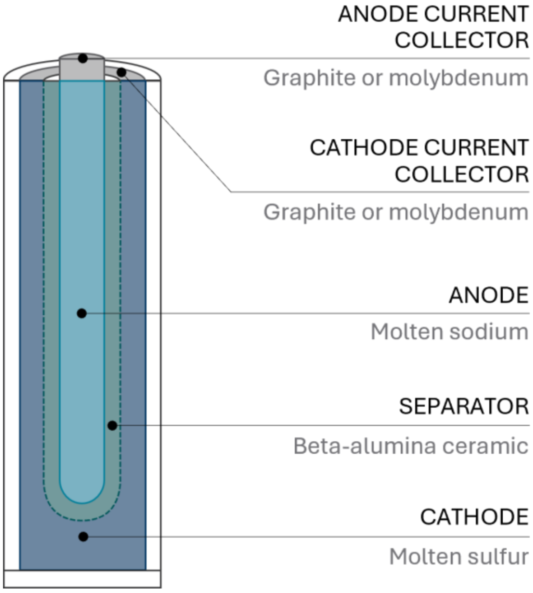


Figure 39 Schematic representation of the internal structure of a Na-S battery and materials used

Redox couples – Na-S batteries operate through the reversible oxidation/reduction of sodium metal and elemental sulfur. As summarised in Figure 40, when fully charged, the active materials are a molten sulfur bath at the cathode and molten sodium metal at the anode. During discharge, the sodium metal loses its electron to form a sodium cation (Na^+) that is released to the molten bath. The electron travels through the external circuit to the cathode to reduce elemental sulfur (S^0) to different polysulfide ions (S^{2-}, S_2^{2-} S_x^{2-}). The charge balance of the cell is maintained through the migration of the sodium cations through a membrane to the catholyte compartment. This process is reversed during the charging process.

The formation of the polysulfides is a complex process and influenced by multiple interdependent parameters intrinsic to the battery (such as the electrolyte or electrode material) or linked to the operating conditions (temperature, cycling, etc.).

The detailed chemical reactions are outlined in Equations 33-37 in Appendix A.10.

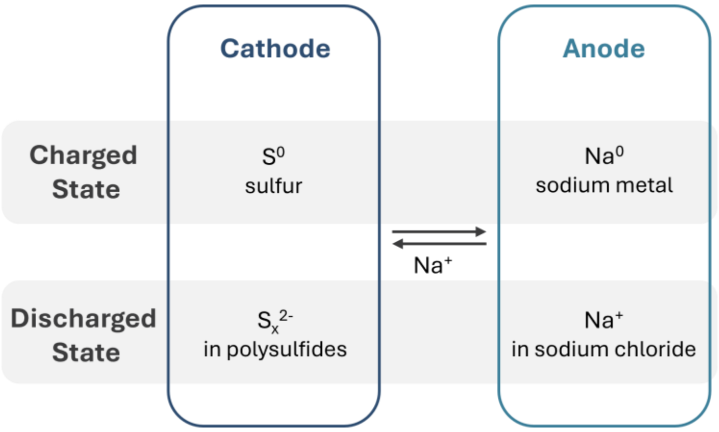


Figure 40 Redox couples involved in the charge and discharge states of Na-S battery electrodes

Form factors and battery types – Na-S batteries are typically manufactured in a cylindrical cell design. The cell casing is usually made of steel due to its high temperature resistance and mechanical strength, often with internal coatings to resist corrosion from the molten reactants. This form factor offers several advantages, including high energy density and efficient packaging, making them suitable for large-scale energy storage applications. In a similar way to the previously described SNCBs, the cylindrical/tubular cells can be easily integrated into various battery pack configurations, allowing for scalability and flexibility in meeting specific energy storage requirements. This modular approach enables the construction of large-scale battery systems by connecting multiple cylindrical cells in series and parallel arrangements to achieve the desired voltage and capacity. Na-S batteries are initially heated to reach a molten state in the same way than SNCBs.

Performance – Na-S batteries perform well in large-scale energy storage applications (Figure 41). They offer a nominal cell voltage of 2.0 V while reaching an energy density of 220 Wh/kg. Real device power density is reported at 36 W/kg by their manufacturer NGK; however, conceptual designs can reach hundreds of W/kg. These batteries operate within an optimal internal operating temperature of 300-340°C. As per their molten salt analogue presented above, they demonstrate a longevity typically exceeding 7,300 cycles, translating to an estimated lifespan of approximately 20 years.[49]

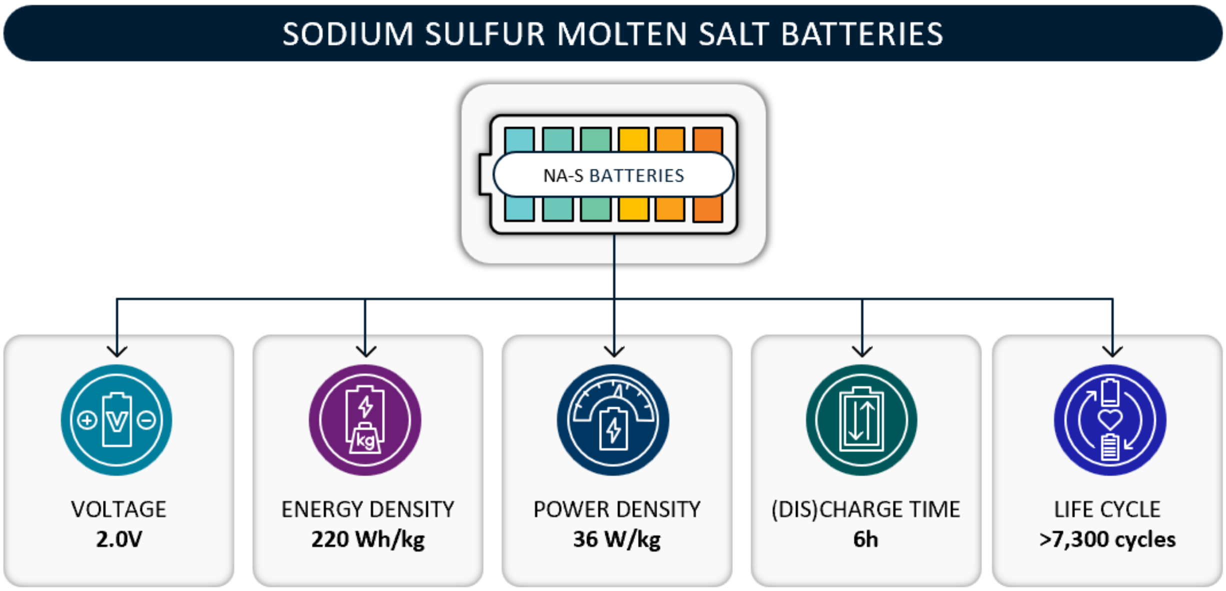


Figure 41 Key Performance Indicators of Na-S batteries

SWOT analysis – A summary of Na-S batteries' strengths, weaknesses, potential threats, and opportunities is presented in Figure 42. A detailed discussion of these aspects is presented in Appendix B.10. The main strength of Na-S batteries is their suitability for large ESS based on abundant and relatively inexpensive materials.

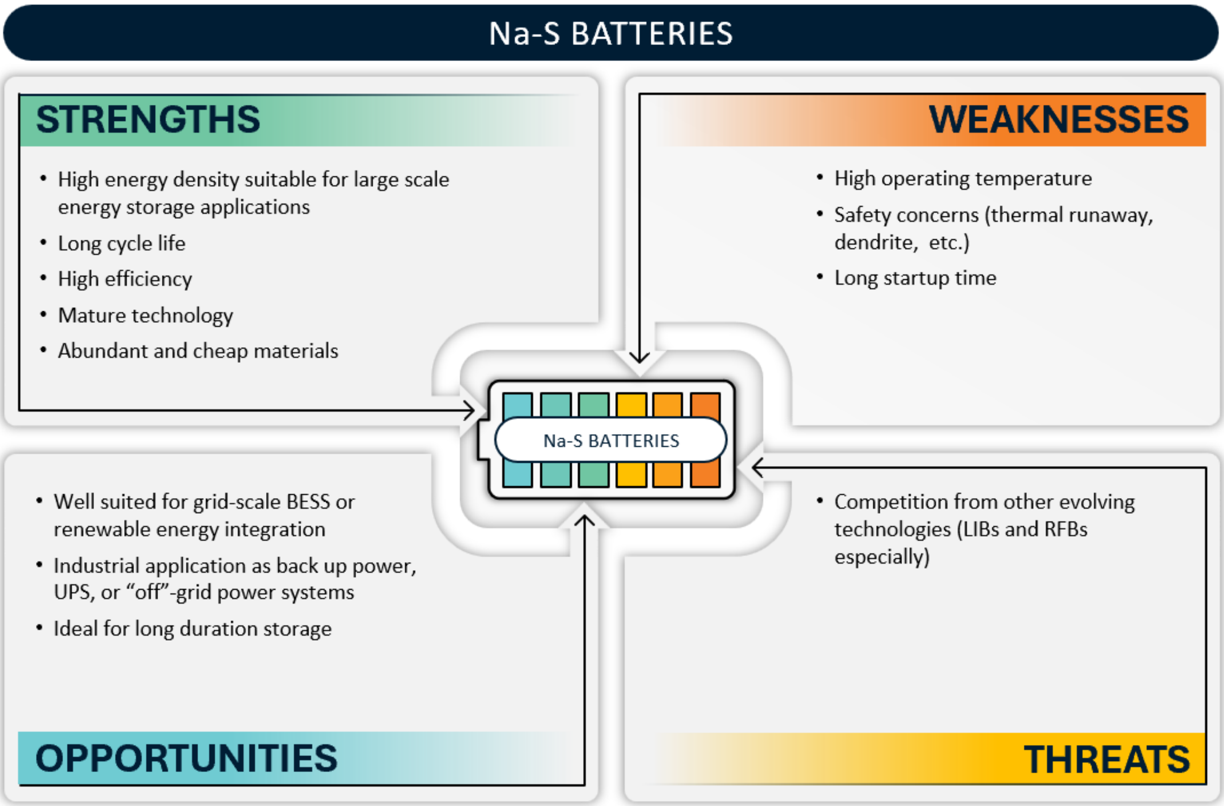


Figure 42 SWOT analysis of Na-S batteries

2.1.6 Metal-air batteries

Metal-air (M-air) batteries are a class of electrochemical energy storage devices using a metal M as the anode and oxygen from the air as the cathode reactant. While in the previously described battery chemistries all reactants were contained inside the battery case, M-air batteries ‘breathe’ oxygen from the surrounding air, which significantly reduces the weight and volume of the battery, leading to record high theoretical energy densities. Such high energy densities make them attractive for applications requiring long runtimes or lightweight energy storage solutions. While various metal-air battery systems are under development, iron-air batteries are the only chemistry that has been commercialised. It is worth noting that the zinc-air system, which was commercialised many years ago for applications such as hearing aids, is only available in the form of primary cells; in other words, they are non-rechargeable.

Iron-air batteries (Fe-air)

The iron-air battery chemistry has a lengthy history, from a time when many battery chemistries were being investigated. Interest was rekindled recently in the context of the growing need for affordable and safe forms of large-scale (stationary) electrical energy storage. Form Energy is currently the only manufacturer of Fe-air batteries.

Structure and materials – A schematic representation of the internal structure of a Fe-air battery is presented in Figure 43, along with materials composing the main components of the system described below.[50,51]

Cathode	Oxygen from the air, which is reduced within a porous host (typically carbon-based) in the presence of a catalyst, often a noble metal, and collected by a nickel mesh current collector.
Anode	Elemental iron, which is either made porous (e.g., via iron carbonyl decomposition) or formed as a composite with conductive carbon to accommodate expansion during discharge and achieve reasonable capacity, connected to a steel mesh current collector.
Electrolyte	An aqueous potassium hydroxide (KOH) solution. Although no commercial data seem to be available, published research estimates a concentration of 6 M.
Separator	Porous polytetrafluoroethylene (PTFE).

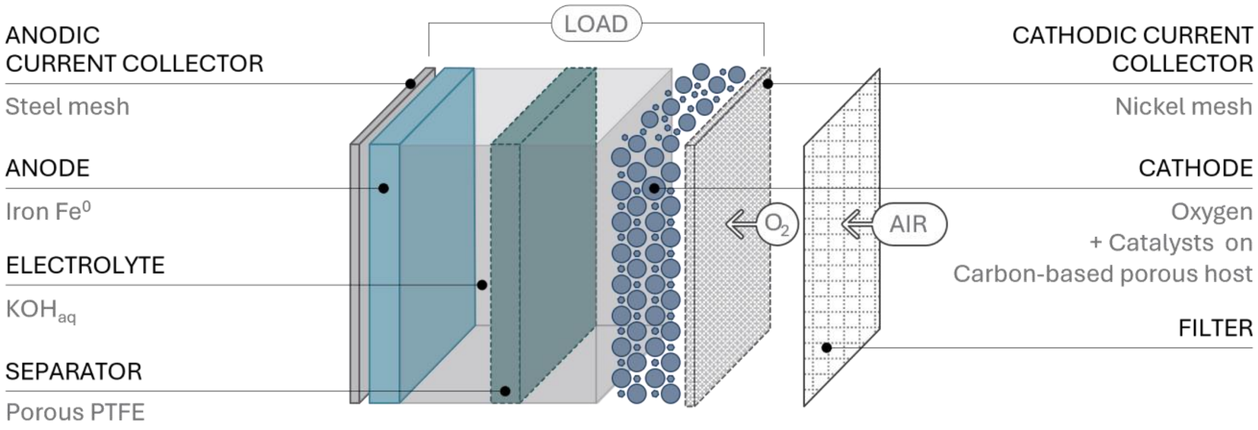


Figure 43 Schematic representation of the internal structure of a Fe-air battery and materials used

Redox couples – Fe-air secondary batteries are based on a reversible rusting process using the oxygen of the air as a redox species. As depicted in Figure 44, when fully charged, the active materials are oxygen gas (O_2^0) at the cathode and iron metal (Fe^0) at the anode. The oxygen is supplied either in pure form or filtered from ambient air composition. During discharge, the iron metal loses electrons to form iron oxide species (rust) and consumes a hydroxide ion (OH^-) from the electrolyte. The electrons travel through the external circuit to an oxygen/air breathing cathode where they are used to reduce the oxygen molecules to produce a hydroxide ion. This process is reversed during the charging process. Meanwhile, hydroxide ions move between the anode and cathode compartments to maintain charge balance.

The electrochemical processes at the cathode and anode are complex and some require noble metal catalysts to enhance the rates (make them faster) or optimise the products.

The detailed chemical reactions and discussions are outlined in Equations 38-43 in Appendix A.11.

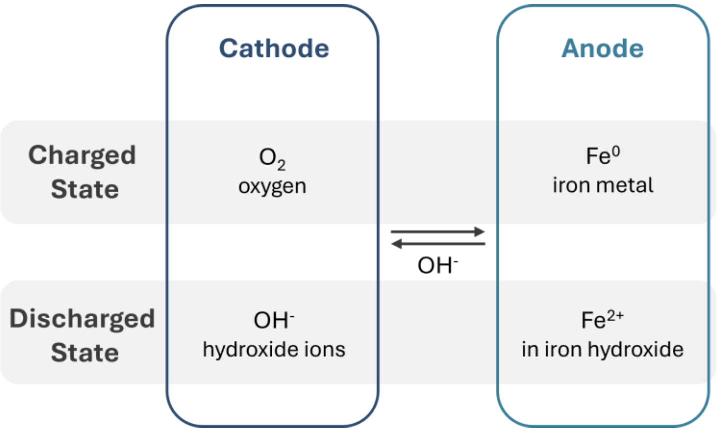


Figure 44 Redox couples involved in the charge and discharge states of Fe-air battery electrodes

Form factors and battery types – At the time of publication of this report, iron-air cells are found in a prismatic form factor and are manufactured by Form Energy only as a modular, scalable storage system.[52] Each battery module, reported to be roughly the size of a side-by-side washer and dryer, contains a stack of approximately 51 cells. These modules are then grouped within environmentally protected enclosures. Hundreds of these enclosures are further combined to form modular megawatt-scale power blocks. Depending on the system size, tens to hundreds of these power blocks can be connected to the grid.

Performance – To describe the performance of iron-air batteries, it is important to note that iron-air battery technology is still very recent, with limited commercial availability and primarily designed for the specific application of complementing lithium-ion batteries in large-scale energy storage systems. Iron-air batteries present a nominal cell voltage of 1.3 V. While the theoretical energy density reaches 1,230 Wh/kg (based on the mass of iron only), and actual device-based values are hard to find, it is estimated that commercial devices could be around 120 Wh/kg, with a power density of 40 W/kg.[53] Operating temperature range is expected to be similar to Ni-MH batteries, but specific details are still to be determined. Cycle life is estimated to be between 200 and 1000 cycles.

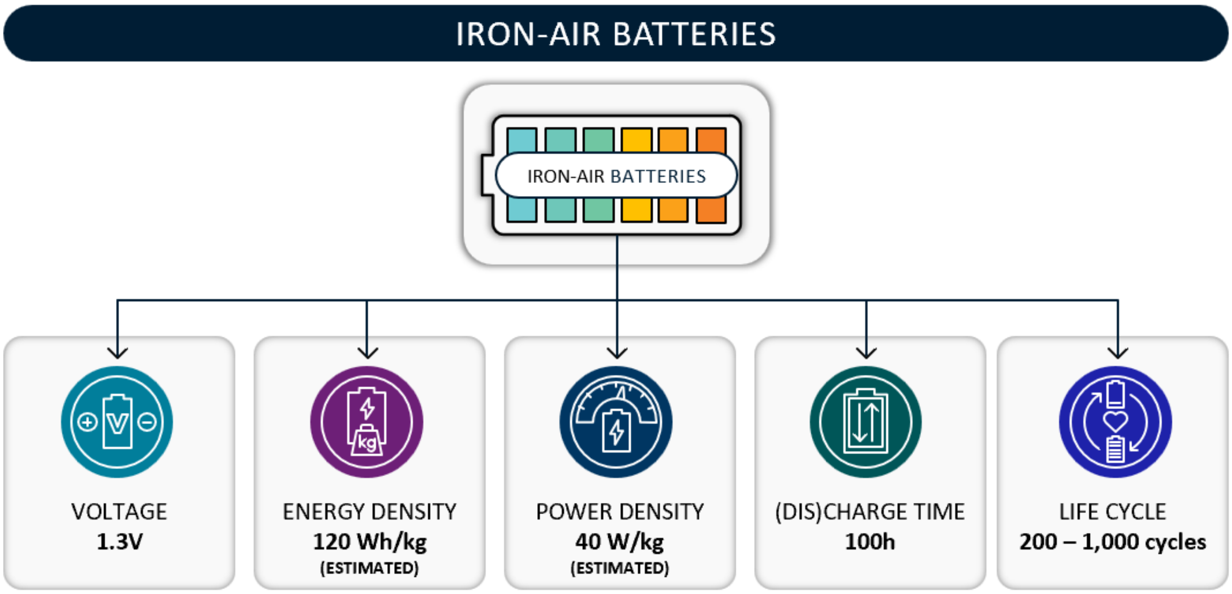
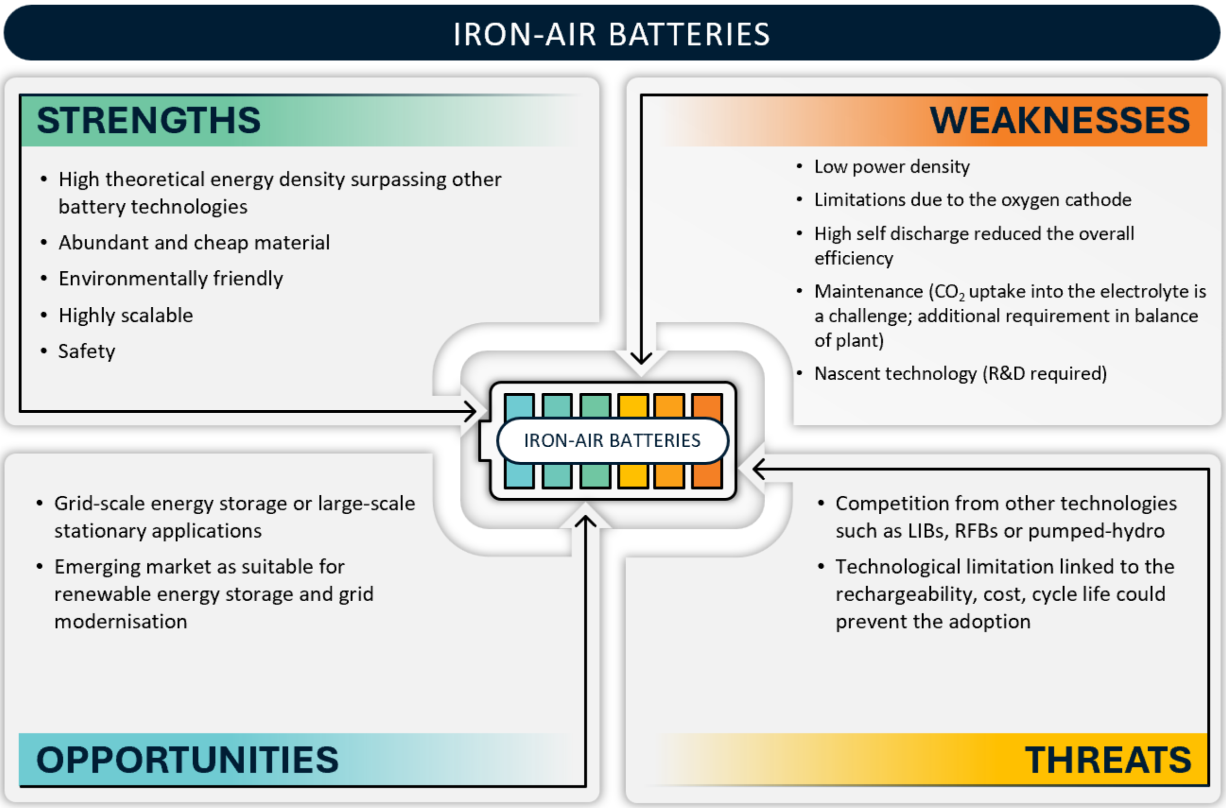


Figure 45 Key Performance Indicators of Fe-air batteries

SWOT analysis – A summary of Fe-air battery strengths, weaknesses, potential threats, and opportunities is presented in Figure 46. A detailed discussion of these aspects is presented in Appendix B.11. The main strength of Fe-air batteries could reside in their high energy density in systems containing abundant and inexpensive material.


IRON-AIR BATTERIES

STRENGTHS

- High theoretical energy density surpassing other battery technologies
- Abundant and cheap material
- Environmentally friendly
- Highly scalable
- Safety

WEAKNESSES

- Low power density
- Limitations due to the oxygen cathode
- High self discharge reduced the overall efficiency
- Maintenance (CO_2 uptake into the electrolyte is a challenge; additional requirement in balance of plant)
- Nascent technology (R&D required)

OPPORTUNITIES

- Grid-scale energy storage or large-scale stationary applications
- Emerging market as suitable for renewable energy storage and grid modernisation

THREATS

- Competition from other technologies such as LIBs, RFBs or pumped-hydro
- Technological limitation linked to the rechargeability, cost, cycle life could prevent the adoption

Figure 46 SWOT analysis of Fe-air batteries

Lithium-air batteries (Li-air)

Li-air is the only battery chemistry reported here that is not currently commercialised. However, they are worth noting because of their exceptionally high theoretical values of energy density despite also being the chemistry that poses the most research and development challenges.

Structure and materials – A schematic representation of the internal structure of a Li-air batteries is presented in Figure 47, along with the materials composing the main components of the system described below.[54,55]

Cathode	Porous conductive host, typically various forms of carbon, along with lighter metals such as nickel in a porous foam structure. This high porosity is required to accommodate the gaseous reactant and solid discharge product. The cathode current collector is a metal mesh, often nickel or stainless steel, which supports the porous host material.
Anode	Lithium metal, either in foil form or as an electrodeposited film. The anode current collector is typically copper, chosen for its proven suitability as a host for lithium plating despite its relatively higher cost.
Electrolyte	Either aqueous, with a preference for basic electrolytes like LiOH, or non-aqueous, where ethers are commonly used due to their compatibility with reversible lithium electrochemistry.
Separator	A multicomponent microporous membrane with a gas barrier, designed to prevent the diffusion of oxygen, carbon dioxide, and water to the lithium anode.

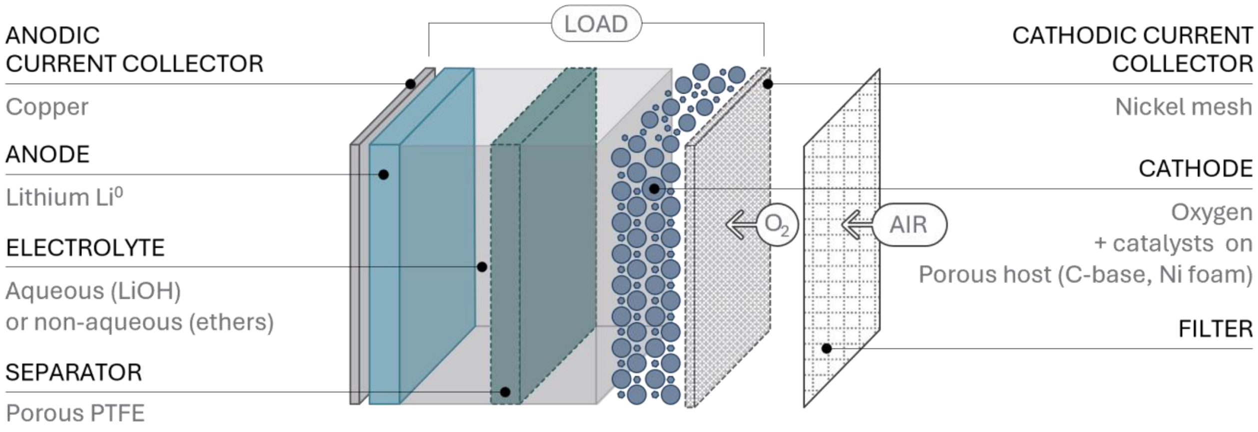


Figure 47 Schematic representation of the internal structure of a Li-air battery and materials used

Redox couples – Li-air batteries are based on the reversible oxidation/reduction of lithium metal by oxygen supplied via an air breathing cathode. As illustrated Figure 48, when fully charged, the active materials are oxygen gas (O_2^0) at the cathode and lithium metal (Li^0) at the anode. The oxygen is supplied either in pure form or ambient air composition. During discharge, the lithium metal loses an electron to release a soluble lithium cation (Li^+) to the electrolyte. The electron travel through the external circuit to an oxygen/air breathing cathode where it is used to reduce oxygen molecules and produce different forms of lithium oxides (Li_2O, Li_2O_2). This process is reversed during the charging process. The cell charge balance is maintained by the transport of the lithium cation (Li^+) across the membrane.

The detailed chemical reactions and discussions are outlined in Equations 44-47 in Appendix A.12.

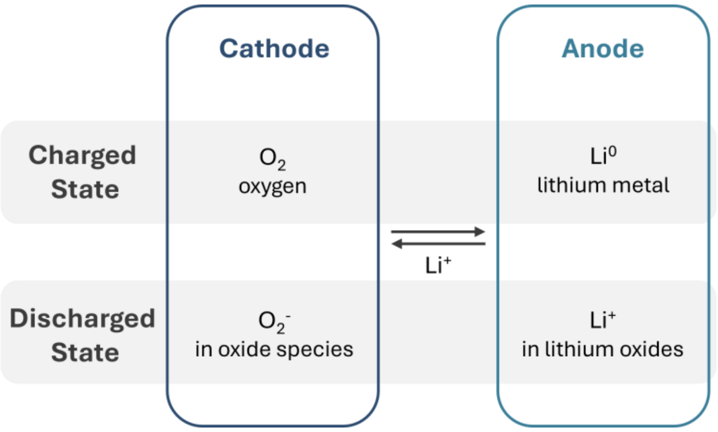


Figure 48 Redox couples involved in the charge and discharge states of Li-air battery electrodes

Performance – Li-air batteries are technologies still under development, hence, many of the KPIs described in this report for other battery chemistries are unavailable. The metrics discussed herein come from academic research, offering a glimpse into the potential of this exciting technology.

Theoretically, a non-aqueous Li-air battery can operate at a voltage of 3.0 V, promising an impressive theoretical energy density of 3,450 Wh/kg, calculated based on the mass of the lithium peroxide produced. This is roughly a third of the energy density obtainable through burning of a fossil fuel. While this figure will likely remain elusive, researchers have achieved energy densities of up to 1000 Wh/kg in laboratory settings, over several cycles. Power density, on the other hand, is harder to determine. Given the likely limitations of the organic electrolytes currently employed, it should be similar to that of LIBs, typically in the range of hundreds of W/kg. The operating temperature range is expected to be close to that of LIBs, given the reliance on organic electrolytes. Most cycle life studies report poor cycling performance, as hundreds of cycles are only typically achieved while operating the battery at very low utilisation levels (in other words, low energy density).

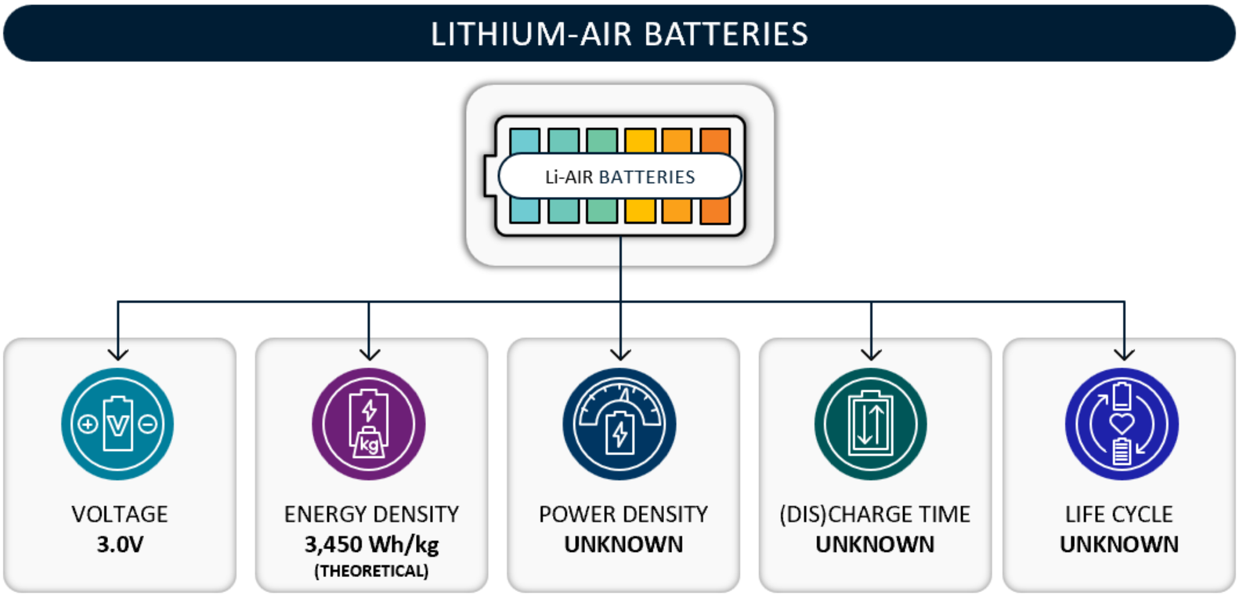


Figure 49 Key Performance Indicators of Li-air batteries

SWOT analysis – A summary of Li-air battery strengths, weaknesses, potential threats, and opportunities is presented in Figure 50. A detailed discussion of these aspects is presented in Appendix B.12. The main strength of Li-air batteries could be their extremely high energy density.

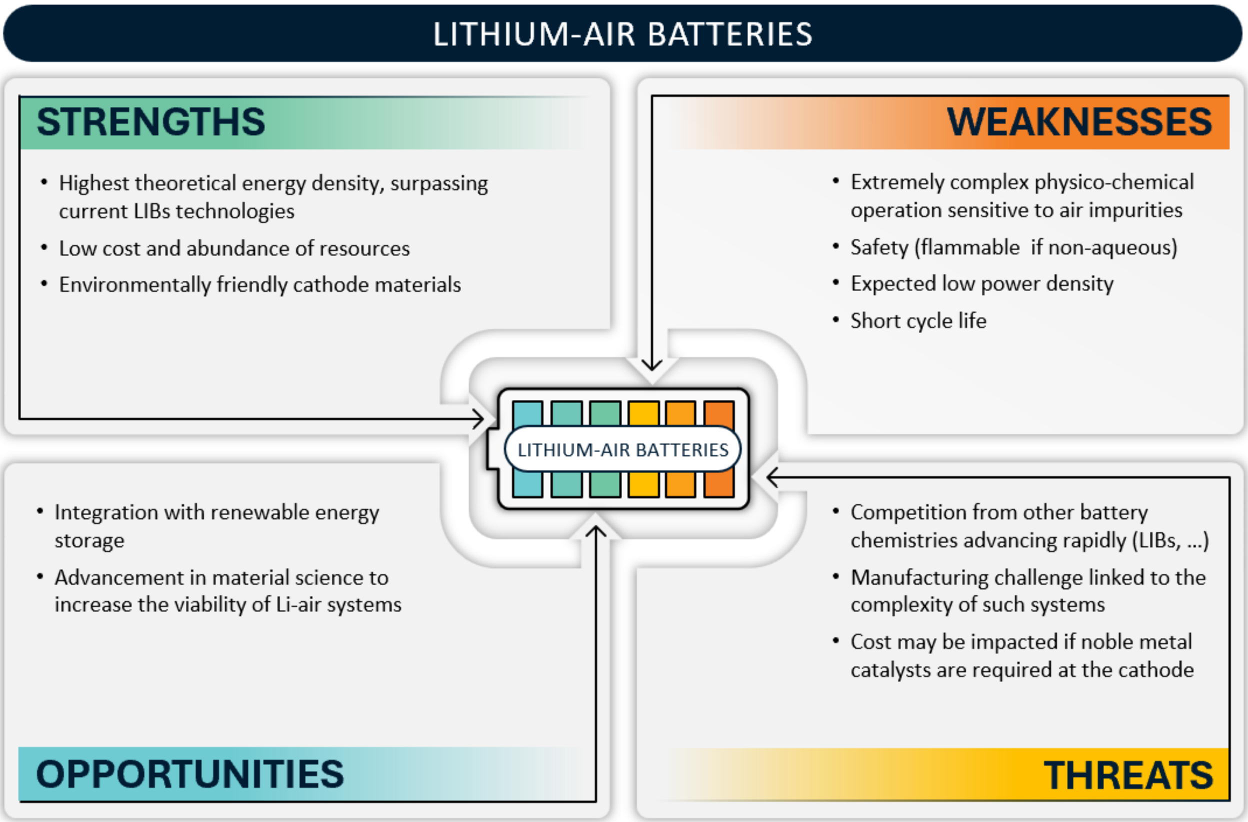


Figure 50 SWOT analysis of Li-air batteries

2.2 Commercial Viability

2.2.1 Technology readiness level and commercial readiness index

Technology readiness level (TRL) and commercial readiness index (CRI) are commonly used to describe a technology's maturity and potential for market success, respectively.

The TRL is a 9-level scale developed by NASA, progressing from basic research to full-scale system demonstration (Figure 51). Although the maturity is described at each level, they are usually grouped and described as 3 blocks or horizons:

- **TRL 1-3:** Basic research and early concepts (Research)
- **TRL 4-6:** Technology validation and demonstration (Development)
- **TRL 7-9:** System demonstration (Deployment).

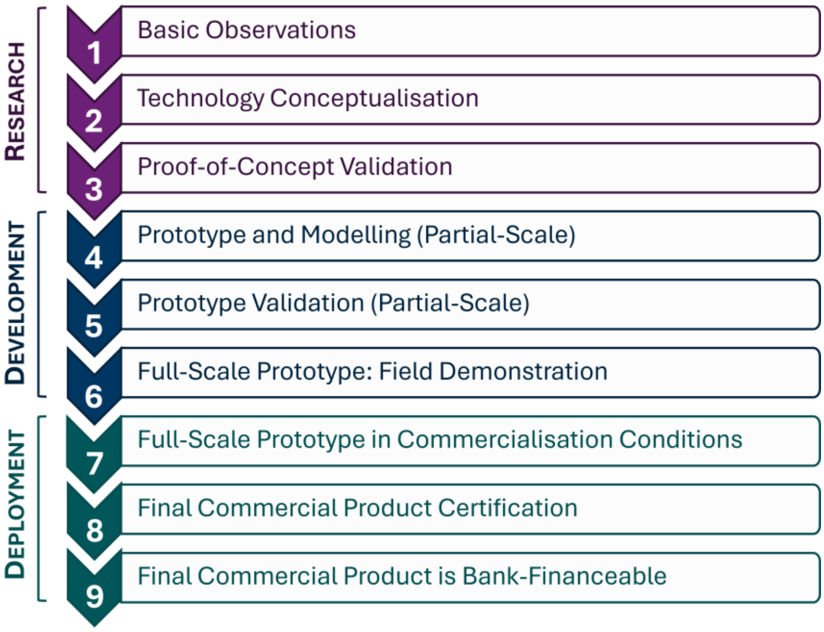


Figure 51 TRL Scale, reflecting the maturity of a technology

Despite the TRL being a good benchmarking tool to assess technological risk, significant commercial uncertainties remain during the deployment and commercialisation process of new technologies. This includes, for example, the competition from other technologies targeting the same needs or the need of a high initial cost investment.[56] The CRI is therefore a multi-faceted index evaluating the commercial viability of a technology, considering factors like market demand, economic feasibility, and environmental impact. A higher CRI indicates greater readiness for market adoption.

The TRL and CRI markers for the chemistries described in this report can be found in Figure 52. Overall, this analysis allows for the identification of 4 groups translating the level of maturity of the chemistries described in this report: emerging, developing, mature and declining, illustrated by the coloured symbols in Figure 52.

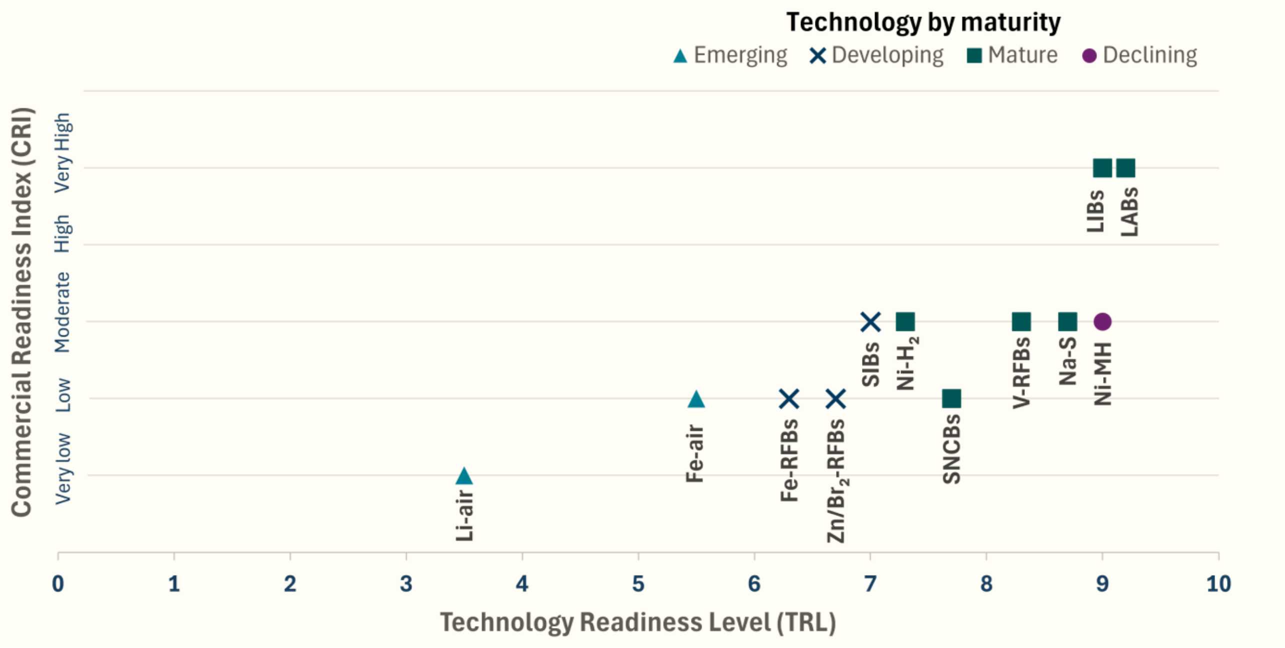


Figure 52 TRL, CRI and level of maturity of the chemistries presented in this report

The battery landscape is constantly evolving, with new chemistries emerging and existing technologies improving. While LIBs currently dominate, the need for higher energy density, lower cost, long-duration storage and improved sustainability is driving research and development in various directions. The TRL and CRI frameworks provide valuable dynamic insights into the maturity and commercial potential of different battery chemistries.

2.2.2 Scale of application

To effectively evaluate the potential of different battery technologies, this section covers their optimal application areas and assesses their current scale of deployment.

Optimal applications

Each battery chemistry and design are carefully tailored to specific applications, with no ‘one-size-fits-all’ solution. Factors such as energy density, power output, cycle life, safety, and cost all play significant roles in determining the most suitable battery for a particular application. It is essential to understand that finding the ‘perfect’ battery is about compromising, as optimising one metric usually negatively affects another.

All batteries described in this report are considered for renewable energy storage, even if their initial optimal applications are not for distributed energy storage. Table 2 lists their optimal applications and performance notes that may be useful in specific distributed energy storage scenarios.

Table 2 Optimal application and performance notes for the battery chemistries of this report

BATTERY CHEMISTRY	OPTIMAL APPLICATIONS	NOTES
LABs	• Automotive starting systems • Motive power equipment like forklifts and golf carts • Uninterruptible power supplies (UPS)	Energy density is relatively low but find limited use in some grid storage applications. Currently the largest production volume of any battery chemistry.
LIBs	• Portable electronics such as smartphones and laptops • Electric vehicles • Grid storage applications	The most versatile and commercialised distributed ESS currently.
SIBs	• Large-scale grid storage applications	Lower cost and abundant raw materials make them a potential cost-effective alternative to LIBs for certain grid storage applications.
Ni-MH batteries	• Hybrid electric vehicles	Offer a balance of performance and cost. Market shares slowly decreasing due to the energy density and performance advantages of LIBs.
Ni-H_2 batteries	• Niche aerospace applications	High energy density and long cycle life.
All RFBs	• Long-duration energy storage applications • Grid storage projects	High efficiency and long cycle life.
Molten-salt batteries	• Specific grid storage scenarios, particularly for peak shaving and load leveling	High operating temperatures and specialised infrastructure requirements limit wider adoption.
All M-air batteries	• Promise for large-scale grid storage	High theoretical energy density and potential for low cost. Challenges related to the development of efficient oxygen cathode and cycle life require significant R&D.

Scale of development for renewable energy integration

Stationary energy storage systems play a fundamental role in integrating renewable energy sources into the grid, improving grid reliability and enhancing energy efficiency, even at the consumer end of the energy chain. This section examines the scale of deployment and suitability of various battery chemistries for grid-connected applications.

Four categories of consumer-centred stationary energy storage systems are considered in this section (Figure 53):

- **Residential** describes situations where each household is generating and storing renewable electricity individually. The capacity required is typically 5-20 kWh for individual households.
- **Community** is an extension of the residential situation where multiple households, each equipped with their own solar panel installation, share a central BESS for backup power

supply. The capacity required by a community depends on its size but is estimated around 50-500 kWh.

- **Commercial** describes a micro-grid system where renewable power is generated and stored at a large-scale central facility. Power is delivered to the community on commercial terms. The capacity required ranges from tens of kWh to several MWh.
- **Industrial** large-scale renewable generation and storage facility designed to serve a single industry user. These have the largest capacity requirement, ranging from hundreds of KWh to tens of MWh or even larger depending on the industry's energy demands, production processes, and grid reliability requirements.

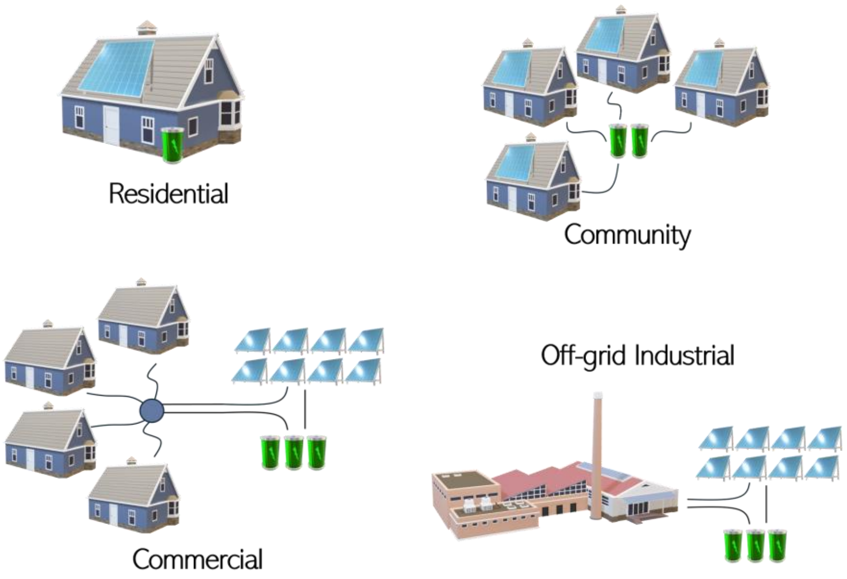


Figure 53 Scale of consumer-centred BESS

All the battery chemistries discussed in this report can technically contribute to grid stability by providing grid services such as frequency regulation, voltage support, and peak shaving. The specific application of a technology/chemistry for a specific market segment is based on performance drivers such as cost, energy density and power density, lifespan and cycle life, safety, and environmental impact. More detail about these factors can be found in Appendix section C.1.

These considerations led to the categorisation presented in Table 3.

Table 3 Dominant and possible chemistries in different market segmentations

APPLICATION	DOMINANT CHEMISTRY TYPE	OTHER CHEMISTRIES USED
Residential	LIBs dominate the residential energy storage market due to their high energy density, fast charging, and declining costs, allowing homeowners to store excess solar energy and reduce reliance on the grid.	• While LABs were historically used, their lower energy density and shorter lifespan limit their suitability • Emerging SIBs show great promise to reduce even further the cost of home storage in the future • Other technologies, such as Ni-MH, Ni-H_2, and RFBs, are generally less suitable for residential applications due to higher costs, lower energy density, or technical challenges
Community	While LIBs dominate community applications, V-RFBs can be suitable for the largest community systems due to their long lifespan and high efficiency, though initial costs may be higher.	• LABs may have limited applications in specific community scenarios, such as backup power for essential services • Other chemistries find limited application at this scale due to cost and complexity
Commercial	LIBs lead here again the sector of commercial applications, enabling peak shaving, demand charge reduction, and grid support services.	• V-RFBs are increasingly used in microgrids due to their long lifespan and high efficiency • Emerging Fe-RFBs and Zn/Br_2-RFBs also show great promises for such commercial applications based on whether a cost-effective or high-density solution is required, respectively • While LABs are still used for backup power, their role is decreasing • Other technologies, such as Ni-MH, Ni-H_2, SNCBs, Na-S, and M-air batteries, have limited commercial application due to high costs or technical challenges
Industrial	LIBs are the predominant type of battery used in an industrial context.	• For large-scale deployments, a diverse portfolio of battery chemistries can offer significant advantages. This helps match the application needed by the industrial activities or the profile of the energy demand • For example, fast response will be best provided by LIBs, while RFBs will ensure a long-term storage (overnight or seasonal variations) • There are strategic challenges to consider in a mix of chemistries as integrating different chemistries into a single system can increase the complexity of the management or the maintenance. Some companies offer a tailored design using carefully designed algorithms to precisely map the energy demand of the system[57]

Implementing Distributed BESS in a Tropical Climate: Case Study 1 – Puerto Rico[58]

Location: Adjuntas, Puerto Rico (30 - 50 km from coastline).

Puerto Rico, with a land area of 8,900 km², is roughly equivalent in size to the combined area of Kuala Lumpur, Selangor, and Putrajaya, collectively known as Greater Kuala Lumpur. Its main island, which is 180 km east to west, is equivalent to the distance between coastal town of Mersing on the East Coast to another coastal town of Batu Pahat on the West Coast of Peninsular Malaysia.

Climate: Puerto Rico has a tropical marine and rainforest climate, characterised by year-round sunny, hot, and humid conditions, with an average humidity of around 80%. Temperatures typically reach around 30°C in lower elevations and 21°C in mountainous areas, with daily solar irradiance of about 5.53 kW/m² (similar to Malaysia). The island is prone to hurricanes and earthquakes, with an average annual rainfall of approximately 1,500 mm.

Capacity:

1999: Initial system – 45 power photovoltaic panels, total 13.05 kW capacity, 850 kWh battery energy storage (presumed lead-acid batteries)

2020: Microgrid project – 2,000 solar panels, 900 kW capacity, 850 kWh energy storage

Planned expansion – 1 MW storage using second-life EV batteries storage (presumed lithium-ion batteries)

Purpose:

- Provide a resilient, community-based electricity supply independent of the centralised grid
- Ensure access to power for critical needs (e.g., medical equipment, communications)
- Promote local self-sufficiency and energy security

Challenges:

- Centralised power grid failures due to hurricanes and earthquakes
- Slow response from government agencies
- Geographic constraints (mountainous terrain), making power restoration slow
- Socioeconomic disparities in energy access

Solution:

- Transition to solar-powered microgrid for community resilience
- Community-driven approach with local leadership and knowledge-sharing
- Partnerships with external organizations
- Distribution of solar lanterns and essential energy supplies

Outcome:

- Significant reduction in reliance on fossil fuels
- Over 60 homes fully solar powered
- Solarised critical infrastructure (fire station, emergency response unit, senior home, businesses)
- Reduced energy costs and improved disaster preparedness

Takeaways for Malaysia:

- Importance of decentralised, community-led renewable energy solutions
- Role of solar microgrids in enhancing disaster resilience
- Necessity of proactive investment in energy resilience rather than reactive disaster response
- Potential for integrating second-life EV batteries for energy storage
- Value of strong local leadership and education in sustainable energy transition

Implementing Distributed BESS in a Tropical Climate: Case Study 2 – Hawai’i[59]

Location: O’ahu, Hawai’i, USA (about 5 km from coastline).

Hawai’i, with a land area of 28,300 km², is roughly equivalent in size to the combined area of Selangor and Perak. Oʻahu is the third largest and most populated island of the Hawai’ian Islands. With a land area of 1,545 km², it is slightly smaller than the Malaysian state of Malacca (1,775 km²).

Climate: O’ahu, Hawai’i, has a tropical climate that is generally mild throughout the year, with 2 main seasons: dry and wet. Average daytime temperatures ranging from 24°C to 29°C with daily solar irradiance of about 5 to 6 kW/m², which is similar to Malaysia. O’ahu has moderate humidity with an average relative humidity of around 60-70%. There is substantial variation in rainfall: Honolulu and the leeward side of the island are relatively dry (500 - 750 mm), while the windward side can be quite wet, with an annual rainfall between 1300 - 2500 mm.

Capacity:

42 MW Solar PV with 42 MW (168 MWh) of battery energy storage systems on approximately 131 acres of underutilised Navy land

Purpose:

- Address the growing need for energy security on the island of O’ahu
- Deliver 42 MW of clean, renewable energy to the local grid
- Power 10,000 Hawaiian homes and support the state's renewable energy goals
- Stabilise energy costs and reduce the use of fossil fuels, while contributing to the state’s goal of achieving 100% renewable energy by 2045

Challenges:

- Centralised power grid failures because Hawai’i is prone to hurricanes, storms, and heavy rainfall
- Integrating the solar power generated into Hawai’i's electrical grid posed technical challenges
- The location of the project at a coastal site meant accounting for potential saltwater corrosion

Solution:

- Transition to solar-powered microgrid for community resilience
- Demand response programs to balance electricity supply and demand
- Use corrosion-resistant materials or coating and protective layers

Outcome:

- Reduce dependence on fossil fuels and create a pathway to increased energy independence
- Reduce 50,000+ tons of CO_2 annually from Hawai’i’s environment — the equivalent of offsetting emissions from 12,000 cars every year
- Provide energy security and stabilise cost of energy for Hawaiian Electric Co’s (HECO) customers
- Create local construction jobs and boost economy through purchase of local materials

Takeaways for Malaysia:

- Importance of decentralised energy systems – use of microgrids and distributed energy resources
- Role of solar microgrids in enhancing disaster resilience and leverage battery storage for grid stability
- Public-private partnerships and stakeholder engagement

2.2.3 Levelised cost of storage

The levelised cost of storage (LCoS) is a metric used to assess the cost effectiveness of different renewable energy storage technologies. It is defined as the sum of **all** costs per unit of energy delivered by a storage system throughout its lifetime. It is analogous to the levelised cost of energy (LCoE) which is more commonly used to compare the cost of renewable energy generation technologies, considering costs (operating and capital) and performance parameters. The approach has also been used to assess other technologies, such as hydrogen generation and carbon capture.

Drivers of LCoS:

The LCoS captures the total capital and operating costs of a system, adjusted for today's dollar value, and performance drivers such as the total energy inputs and total energy outputs in KWh. It is sensitive to other market and operational cost drivers such as the boundaries of the analysis, the storage duration and the utilisation rate.

Cost analysis boundaries

The term 'boundaries' refers to the scope of the analysis, specifically which cost and performance parameters are included and excluded. Typically, LCoS analysis focuses on the direct costs of storing and releasing electricity, excluding other electricity generation, transmission and distribution costs (Figure 54). This approach enables an analysis that is agnostic to the power generation source (hydro, solar, wind or other) and the distance between the power generation, storage and utilisation points.

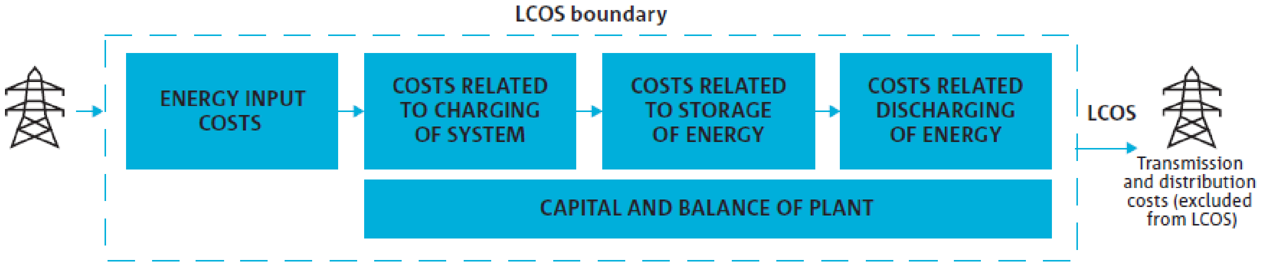


Figure 54 LCoS boundaries

Source: CSIRO Renewable Energy Storage Roadmap, 2023[60]

For electrochemical storage, the in-boundary components include the electricity input, the energy storage components (cells, tanks, etc.), and the electrical/electronic components supporting the systems (inverters, transformers, and battery management systems).

Cost drivers

- **Power capital cost**: reflects the capital cost of the components for charging and discharging the system, expressed in dollar per unit of power ($/kW, $/MW, etc.). The inverters and the transmission lines required to transfer electricity into and out of the BESS system are examples of components included in the power capital cost.

- **Energy capital cost**: is the capital cost of the storage component of the system, expressed in dollar per unit of energy ($/kWh, $/MWh, etc). For a BESS system, the energy components are the batteries, supporting BMS, and additional infrastructure (such as pumps and tanks used for redox-flow systems).
- **Charging cost**: It is the cost of electricity needed to charge the system. It is calculated based on the required energy output, accounting for any losses incurred during the charge and discharge cycles. Such losses are described by the round-trip efficiency of the system, defined as the ratio of output energy to input energy. The charging cost is, therefore, the product of the unit cost of electricity, expressed in $/MWh or $/kWh, by the energy required to charge the system.
- **OPEX**: covers the recurring cost associated with the operation and maintenance of the system. In the CSIRO analysis,[60] this was calculated as a percentage of the total installed capital cost.

When comparing LCoS of different studies, it is important to ensure that the assumed asset lifespan and depreciation rates are clearly presented and well understood.

Storage duration

Storage duration is a critical factor to consider when comparing LCoS analysis of different technology options. Although the categories of storage duration are inconsistent in the literature, CSIRO's preferred definitions[60] are:

- **Short duration:** storage for 1-4 hours, which is typically used as network support, time shifting energy, defined as storing and distributing energy based on availability and demand, and helping avoid or defer transmission and distribution investment
- **Medium-duration**: storage for 4-12 hours to offer major grids the flexibility to manage imbalances between supply and demand, as well as support grid capacity
- **Long intraday:** Storage for 12-24 hours typically used for network support to stabilise day-to-day variation in electricity supply and the time shifting of energy to manage differences between peak variable renewable energy (VRE) generation and peak energy use times each day
- **Multiday:** storage for 24-100 hours and/or seasonal storage (> 100 hours) required to manage significant and long-term imbalances between electricity supply and demand, discussed earlier as seasonal storage. This is more critical for locations with significant variation in the availability of renewable energy sources throughout the year. It may be of less relevance to Malaysia because of the tropical climate.

Cycles and storage duration

LCoS analyses are typically based on specific assumptions related to annual cycles, which are also dependant on the storage duration. For example, short-duration applications would imply higher number of cycles, compared to the long-intraday storage scenario.

Table 4 shows the assumptions underpinning CSIRO's analysis, provided as a reference point only. Whilst these values are based on reliable renewable energy availability data and case studies from Australia's eastern states, they remain indicative values, providing useful insights for Malaysia. The optimal number of cycles are contingent upon local factors, including daylight duration and different weather patterns, which differ both within and across Australia.

Table 4 Number of cycles assumed for different durations of storage in Australia

Duration	Short (2 hours)	Medium (8 hours)	Long intraday (24 hours)	Multiday (48 hours)
Number of cycles	394	230 to 285	117	68

LCoS of battery energy storage systems

The sensitivity of the LCoS analysis to numerous variables has resulted in a high degree of discrepancy in reported values across technology and market studies, hindering direct comparison. LCoS data published in academic literature is also limited to mature technology options, such as LABs, LIBs and V-RFBs. Therefore, the following section presents a comparative analysis of different technology options, providing an indicative cost curve position (the relative position of a technology on a graph representing the cost versus output levels) for each technology within the specified application.

LIBs versus V-RFBs: the CSIRO Renewable Energy Storage Roadmap analysis

The CSIRO roadmap investigated 11 energy storage options in terms of their maturity, applications and costs, including 4 electrochemical storage systems: LIBs, V-RFBs, Zn/Br_2-RFBs and SIBs. However, the LCoS analysis was limited to the more mature systems that were considered a viable option for specific storage durations.

Figure 55 show the forecasted 2025 (left) and 2050 (right) LCoS of LIBs and V-RFBs under different usage scenarios. LIBs offer the lowest storage cost within the 8 hour-range. While still more expensive than LIBs, V-RFBs systems become increasingly competitive for 8-hour storage further in the future. Whilst this relative advantage strengthens with higher utilisation rates (higher number of cycles), neither option was found to be economically viable for storage duration exceeding 24 hours.

By 2050, the LCoS of both energy storage options is projected to nearly halve, with LIBs maintaining their competitive edge.

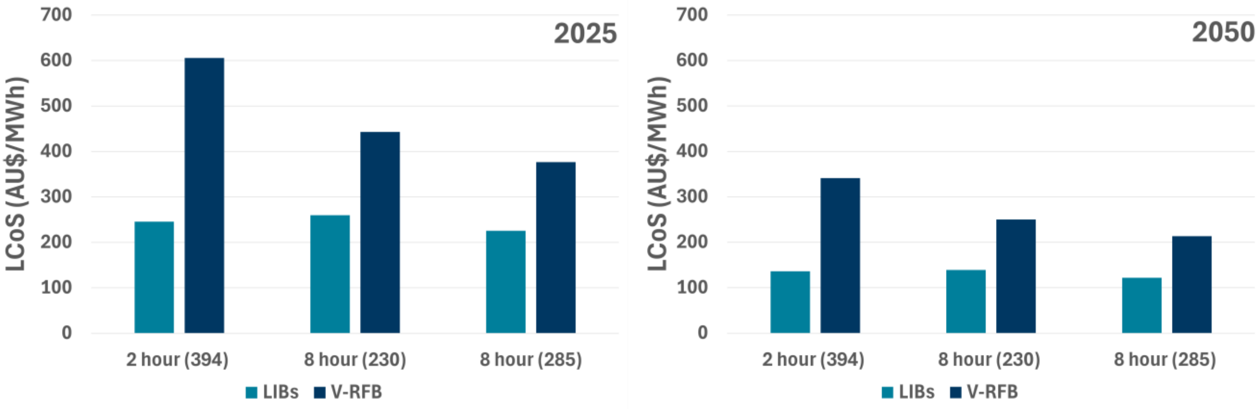


Figure 55 Forecasted LCoS of LIBs and V-RFBs in 2025 (left) and 2050 (right)

Source: CSIRO Renewable Energy Storage Roadmap, 2023[60]

LIBs versus V-RFBs versus LABs

For benchmarking purposes, Figure 56 shows the LCoS of LABs compared to that of LIBs and V-RFBs systems. It is important to note that these costs estimates are based on a different assumption than the CSIRO roadmap quoted above: they are reported in US$ and for 5,000 cycles per year at a discharge duration of 30 minutes.[61] Under these assumptions, LABs are the least favourable due to their lower energy density, slower charging time and limited scalability when compared to the other 2 candidates.

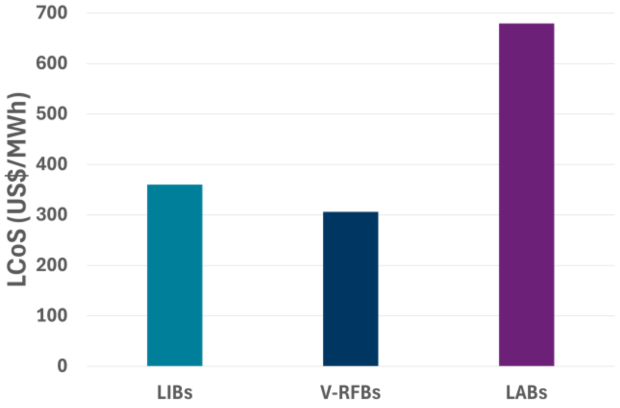


Figure 56 LCoS of LIBs, V-RFBs and LABs for a duration of 5,000 cycles per year at a discharge duration of 30 min

Source: data from Mugyema, et al. [61]

2.3 Sustainability

2.3.1 Operational risks

Each of the battery chemistries described above possess their own operational risks. Batteries of the same families share some risk, while others are inherent to the chemicals they contain.

Acidic electrolyte chemistries – For vented LABs (i.e. those that can be replenished with water), overcharging at high rates can expel a mist of acidic electrolyte which will cause corrosion in the immediate surroundings, as well as posing a hazard to people in the vicinity. In addition, the gas evolution that causes this misting is a mixture of oxygen and hydrogen, which occurs in the latter stages of charging. Given that such mixtures can explode in the presence of a source of ignition, battery enclosures must always be well ventilated. For sealed LABs, gas evolution is internally recombined so that acid release and the potential for hydrogen ignition are both removed. The internal recombination process does however generate heat. Hence, prolonged charging of sealed batteries at high rates can lead to uncontrolled heating of the battery. If unchecked, this will end with battery failure due to a combination of electrolyte loss and thermal damage. Finally, if the recommended operational procedure is not followed (typically leaving a battery for extended periods in a discharged state), the formation of relatively large lead sulfate crystals on the battery plates will occur, in a process known as 'sulfation'. In some cases, this can be irreversible such that the battery permanently loses a portion of its capacity.

Lithium-based chemistries – LIBs suffer from thermal runaway, a chain reaction where internal exothermic reactions lead to a rapid increase in temperature, potentially resulting in fire or explosion. The flammable nature of the non-aqueous electrolyte and the inherent risk of thermal runaway make LIBs a hazard. Damage to the battery casing can lead to the leakage of the electrolyte, which is both corrosive and flammable.

Sodium-ion batteries – This technology is still under development, and its long-term reliability and safety are yet to be fully understood. SIBs are generally considered safer than most LIBs, with thermal runaway characteristics intermediate between LFP and NCM lithium batteries.[62] However, as both battery types use similar working principles and flammable non-aqueous solvents, they present comparable safety challenges.

Alkaline chemistries – Similar to LABs, Ni-MH batteries also release hydrogen gas when overcharging, presenting a potential fire hazard.

High pressure systems – Ni-H_2 batteries operate at extremely high pressures, typically ranging from 80 to 200 bar. This requires the use of robust and meticulously designed containment systems to prevent leaks and explosions. The manufacturing process for these batteries is complex and involves the use of high-pressure tanks, which significantly contributes to their high cost. Similar venting systems are used in any battery chemistry generating gas as a side reaction.

Flow battery chemistries – Vanadium RFBs utilise concentrated sulfuric acid in the electrolyte, and hence share the same environmental risks of lead acid batteries as discussed above. On the other hand, bromine, in the electrolyte, is both toxic and corrosive, requiring stringent containment and handling procedures to prevent fumes exposure. Similar to V-RFBs, Zn/Br_2-RFBs exhibit self-discharge, resulting in energy loss over time.

High-temperature operating chemistries – SNCBs and Na-S batteries operate at high temperatures, typically exceeding 300°C. Hence, specialised materials and robust thermal management systems are used in those technologies. Maintaining the optimal operating temperature can be challenging, especially in environments with fluctuating ambient temperatures. In the case of Na-S batteries, the use of molten sodium introduces inherent safety risks, including the potential for fire and explosion in the event of leaks or accidents.

2.3.2 Environmental impact

Battery chemistries, while essential for the transition to a low-carbon future, present a range of environmental concerns throughout their lifecycle. This section provides an overview of the environmental factors, from mining raw material to the end-of-life management of used batteries.

Mining and raw material extraction – LIBs contain critical minerals that will face shortages in the coming years. Mining for lithium, cobalt, nickel, and other critical materials often involves open-pit mining, leading to habitat destruction, soil erosion, and dust generation. Water pollution can occur through the release of mining waste and chemicals into nearby water bodies. Furthermore, the refining process can release significant amounts of greenhouse gases and other pollutants into the atmosphere.

Lead mining for LABs and smelting processes generate substantial amounts of air and water pollution, including sulfur dioxide, lead dust, and heavy metals. The extraction of materials such as vanadium, zinc, and bromine for RFBs and other chemistries can also have significant environmental impacts, depending on the mining practices employed. For instance, vanadium extraction can involve the use of strong acids, which can contaminate soil and water if not properly managed.

Manufacturing and production – Battery manufacturing is an energy-intensive process, often relying heavily on fossil fuels, particularly in regions with limited access to renewable energy sources. This contributes to greenhouse gas emissions and exacerbates climate change. From a chemical point of view, the production process involves the use of various chemicals, including solvents, acids, and alkalis. These chemicals can pose significant environmental risks if released into the environment. Furthermore, the production of some battery components, such as electrodes and separators, can involve high-temperature processes with significant energy consumption and greenhouse gas emissions.

Specific concerns for certain chemistries – The high lead content in LABs poses a significant environmental hazard throughout the entire cycle life. Lead exposure can have detrimental effects on human health and the environment, including damage to the nervous system, kidneys, and reproductive system. The use of cobalt also raises ethical and environmental concerns.

Mitigation strategies – Implementing sustainable mining practices, such as minimising waste and reducing water consumption, is fundamental to mitigate the environmental impact of raw material extraction. Meanwhile, shifting to renewable energy sources for battery manufacturing can significantly reduce greenhouse gas emissions and minimise the carbon footprint of the entire industry.

Technological advancements also contribute to lowering the environmental impact of the battery industry as continuous R&D leads to more sustainable battery chemistries with reduced environmental impacts. The development of fully organic batteries, for example, could have the potential to significantly mitigate the environmental impact of current battery technology. Traditional batteries rely on potentially toxic heavy metals, such as lead or cadmium, which can contaminate soil and water if not disposed of properly. In contrast, organic batteries may use biodegradable and non-toxic materials, such as plant-based electrolytes and natural dyes, that can easily decompose. They may also offer improved recyclability and compostability, allowing for a closed-loop system where used batteries can be converted into nutrient-rich soil. By adopting fully organic battery technology, reliance on polluting materials could be reduced to promote a more sustainable future for energy storage.

2.3.3 End-of-life management

Storing energy requires the use of a variety of different types of rechargeable battery technologies described in previous sections. Despite being rechargeable, all of them have a life span. At the end of their intended use, the spent batteries become a solid waste that requires careful management to minimise environmental impact. Understanding current and future battery waste streams, along with the technologies required for recycling different battery types, enables governments to effectively plan.

LABs and LIBs dominate the rechargeable battery market (Figure 57). The other chemistries represent around 4.3%, with nickel-based batteries representing a consequent fraction of these. LIB adoption for energy storage is rapidly increasing due to their superior energy density, lifespan, and low maintenance. While LABs currently constitute most of the battery waste, spent LIBs are rapidly accumulating and will eventually dominate. Consequently, various countries are pursuing different waste management strategies. This section discusses recycling technologies and the status for both LABs and LIBs.

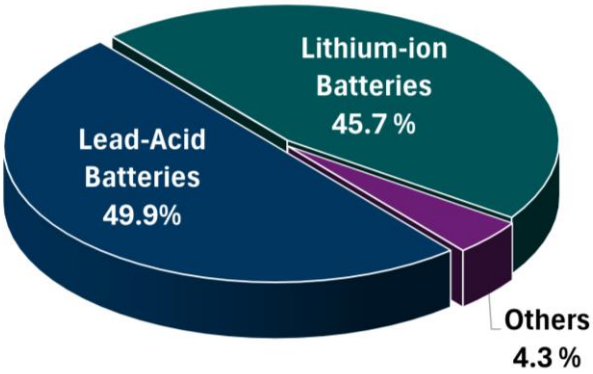


Figure 57 Global battery market share by different types of secondary battery usage and chemistries in 2019

Source: Zhao, et al., 2021

Lead-acid battery recycling

While developed regions achieve high recycling rates (98-99%) through strict regulation and efficient systems, developing regions often struggle with lower rates and informal recycling, causing substantial pollution and health hazards. Promoting sustainable recycling and enforcing regulations are crucial to minimizing the impacts of LABs.[63]

Current recycling processes – Pyrometallurgy is the primary method for recycling LABs. However, this process is energy-intensive, can generate air pollution, and exposes workers to hazardous substances. Researchers are exploring alternatives such as citric acid calcination and electrokinetic separation, which offer lower energy consumption, reduced environmental impact, and simpler processing for more sustainable recycling. A flow chart of LAB recycling is presented in Figure 58.

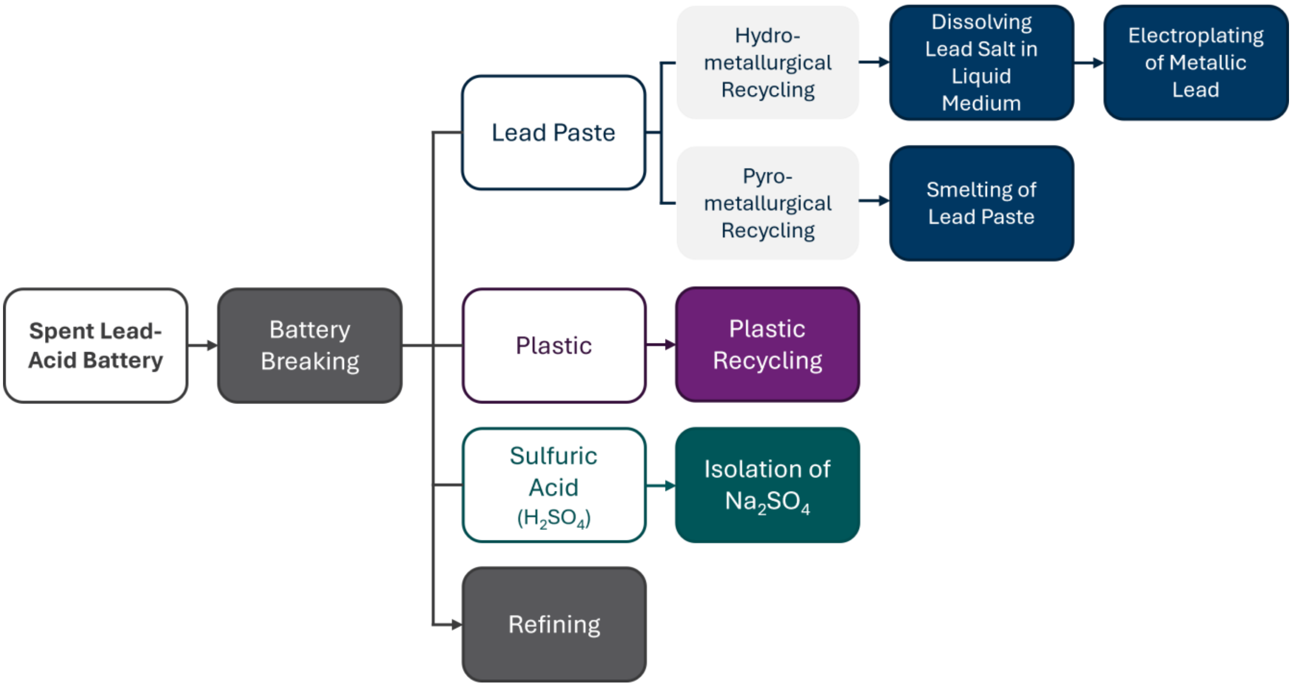
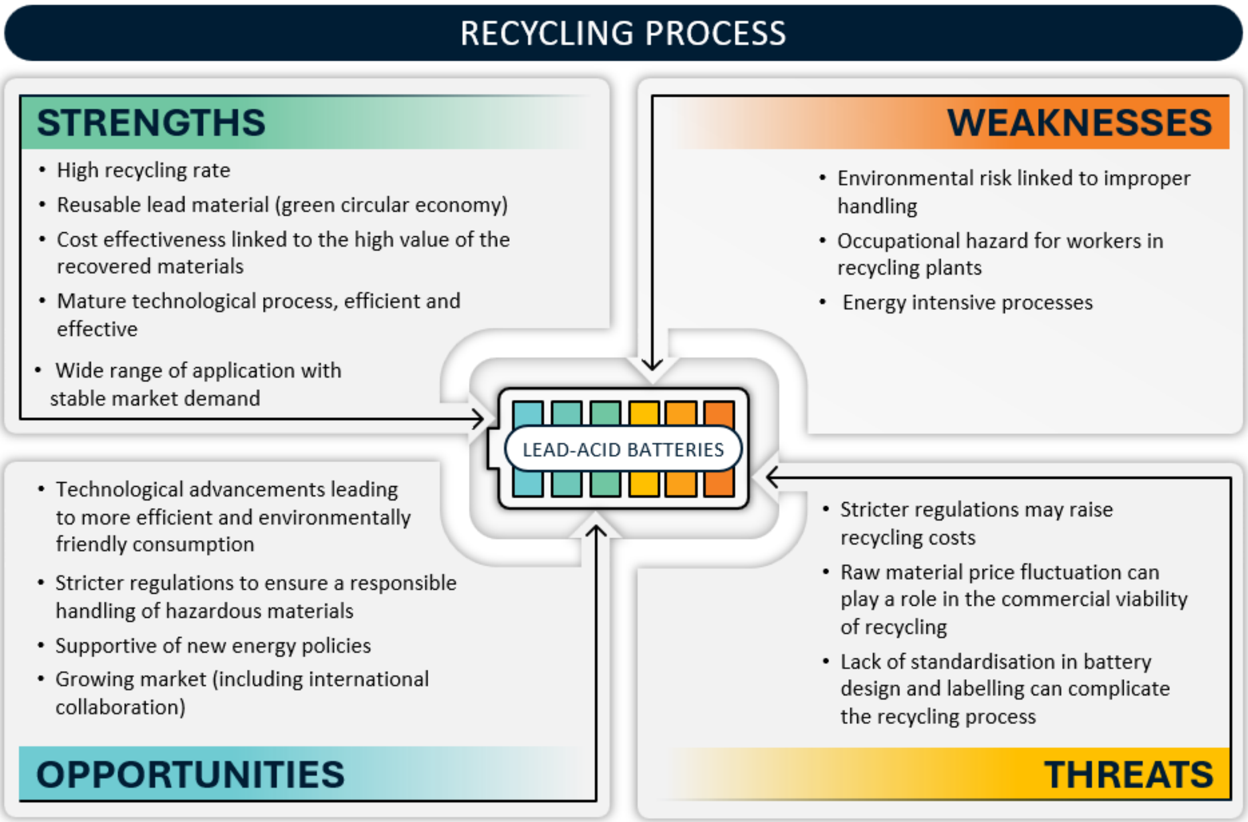


Figure 58 LAB pyrometallurgical and hydrometallurgical recycling processes

Flow diagram plotted based on Zhao, et al.[63]

Commercial viability – LAB recycling is a well-established and highly efficient process where up to 99% of the material is recyclable. Lead content generally has the highest recycling rate among the common metals and its recycling costs range from US$200-500 per ton. This figure can be increased based on the regulation in place at the location, energy-intensive processes, or waste management costs. While recycling requires energy, especially for smelting, it uses about 40% less energy than mining new lead, making it a sustainable and economical option.

SWOT analysis of the recycling process – A SWOT analysis of the recycling processes in presented in Figure 59 for LABS.



STRENGTHS

- High recycling rate
- Reusable lead material (green circular economy)
- Cost effectiveness linked to the high value of the recovered materials
- Mature technological process, efficient and effective
- Wide range of application with stable market demand

WEAKNESSES

- Environmental risk linked to improper handling
- Occupational hazard for workers in recycling plants
- Energy intensive processes

OPPORTUNITIES

- Technological advancements leading to more efficient and environmentally friendly consumption
- Stricter regulations to ensure a responsible handling of hazardous materials
- Supportive of new energy policies
- Growing market (including international collaboration)

THREATS

- Stricter regulations may raise recycling costs
- Raw material price fluctuation can play a role in the commercial viability of recycling
- Lack of standardisation in battery design and labelling can complicate the recycling process

Figure 59 SWOT analysis of the recycling process of LABs

Lithium-containing batteries

Many countries now regulate LIB waste, promoting recycling via Extended Producer Responsibility (EPR) policies. With rising LIB demand, robust recycling infrastructure and sustainable sourcing are crucial to mitigate negative environmental impacts.

Current recycling processes – LIB recycling can recover between 50 and 95% of materials, using several methods (Figure 60):

- **Pyrometallurgy:** Mature and fast, but energy-intensive (linked to the > 1500°C treatment) and generates pollutants. While it is quick, requires minimal equipment and can handle mixed waste, this process has limitations in recovering valuable metals like lithium and aluminium due to their affinity with oxygen.
- **Hydrometallurgy:** More energy-efficient and recovers lithium at low temperatures but requires large volumes of leaching agents due to the low solubility of the materials to recover, producing significant acid waste.
- **Solvometallurgy:** An emerging process using ionic liquids or deep eutectic solvents (DESs), offering lower energy use, less waste, and high metal recovery. DESs may offer a cost-effective alternative to ionic liquids.
- **Direct recycling**: Reuses cathode materials directly, offering cost and environmental benefits, but limited to specific cathode chemistries.

Reuse opportunities of LIBs – LIBs have a deep penetration in the hybrid and electric vehicle markets. Once these batteries can no longer reliably power vehicles, they often still retain enough capacity for less demanding applications (second-life use) before they are ultimately recycled. Second-life battery applications are being developed, illustrated in Figure 61. Their benefits and limitations are collated in Table 5.

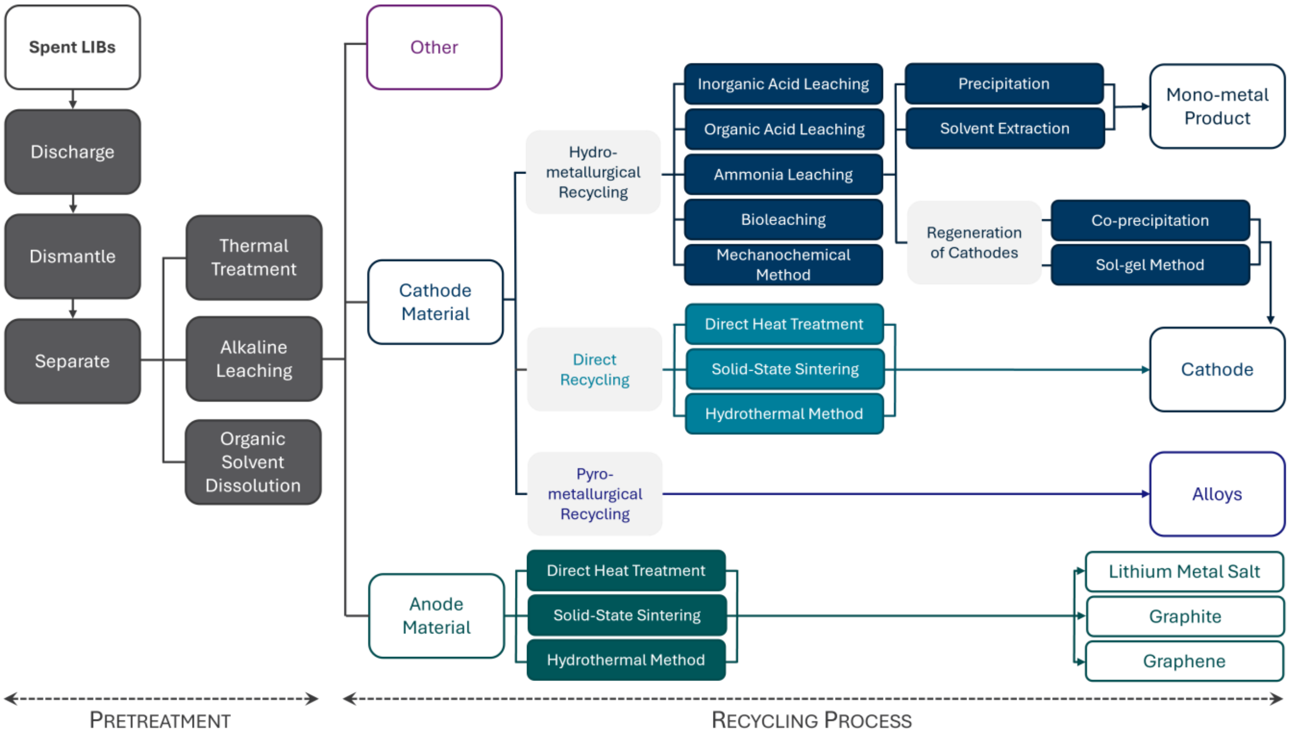


Figure 60 LIB recycling processes[64]

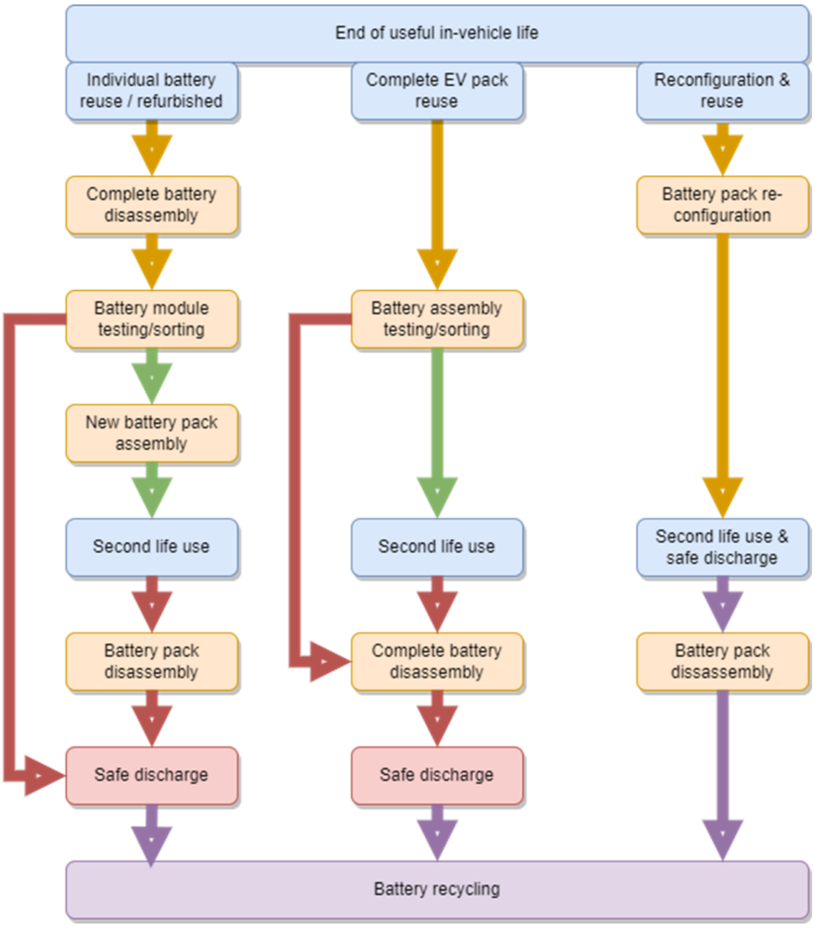


Figure 61 Three differing approaches for the use of second life EV batteries from the end of their useful in-vehicle life to recycling

Table 5 Reuse opportunities for LIBs, their benefits and limitations

REUSE OPPORTUNITY	PROS	CONS
Refurbishment of individual cells *The battery pack is completely disassembled, with all cells tested prior to being built into a new battery pack*	• Ensures best possible capacity and residual life of completed pack • No constraint to maintain original pack configuration or dimensions • Poor quality cells can be discharged and go directly to recycling	• Requires additional time and effort to test and sort all individual batteries • Significant additional labour requirements in rebuilding new battery packs and their final disassembly prior to recycling
Reuse of complete battery pack *The battery pack including BMS is reused. Testing may not be required in cases where sufficient battery health data is retained in the battery pack*	• Lowest additional labour costs	• Requires testing of battery packs where battery history is not available • Systems require significant redesign to support additional manufacturers or models
Pack reconfiguration *The residual capacity and life of any viable modules are utilised until the overall capacity of the pack falls below a nominal value, at which point all batteries in the pack are safely discharged ready for recycling following final disassembly*	• Low additional labour (< 1 hour) requirement beyond that which is necessary for recycling • Additional requirement for testing, sorting and balancing of cells can be avoided with lower impact to overall battery health • Individual batteries can go directly to recycling phase following end-of-life and final disassembly • Can readily support different battery types and chemistries with custom battery interface	• Reduction in effective capacity and projected life compared to other approaches • Increased safety risk

Commercial viability – The economic feasibility of recycling lithium-based batteries is influenced by fluctuating prices of critical metals like cobalt and lithium, as well as the diverse chemistries used in these batteries. Additionally, the high capital and operational costs of establishing and running recycling facilities pose significant challenges. In addition, falling first-life battery prices (approaching US$50/kWh) challenge the economic viability of reuse opportunities. However, with the rising demand for LIBs, the projected shortages of lithium, cobalt, and graphite in the coming decade, and tightening regulations, the economic incentives for recycling are strengthening.

SWOT analysis of the recycling process

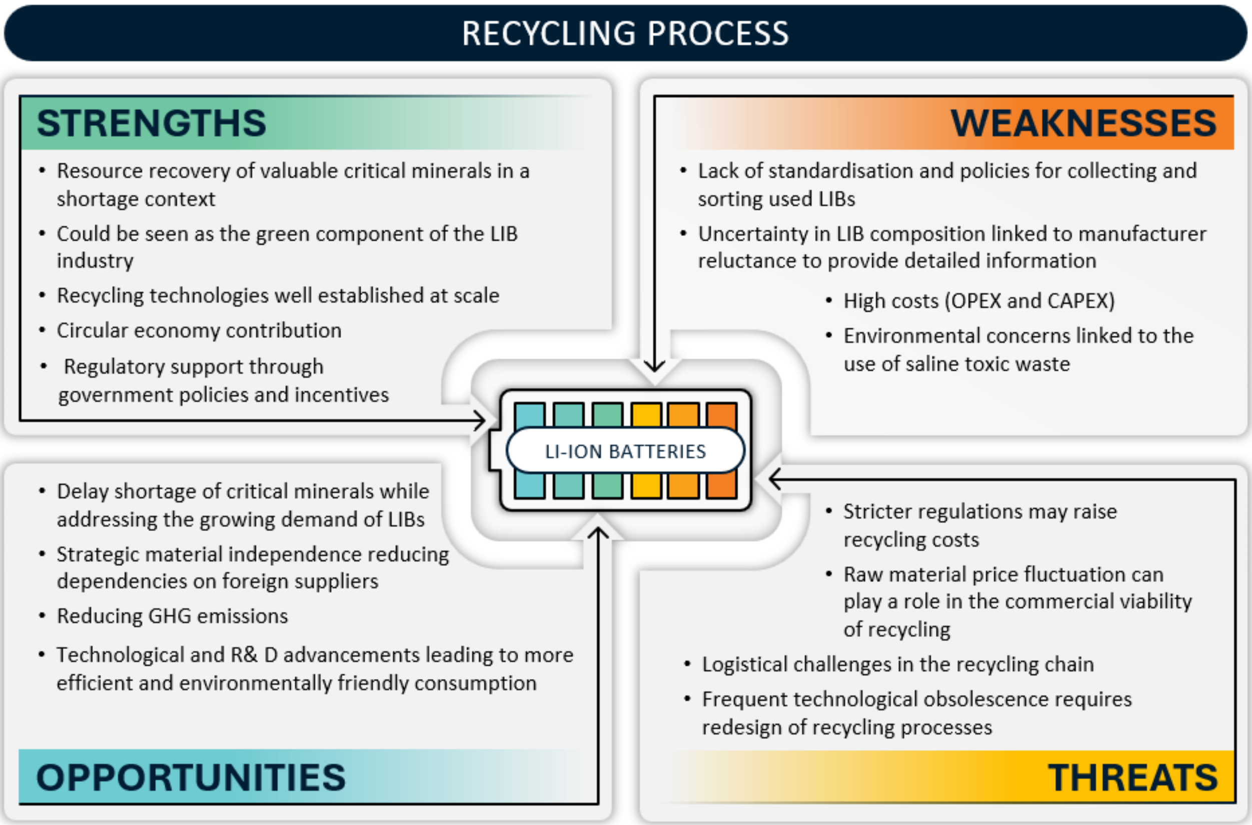


Figure 62 SWOT analysis of the recycling processes of LIBs

3 Evolving Energy Storage: from BESS to TESS

Tropical environments pose challenges for BESSs, including high temperature and humidity that accelerate degradation and reduce efficiency. For example, LIBs operating above 30°C can lose up to 30% of their cycle life compared to temperate climates. Specifically designed Tropical Energy Storage Systems (TESS) would ensure more reliable performance.

3.1 The Malaysian Tropical Rainforest Climate

Malaysia has a single tropical rainforest climate throughout the year, characterised by high rainfalls, high humidity and moderately high temperatures.

- **Temperature:** Due to its tropical location, the seasonal and daily temperature changes in Peninsula Malaysia are consistent and mild. As shown in Figure 63, the temperature rises during the daytime to a maximum typically around 30˚C ± 3°C, during which time batteries on RE systems charge, and drops at night to around 22˚C ± 2°C, when the battery discharges,. The seasonal variation is also mild throughout the year, with April-June being the hottest months.

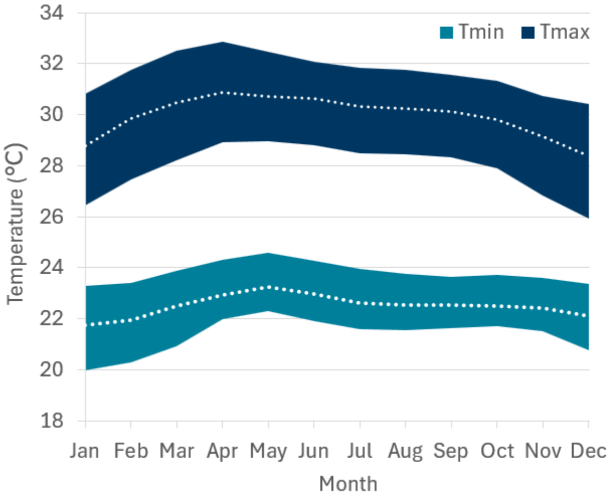


Figure 63 Variations in monthly T_{max} (day) and T_{min} (night) in Peninsula Malaysia for the period 1948 to 2016 based on ERA5 datasets[c] with the 95th percentile confidence interval[65]

- **Humidity:** The average annual rainfall in the Peninsula is between 2,000 – 4,000 mm over 150 - 200 rain days. The pattern of the rainfall is dictated by the Northeast monsoon (November to March) and the Southwest monsoon (May to September). The inter-monsoon rainfalls occur in April and October. Hence, high humidity (>80%) dominates the Peninsula Malaysia consistently throughout the year (Figure 64). The highest humidity is typically observed in the eastern coastal regions, while the less humid zone is in the high-altitude central parts of the land.

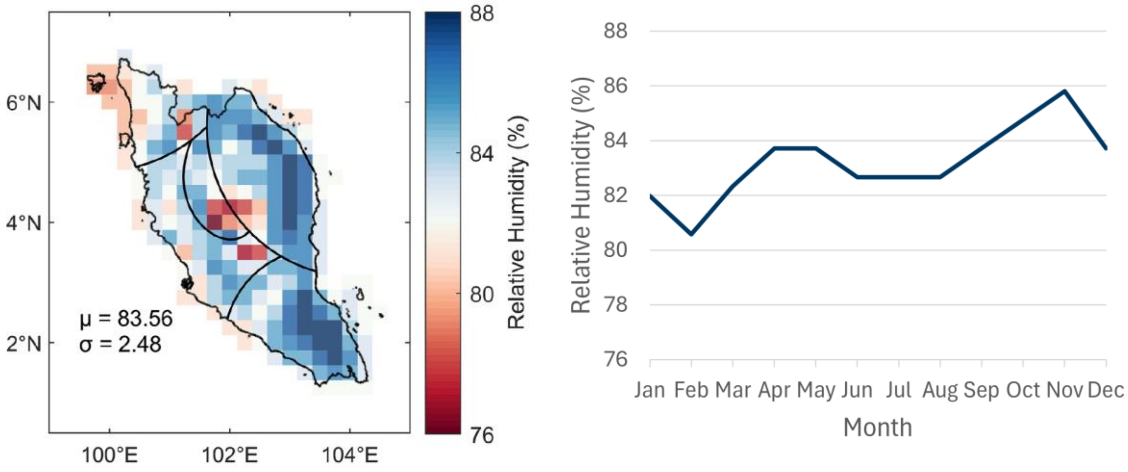


Figure 64 *Left*: Relative humidity across Peninsula Malysia areas[66] *Right*: annual variation[67]

- **Salinity:** As of 2019, about 70% of the Malaysian population lives in coastal areas.[68] The scale of the solutions explored in this report are consumer-based. Therefore, the high

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[c] ERA5 is a a worldwide atmospheric reanalysis dataset released by the European Centre for Medium-Range Weather Forecasts (ECMWF) including data since 1950.

salinity of the costal ambient air, due to the evaporation of nearby salty water, is another factor to be considered for the adoption of BESS in a tropical environment. The high salinity can contribute to increased corrosion of battery casings, further impacting battery lifespan and reliability.

By addressing these 3 specific challenges, battery performance and longevity can be significantly improved in tropical climates.

3.2 Temperature Tolerance

Ambient temperature impacts battery performance (energy and power) and life (number of cycles). High temperatures accelerate the kinetics of chemical reactions within a battery, leading to faster degradation and shorter lifespan. They also increase the rate of side reactions, such as electrolyte decomposition, the non-reversible formation of unwanted chemical species, or the formation of solid-electrolyte interphase (SEI) layers which can alter ion transport and reduce battery performance. Additionally, high temperatures can cause thermal runaway, a dangerous condition where the battery's temperature increases uncontrollably, leading to potential safety hazards. The combined effect of such parameters results in a specific temperature range for optimal performance of different chemistries as illustrated in Figure 65 and discussed below.

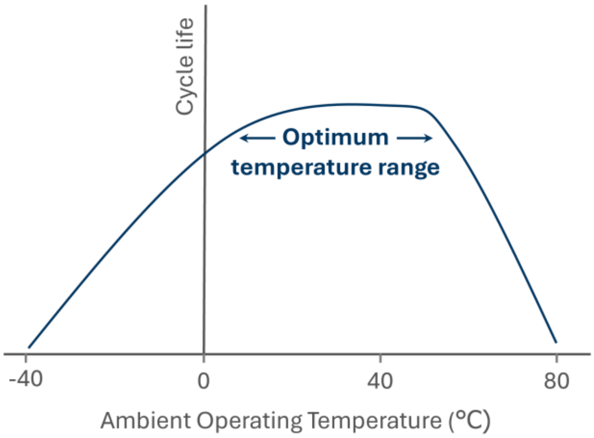

Figure 65 Typical profile of a BESS cycle life at different ambient (operating) temperatures

Hot weather has mixed impacts on the performance of the battery depending on the chemistry:

Lead-acid batteries are negatively impacted by high temperatures (above 40°C). While higher temperatures can initially improve capacity, they also lead to faster degradation over time, impacting performance. Research shows that a 10°C increase above the optimum working temperature would double the reaction rate of the internal processes such as electrode corrosion (aging) or self-discharge, resulting in shorter cycle life.[69]

In term of safety, temperatures above 40°C increase the gassing rate, the generation of hydrogen and oxygen.[70] Oxygen evolution is directly linked to accelerated rates of corrosion of the positive current collector, which progressively lowers the electrode’s mechanical strength, reduces the volume of the electrolyte and undermines the integrity of the battery casing, especially those made of Acrylonitrile Butadiene Styrene (ABS). Although more resistant to impact, ABS is temperature sensitive and tends to deform or soften above 85°C.[71] Hence, polypropylene casings can be used where possible. The overall safety risks are relatively low due to the absence of combustible electrolyte in the system.[72]

X-ion batteries lithium analogues store a significant amount of energy in a compact space. When heat is generated, it can lead to battery fires due to the presence of volatile and flammable organic solvents in the electrolyte. Therefore, preventing LIB overheating is crucial. Thermal runaway involves a chain of exothermic chemical reactions, causing rapid system temperature increase. In the case of LIBs, thermal runaway could happen due to external events (such as mechanical damage, environmental heat), and/ or internal events (such as overcharging, short circuit). Multiple factors could impact this, including low-quality manufactured cells, unsafe charging practice by consumers, or external factors such as extreme heat. Several degradation processes are identified:

- increased side-reaction leading to unwanted changes of the anode surface and increased cell resistance
- increased electrolyte decomposition and oxidation rates, particularly in cells with high nickel content cathodes
- transition metals, especially manganese and cobalt, dissolve more readily from the cathode into the electrolyte, affecting both cathode morphology and anode surface composition.

These temperature-induced degradation mechanisms affect all LIBs to varying degrees, with NMC, NCA, and LTO showing particularly severe effects at temperatures often encountered in tropical climates.[73] An operating temperature above 70°C significantly increases the risk of thermal runaway. Persistent hot weather may impact the function of the safety features embedded in the X-ion battery stack to monitor its performance, detect early stage of thermal runaway and prevent catastrophic failure if it occurs. To mitigate those effects, manufacturers and startups are working on developing LIBs adapted to tropical climates. This is the case of the startup Log, for example, which is developing LIBs suitable for the Indian tropical climate that also use the resources available in the country.[74]

In comparison, SIBs offer a wider temperature operation range.[75] They demonstrate improved sodium-ion mobility in electrolytes compared to LIBs but still face similar challenges at extreme temperatures. Notable recent advancements include the use of carbon-coated cathodes, bismuth anodes, and diglyme-based electrolytes, enabling operation from -70°C to 100°C.[76]

Ni-MH batteries generally still exhibit good performance at temperatures around 40°C as this is in the highest end of their optimum temperature range. However, prolonged exposure to high temperatures (above 50°C) can still accelerate aging and shorten the overall lifespan of the battery.[77]

Manufacturers like GrePow are currently working on developing high temperature Ni-MH batteries (up to 70°C) by adapting 2 aspects: the electrodes material, especially improving the thermal stability of MH alloys at the anode, and the electrolyte formulation, incorporating additives that suppress the formation of gas and minimise electrolyte decomposition while maintaining an optimal ion conductivity.[78]

Ni-MH's nickel-based analogues, Ni-H_2 batteries, have been poorly studied in elevated temperatures. However, some studies on isolated electrodes show that the electrochemical performance of nickel electrodes for hydrogen evolution in a 30 wt% KOH solution increases with the temperature (from 28 to 77°C).[79] Although these results seem promising, it does not encompass the safety risk associated with pressurised hydrogen in a battery system operated in hot weather.

Redox-flow batteries exhibit improved voltage efficiency and power density at higher temperatures; however, they also accelerate the rate of capacity losses, leading to shorter lifespans. V-RFB operated above 40°C present side reactions, leading to undesirable chemical processes that diminish efficiency and potentially damage internal components. Moreover, elevated temperatures accelerate membrane degradation, particularly with proton exchange membranes, resulting in performance losses and a shortened lifespan.[80] Some advanced V-RFB systems with modified electrolytes (like mixed sulfate-chloride electrolytes) have been shown to operate in wider temperature ranges, down to -20°C and up to 50°C.[81] However, the standard sulfuric acid-based V-RFBs have a 10-40°C limitation, which can be improved by a good thermal management system to maintain the electrolyte temperature within the optimal range, especially in extreme climates.

Molten salt batteries exhibit exceptional thermal stability, linked to their operating temperature of several hundred degrees. Hence, they work effectively across a broad temperature range. This unique characteristic distinguishes them from many other battery technologies, enabling reliable performance in both extremely cold and hot environments.

Metal-air batteries are currently in early stages of development, and their performance in hot climates remains uncharacterized.

3.3 Humidity Tolerance

While thermal management is required at the cell level, humidity management occurs at the system level as well. Elevated humidity can affect the performance of battery by 2 main methods: i) accelerating the corrosion of external-facing components such as casings, terminals and connections, and ii) interfering with internal electrochemical processes when the system is unsealed (such as M-air technologies). Although the second method may not initially impact sealed systems, the degradation of external elements can create pathways for humidity to penetrate the internal components, potentially affecting the electrochemical processes within sealed systems over time. Overall, manufacturers recommend that for all battery chemistries, moisture should be avoided during manufacturing, storage, and use.

Lead-acid batteries exist under sealed and open systems. Open systems are more susceptible to humidity, which influences electrolyte evaporation rates. This phenomenon has also been observed in small sealed VRLA where the separator contracts as the electrolyte content decreases. This may result in poorer contact between the separator and the battery plates, leading to decreased discharge performance.[82]

Damage caused by humidity on the external casing primarily affects the current collector terminals. This is because the majority of the casing is composed of plastic materials such as polypropylene or acrylonitrile butadiene styrene. Since corrosion of lead alloys significantly impacts LAB lifespan, research has focused on improving these alloys. This includes the addition of antimony, calcium, or tin, or the application of coatings like polypyrrole, resulting in enhanced corrosion resistance.[83] Overall, the failure of VRLA batteries appears to be more related to duty cycle and maintenance than ambient humidity.

X-ion batteries require strong control of the humidity during LIB manufacturing, storage, and operation to optimise performance and longevity. In general, humidity often exacerbates existing problems. A 2021 study identified humidity during the manufacturing process as the root cause of failures of LIBs used at high temperatures, creating defects within the SEI.[84] In addition to these corrosion issues, moisture ingress in the electrolyte can result in hydrogen generation at the cathode, increasing the risk of hazard. Nickel-rich cathodes such as NMC or NCA are particularly sensitive to humidity.

While aluminium is generally preferred for its lighter weight in battery casings, stainless steel 304 or 3XXX and 6XXX series aluminium alloys are often used where resistance to damage, temperature, and corrosion is required by the targeted application. This is particularly true for LIBs used in electric vehicles, where safety takes precedent over weight considerations. A main concern is the potential failure of the aluminium overpressure safety system on the anode side. Humidity (and salinity) exposure can compromise these burst disks, leading to electrolyte leaks, accelerated corrosion of adjacent batteries, and increased fire risk.

In *Ni-MH batteries*, similarly to LIBs, high moisture content has a negative impact on the performance of the nickel-rich electrodes. However, a moderate moisture content (~ 12%) on $Ni(OH)_2$ electrodes is favourable as it results in increased discharge capacity.[85] This suggests that maintaining an appropriate and controlled level of moisture within the battery is important for longevity and safe operation.

Externally, AB_5-type alloys seem to be the most sensitive to corrosion, requiring the addition of yttrium oxide Y_2O_3 powder to improve corrosion resistance. Altering the electrode alloy formulation has been shown to double the cycle life of some Ni-MH batteries.[86]

Redox-flow battery performance is linked to the concentration of active species in the electrolyte, carefully balanced for optimum kinetics. Moisture absorption can alter the water content of the electrolyte, affecting the battery's voltage, capacity, and overall efficiency.[87] In RFBs using ion-exchange membranes to separate electrolytes, high humidity can also cause these membranes to swell. This results in increased internal resistance, hindered flow of ions and reduced overall energy efficiency.[88]

Externally, humidity-induced corrosion can affect various components, from connectors, to tanks and piping, leading to increased maintenance frequency and operating costs for RFBs in tropical climates.

Molten salt batteries are typically built with solid beta alumina acting as electrolyte for the transport of sodium-ions in high temperature Na-S and SNCBs. While generally less hygroscopic than liquid electrolytes, prolonged exposure to humidity can still lead to gradual degradation of the ceramic, drastically affecting its ionic conductivity.[7] The chemistry of sulfur and sodium polysulfide can also be complicated in the presence of moisture, interfering with the electrochemical processes of molten-salt batteries.

At the elevated operating temperatures of these batteries, careful humidity control can prevent accelerated corrosion of the cell casing and current collectors. In the case of molten salt batteries, corrosion may compromise the integrity of the battery, potentially exposing the highly corrosive reactive materials to atmospheric moisture as well as creating a fire hazard.

Metal-air batteries, operating as open systems, are inherently susceptible to atmospheric moisture. Fundamental studies have demonstrated the detrimental effects of humidity, CO_2, and other small molecules on their internal processes.[89] Current mitigation strategies seem to address the problem at a systemic level, using filters or oxygen-selective membranes at the cathode's air inlet.[90] However, operating in tropical climates will significantly increase the burden on the air pre-filtration system, likely leading to increased maintenance requirements. While non-aqueous systems, sensitive to moisture, might present challenges in tropical environments, aqueous analogues could potentially offer a more viable alternative.

While the internal humidity tolerance is specific to the battery chemistry, external corrosion of connectors or casing can likely be addressed using common mitigation strategies. Some of these strategies, such as coating or the development of corrosion-resistant alloys,[91] can be inspired from the humidity-proofing knowledge for electronics, a well-established industry sector in Malaysia representing approximately 6% of the country's GDP.

3.4 Salinity Tolerance

Corrosion of metal surfaces, particularly in marine environments, is significantly accelerated by the presence of airborne salt particles (primarily chlorides). While most batteries are manufactured with protective casings, exposed terminals remain vulnerable to corrosion over time. Increased salinity will likely accelerate the processes described in the previous section of this report.

The accelerated rate of corrosion due to increased salinity is directly correlated with the chloride concentration in atmospheric droplets. This chloride concentration is influenced by various factors, including proximity to the shore, wind strength and direction, wave height, and geographical topographies. While models exist to describe the intensity of this phenomenon, ranging from simple exponential models near the shore (400-600 m) to more complex models in land,[92] a detailed exploration of these models to predict the corrosion tolerance of battery external components is outside the scope of this report.

A notable specific concern linked to increased atmospheric salinity is the potential formation of conductive salt bridges between corroded battery terminals. These bridges could lead to self-discharge and reduced battery life. Research specifically examining the effects of saline air on battery performance is scarce. However, it is reasonable to assume that external casings and terminals will degrade similarly to any other electronic technologies used in similar environments.

4 The Way Forward

The selection of an optimal energy storage system for a specific application is a complex process of compromise and optimisation, driven by a wide range of factors. The optimal solution is dependent on the location of the application and the nature, intensity and availability of the associated renewable energy source. It is also sensitive to the characteristics of the application in terms of duration (short versus long), scale (residential versus large-scale) and costs.

Hence, it is not possible to conclude this report with a definitive recommendation for SEDA's consideration. A definitive design of the optimal energy storage systems across Malaysia would require a holistic, methodical and data driven approach, underpinned by 4 key components:

- undertaking an in-depth study of Malaysia's solar energy resources in terms of radiance intensity, duration, intermittency patterns and predictability for solar, enabled by site-specific data collection throughout a year
- collating data on the demand profile of high priority targets such as grid-connected or off-the-grid communities and high energy intensity industries
- building a system-level digital twin of Malaysia's electricity network (connected and isolated) to model and simulate the integration of solar energy into the network
- utilising the digital twin to design an optimal energy storage support for different applications.

These technical studies should be supported by regulations, policies, government actions, and market incentives to accelerate the transition to renewable energy sources. Although specific measures vary by country and are beyond this report's scope, Malaysia can learn from other jurisdictions more advanced in renewable energy adoption. Table 6 highlights strategies from Australia, the United States of America (USA), and Europe for SEDA's consideration to aid Malaysia's transition. They are regrouped under 3 categories:

- regulatory, policies and governmental actions
- multiscale infrastructure development strategies
- innovation cultures to foster rapid scientific progress.

Table 6 Examples of strategies implemented by Australia, the USA and Europe to support the adoption of BESS

STRATEGY	AUSTRALIA	USA	EUROPE
Regulatory, Policies and Governmental Actions			
Regulatory Framework	• In 2021, Australia changed the National Electricity Market (NEM) to help with the registration and integration of bi-directional energy generation (where the consumer acts both as generator and load). The changes were implemented in June 2024.[93,94]	Federal Level Examples: • Federal Energy Regulatory Commission (FERC) issued Order 841 in 2018, requiring regional grid operators to allow BESS to participate in wholesale energy markets.[95] State Level Examples: • California Net Energy Metering 3.0 in 2023: although decreasing the incentive for solar installation on its own, it significantly increases the financial benefit of pairing it with BESS.[96] • New York Value of Distributed Energy Resources (VDER): it compensates distributed BESS for the grid services they provide, such as peak shaving and demand response.[97] • Reforming the Energy Vision (REV) is promoting the integration of DERs into the grid.[98]	Europe's general strategy to support the adoption of BESS blends top-down European Union (EU) policies and bottom-up national initiatives: EU Level: • EU Clean Energy Package of 2019, mandating member states to integrate energy storage into their energy market.[99] National Level: • Germany's Energy Storage Strategy supporting the deployment of BESS for renewable energy integration [100] • UK simplified grid connection rules
Financial Incentives	• Funding of large-scale BESS through grants supported by the government (via the ARENA).[101] These opportunities take on the first investment risk to reassure future private investors. • Consumer-level funding opportunities[102] • Governmental Investment fund to 'increase the flow of finance into the clean energy sector'.[103]	Federal Level Examples: • In the Inflation Reduction Act (IRA), the USA set up an Investment Tax Credit (ITC) expended to BESS with 30% tax credit for residential systems.[104] • The Energy Storage Tax Incentive and Deployment Act of 2021 (also known as the bipartisan law) includes $73 billion to overhaul the energy policy of the USA including $3 billion in battery material reprocessing and $3 billion in battery recycling.[105]	EU Level: • The European Investment Bank offers low-interest loans for BESS under its Climate Bank Roadmap.[107] • Innovation Fund for large-scale BESS linked to renewable energies.[108] National Level: • Germany's low-interest loans for residential and commercial BESS projects coupled with solar generation.

STRATEGY	AUSTRALIA	USA	EUROPE
		State Level Examples: • Solar Massachusetts Renewable Target (SMART) Program provides incentives for photovoltaic projects up to 5 MW in size.[106]	• Italy's Superbonus offering tax deduction for residential renovation including renewable energy systems.[109]
Multiscale infrastructure development strategy *Parallel and integrated development of technologies at all scales*			
Large-scale projects	Examples:[110] • Hornsdale Power Reserve (150 MW/194 MWh), in South Australia • Victorian Big Battery Installation (300 MW/450 MWh) • Collie, WA. In construction by 200 MW portions (as of 2024). Could provide a total of 1 GW.	Examples: • Manatee Energy Storage Center in Florida (409 MW/900 MWh), integrated solar-powered battery system. • Moss Landing Energy Storage Facility (BESS) in California (400 MW/1,600 MWh)	• UK's Clay Tye project (99 MW / 198MWh).[111] • Return Energy includes multiple BESS location over Europe including Netherland's Mufasa (364 MW/1457 MWh).[112]
Distributed Storage	Australia has been pursuing distributed storage via multiple strategies: • Virtual power plant (VPP)[113] • Subsidised funds for homeowners to install BESS	The USA rely on incentives programs such as the ones mentioned above or the following examples: • *Self-Generation Incentive Program* (SGIP) in California.[114] at the residential level • *Green Mountain Power* in Vermont at the community level.[115]	• Virtual power plant (VPP) • *Sonnen Community* allows users to trade stored solar energy peer-to-peer.[116]
Grid Integration	• *Fast Frequency Response* (FFR): The Australian Energy Market Operator (AEMO) introduced FFR markets, where BESS can provide rapid grid stabilisation services, creating new revenue streams. • *Grid integration* (with all the stabilisation it represents) is fundamental in the vision of multiple tailored local solutions well integrated into an ancillary framework from a technical and economical point of view.	• Regional Transmission Organisation such as PJM Interconnection.[117] • State-level storage mandates such as California's 1.3 GW target.[118]	• Harmonised rules for BESS grid connection, ensuring interoperability across member states

STRATEGY	AUSTRALIA	USA	EUROPE
Maintain an innovation-focused culture to foster rapid scientific progress			
R&D	• ARENA has funding opportunities with universities for the development of novel battery chemistries, safety or grid stabilisation, in practical and theoretical aspects • Pilot projects, such as the Dalrymple BESS in South Australia, test the integration of BESS with renewable energy and grid infrastructure.	• Department of Energy (DOE) funding for storage R&D • National laboratories such as the Renewable Energy Laboratory (NREL) or Lawrence Berkeley National Laboratory (LBNL) leads BESS research	• EU funding programs such as Horizon Europe for next gen storage technologies[119] • Battery 2030+ is a €1 billion initiative to develop high performing batteries.[120] • European Battery Alliance (EBA), supporting a full battery value chain from raw material to recycling.[121]
Safety and regulations Framework	BESS Safety Guidelines: • Comprehensive safety guidelines for Battery Energy Storage System (BESS) installation and operation are outlined in the Australian Standard AS/NZS 5139:2019 • Clear and accessible regulation at the national and state levels[122] • Several initiatives for recycling and end-of-life batteries: B-cycle, the Australian Battery Recycling Initiative (ABRI), Envirostream, CSIRO, Ecobatt, Ecoactiv, etc.	• National Fire Protection Association (NFPA) 855c standards for BESS Safety outlines the requirements for installing stationary ESS.[123] • State legislation such as California's Responsible Battery Recycling Act of 2022 (AB2440).[124]	• EU Battery Directive of 2022 mandates recycling targets and sustainability requirements.[125] • Safety standards are published such as the International Electrotechnical Commission's IEC 62933 [126] • European Standardization system (CENELEC) certifies fire safety and thermal management systems.[127]

5 Concluding Remarks

This report presents an overview of the different battery energy storage systems (BESS) that may be used to enable a higher adoption of intermittent renewable energy sources in Malaysia. The simple and consistent framework presented here is intended as an additional data point available for SEDA's internal and external stakeholders as they consider the potential applications of conventional and emerging energy storage options in supporting the transition to renewable energy systems.

The key takeaways from this report are:

- Energy storage systems are crucial for Malaysia to meet its emissions reduction goals. Among various options, electrochemical systems stand out as flexible, cost-effective, and reliable.
- There is no 'silver bullet' energy storage solution that meets the requirements of all applications across different locations. The design of an optimal system would require a methodical assessment of the supply and demand profiles of the application. This is best addressed at a community or regional level, in particular for isolated (not grid connected) applications. However, the report presents the following highlights:
  - Lead-acid batteries are likely to continue dominating the 'Starting, Lighting and Ignition' market of conventional vehicles. However, the increased penetration of EVs is likely to result in reducing the market size of these applications. This may create incentives for LAB manufacturers to target other markets such as stationary application/long-duration storage.
  - Lithium-ion batteries have a strong competitive advantage because of their broad performance criteria (enabled by the diversity of possible chemistries), their adaptability to different forms, a strong supply chain (from minerals to product), and the ongoing reduction in production costs. These features make LIBs attractive across different market segments, ranging from low energy and power density (microwatt hours for sensors or biomedical devices) to MWhs for grid scale applications. The challenges the LIBs likely to face are related to the safety of operation (at higher energy and power densities) and bottlenecks in the supply chain of critical minerals.
  - Redox-flow batteries are emerging as a viable option for stationary applications, in particular for large-scale and long-duration storage requirements. These chemistries are expected to be more competitive than LIBs for > 8-hour storage duration. Amongst the different RFB systems, Zn/Br_2-RFBs show the highest energy and power densities but are hindered by the toxicity of the bromine solution. V-RFBs show an acceptable performance for long-duration storage but vanadium minerals are expensive. In comparison, Fe-RFBs have the lowest energy density, but are attractive because of the low cost of the iron minerals.
- Levelised cost of storage (LCoS) is not a sufficient metric to compare and prioritise different energy storage systems. The metric is sensitive to the duration of storage, degree of utilisation,

and the cost drivers of the specific location of the application. Hence, this metric should be considered only if the analysis is underpinned by the same set of common assumptions.

- Malaysia’s tropical weather introduces additional challenges to the adoption of energy storage systems. The combined high temperature, high humidity, and salinity of the ambient conditions triggers different side reaction and undesired processes that lower battery performance, affect the integrity of key components (electrodes, electrolyte or membranes), exacerbate some hazards such as thermal runaway, buildup of pressure (explosion risks), and damages to the casing of the battery (spillage hazards).

It is important to reiterate that, whilst this report presents a simple and consistent framework, it is not meant to offer advice on designing an optimal energy storage system for specific applications. Such a process would require a holistic, methodical and data driven approach as outlined in Section 4.

6 Acknowledgments

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Appendix A Technical Supplementary Information

A.1 LABs

Chemical reactions involved:

$PbO_2 + 2e^- + 2H^+ + H_2SO_4 \leftrightharpoons PbSO_4 + 2H_2O$ E° = 1.7 V vs SHE **Eq. (1)**

$Pb + H_2SO_4 \leftrightharpoons PbSO_4 + 2e^- + 2H^+$ E° = -0.4 V vs SHE **Eq. (2)**

Overall equation:

$PbO_2 + Pb + 2H_2SO_4 \leftrightharpoons 2PbSO_4 + 2H_2O$ E = 2.1 V **Eq. (3)**

Performance additional details:

Capacities range from 1 to 1000 Ah, depending on the applications requirements from small devices such as car starters (ca. 40-65 Ah) to large-scale systems (the capacity of a submarine battery is typically 100 times that of a car-starter battery). LABs can handle C-rates from 0.01C to 100C.

A.2 LIBs

Chemical reactions involved:

LIBs Redox equations can be split in 3 types of reaction:

- **$LiMO_2$ / Graphite**, where M represents one or a combination of Co, Ni, Mn, or Al. The processes occurring at the electrode is described below for NMC, NCA, or LCO chemistries at the cathode (Equation 4) and anode (Equation 5). In the overall Equation 6, the lithiation ratio (1-x) changes depending on the battery's stage of charge.

  $Li_{(1-x)}MO_2 + x\,Li^+ + e^- \leftrightharpoons LiMO_2$ E° = 0.5 V vs SHE **Eq. (4)**

  $Li_xC_6 \leftrightharpoons 6\,C + x\,Li^+ + e^-$ E° = -3.0 V vs SHE **Eq. (5)**

  Overall Equation:

  $Li_xC_6 + Li_{(1-x)}MO_2 \leftrightharpoons 6\,C + LiMO_2$ E = 3.7 - 4.2 V **Eq. (6)**

- **LFP/ Graphite.** In this type of LIB, while the anode reaction remains the same, the cathode sees the reduction of iron phosphate following Equation 7.

  $FePO_4 + Li^+ + e^- \leftrightharpoons LiFePO_4$ E° = -0.3 V vs SHE **Eq. (7)**

  Overall equation:

  $Li_xC_6 + FePO_4 \leftrightharpoons 6\,C + LiFePO_4$ E = 3.2 - 3.5 V **Eq. (8)**

- **LFP/ LTO.** The LTO analogues will be described here in combination with LFP cathodes. Hence, while the reduction of iron phosphate following Equation 7 occurs at the cathode, lithium titanate is oxidised on the anode side following Equation 9.

  $Li_7Ti_5O_{12} \leftrightharpoons Li_4Ti_5O_{12} + 3\,Li^+ + 3\,e^-$ E° = -1.8 V vs SHE **Eq. (9)**

  Overall equation:

  $Li_7Ti_5O_{12} + 3\,FePO_4 \leftrightharpoons Li_4Ti_5O_{12} + 3\,LiFePO_4$ E = 1.8-1.9 V **Eq. (10)**

Performance additional details:

While NMC and NCA chemistries currently offer the highest capacities around 200 Ah, LTO cells provide a competitive 175 Ah, followed by LFP at 160 Ah, with LCO cells typically exhibiting the lowest capacity at 140 Ah.

NMC, NCA, LMO, and LCO batteries typically operate within a C-rate range of 1C to 3C. LFP batteries offer slightly faster charging capabilities, reaching up to 4C. Among the chemistries described in this report, LTO batteries present the fastest charging rate, supporting C-rates from 1C to 5C.

A.3 SIBs

Chemical reactions involved:

$Na_{(1-x)}MO_2 + x\,Na^+ + e^- \leftrightharpoons NaMO_2$ E° = 3.0 - 3.5 V vs SHE **Eq. (11)**

$Na_xC_6 \leftrightharpoons 6\,C + x\,Na^+ + e^-$ E° = 0.1 - 0.2 V vs SHE **Eq. (12)**

Overall reaction:

$Na_xC_6 + Na_{(1-x)}MO_2 \leftrightharpoons 6\,C + NaMO_2$ E = 2.0 - 4.5 V **Eq. (13)**

Performance additional details:

Although this is still an area of active development, SIBs offer a range of C-rates, from around 1C for typical applications up to 3C or more for high-performance needs.

A.4 Ni-MH Batteries

Chemical reactions involved:

$NiO(OH) + H_2O + e^- \leftrightharpoons Ni(OH)_2 + OH^-$ E° = 0.5 V vs SHE **Eq. (14)**

$MH + OH^- \leftrightharpoons M + H_2O + e-$ E° = -0.8 V vs SHE **Eq. (15)**

Overall equation:

$NiO(OH) + MH \leftrightharpoons Ni(OH)_2 + M$ E = 1.2 – 1.4 V **Eq. (16)**

Performance additional details:

With a typical capacity of around 2 Ah for an AA battery and a C-rate range of 1C to 5C, Ni-MH batteries can deliver both sustained power and high discharge rates.

A.5 Ni-H_2 Batteries

Chemical reactions involved:

$NiO(OH) + H_2O + e^- \leftrightharpoons Ni(OH)_2 + OH^-$ E° = 0.5 V vs SHE **Eq. (17)**

$\frac{1}{2} H_2 + OH^- \leftrightharpoons H_2O + e^-$ E° = 0 V vs SHE **Eq. (18)**

Overall equation:

$NiO(OH) + \frac{1}{2} H_2 \leftrightharpoons Ni(OH)_2 + H_2O$ E = 1.2 – 1.4 V **Eq. (19)**

Performance additional details:

Ni-H_2 batteries offer a flexible charge/discharge range, typically operating between C/2 and C/12.[128]

A.6 V-RFBs

Chemical reactions involved:

$VO_2^{+} + 2\,H^{+} + e^{-} \leftrightharpoons VO^{2+} + H_2O$ E° = 1.0 V vs SHE **Eq. (20)**

$V^{2+} \leftrightharpoons V^{3+} + e^{-}$ E° = -0.3 V vs SHE **Eq. (21)**

Overall Equation:

$VO_2^{+} + 2\,H^{+} + V^{2+} \leftrightharpoons VO^{2+} + H_2O + V^{3+}$ E = 1.3 V **Eq. (22)**

Performance additional details:

While their capacity is scalable, systems for grid-scale applications typically range from 100 kW to 10 MW. V-RFBs typically handle C-rates from 0.01C to 1C.

A.7 Fe-RFBs

Chemical reactions involved:

$Fe^{2+} \leftrightharpoons Fe^{3+} + e^{-}$ E° = +0.8 V vs SHE **Eq. (23)**

$Fe^{2+} + 2\,e^{-} \leftrightharpoons Fe^{0}$ E° ≈ -0.4 to -0.7 V vs SHE **Eq. (24)**

Overall equation:

$3Fe^{2+} \leftrightharpoons 2\,Fe^{3+} + Fe^{0}$ E ≈ 1.1 to 1.4 V **Eq. (25)**

Performance additional details:

Iron RFB support charge/discharge rates from 0.1 to 1 C.

A.8 Zn/Br$_2$-RFBs

Chemical reactions involved:

$Zn \leftrightharpoons Zn^{2+} + 2e^{-}$ E° = -0.8 V vs SHE **Eq. (26)**

$Br_2 + 2e^{-} \leftrightharpoons 2Br^{-}$ E° = +1.1 V vs SHE **Eq. (27)**

$Zn + Br_2 \leftrightharpoons Zn^{2+} + 2Br^{-}$ E = 1.9 V **Eq. (28)**

Performance additional details:

Zn/Br$_2$-RFB present capacities varying from 40 to 400 kWh systems with storage for 2 to ten hours and an efficiency above 70%.

A.9 SNCBs

Chemical reactions involved:

$Na^{+} + e^{-} \leftrightharpoons Na$ E° = -2.7 V vs SHE **Eq. (29)**

$Ni + 2\,NaCl \leftrightharpoons NiCl_2 + 2\,Na^{+} + 2e^{-}$ E° = -0.3 V vs SHE **Eq. (30)**

Overall equation:

$2\,NaCl + Ni \leftrightharpoons NiCl_2 + 2\,Na$ E = 2.6 V **Eq. (31)**

On top of the main redox active species described above, redox chemical additives can enhance the performance and longevity of SNCBs:

- **Aluminium powder** is usually added to the positive electrode, resulting in additional voltage plateaus at lower voltages during discharge following equation 32. This increases the tolerance of the cell for over discharge.

$Al + 4\,NaCl \leftrightharpoons Na + NaAlCl_4$ E = 1.6 V **Eq. (32)**

- **Iron sulfide** is included to stabilize the size of the nickel microstructures dissolved and redeposited during operation. In the absence of iron sulfide, nickel grains can grow significantly, from 1-2 µm to over 40 µm within 50 cycles, impacting battery performance.
- **Three times the stoichiometric amount of nickel** to prevent the formation of chlorine gas during charging. This excess also serves as a conductive backbone in the positive electrode that helps to obtain a stable cycling behaviour. Despite the substantial amount of nickel, SNCBs exhibit a significantly lower nickel content per kWh compared to Ni-MH cells described above.

Performance additional details:

SNCBs present a discharge rate of C/2 at *ca.* 90% of its capacity. They present capacities of 30 to 300 Ah depending on the size of the system.

A.10 Na-S Batteries

Chemical reactions involved:

Cathode:

Sulfur to sulfide: $S + 2e^- \leftrightharpoons S^{2-}$ E° = -0.5 V vs SHE **Eq. (33)**

Sulfur to disulfide: $2S + 2e^- \leftrightharpoons S_2^{2-}$ E° = -0.5 V vs SHE **Eq. (34)**

Sulfur to polysulfide: $x\,S + 2e^- \leftrightharpoons S_x^{2-}$ E° = depends on x (x = 2 - 8) **Eq. (35)**

Anode:

$Na^+ + e^- \leftrightharpoons Na$ E° = -2.7 V vs SHE **Eq. (36)**

Overall Cell:

$X\,S + 2\,Na \leftrightharpoons Na_2S_x$ E = 2.1 – 1.8 V **Eq. (37)**

Performance additional details:

Na-S molten salt batteries typically operate with charge/discharging rates of 1C to 6C. They can be find displaying capacities of several hundreds to a thousand Wh depending on the size of the system.

A.11 Fe-air Batteries

Chemical reactions involved:

Although using oxygen from the air seems like an attractive option in various electrochemical applications, the kinetics of oxygen's redox processes is sluggish, which means that catalysts play a fundamental role. Precious metals like platinum and palladium, along with more cost-effective materials such as transition metal oxides and carbon-based nanostructures, are added to the cathode structure to enhance the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER). Simultaneously, at the anode, iron oxidation yields 2 potential plateaus. The first one sees elemental iron oxidised to iron(II) oxide, $Fe(OH)_2$ (Equation 39). The second plateau presents 2 competitive electrochemical processes: the further oxidation of iron hydroxide $Fe(OH)_2$ to Fe^{3+} in iron oxohydroxide FeO(OH) on one hand, or to iron oxide (magnetite) $Fe^{II}Fe^{III}{}_2O_4$ on the other end (Equations 40 and 41). It is possible to preferentially favour one process via the design of specific electrolyte composition. For example, sodium silicate has been observed to favour $Fe(OH)_2$/FeOOH against $Fe(OH)_2$/Fe_3O_4 conversions.[129] This type of innovation presents a promising approach for developing more sustainable aqueous electrolytes. Although the overall cell reaction can be described by 2 plateaus, in recently commercialised devices, it is assumed that only the first plateau is used, delivering a voltage of 1.28 V.

Cathode:

$O_2 + 2\,H_2O + 4\,e^- \leftrightharpoons 4\,OH^-$ $E^0 = 0.4$ V vs SHE **Eq. (38)**

Anode:

<u>Plateau 1:</u>

$Fe + 2\,OH^- \leftrightharpoons Fe(OH)_2 + 2\,e^-$ $E^0 = -0.9$ V vs SHE **Eq. (39)**

<u>Plateau 2:</u>

$3\,Fe(OH)_2 + 2\,OH^- \leftrightharpoons Fe_3O_4 + 4\,H_2O + 2e^-$ $E^0 = -0.8$ V vs SHE **Eq. (40)**

$Fe(OH)_2 + OH^- \leftrightharpoons FeOOH + H_2O + e^-$ $E^0 = -0.6$ V vs SHE **Eq. (41)**

Overall Cell:

$O_2 + 2\,Fe + 2\,H_2O \leftrightharpoons 2\,Fe(OH)_2$ (first plateau) E = 1.3 V **Eq. (42)**

$3\,FeOH_2 + \frac{1}{2}\,O_2 \leftrightharpoons Fe_3O_4 + 3\,H_2O$ (second plateau) E = 1.2 V **Eq. (43)**

Performance additional details:

These batteries are designed for low discharge rates (C-rate of 0.01C) and offer capacities in the tens of kWh range, making them suitable for long-duration energy storage.

A.12 Li-air Batteries

Chemical reactions involved:

Currently, the lithium electrode redox processes behave reversibly only in non-aqueous electrolytes. For this reason, most of the interest in Li-air cells/batteries focuses on non-aqueous systems, where the reduction of oxygen is limited to 2 electrons, forming the peroxide (LiO_2). If the lithium anode can be protected from contact with water (e.g. with a suitable membrane) then oxygen reduction can proceed through a 4-electron process, which roughly doubles the accessible energy.

Anode: $Li \leftrightharpoons Li^+ + e^-$ E° = -3.0 V vs SHE **Eq. (44)**

Overall: $4\,Li + O_2 + 2\,H_2O \leftrightharpoons 4\,LiOH$ E = 3.4 V **Eq. (45)**

Cathode: $O_2 + 2\,e^- \leftrightharpoons O_2^{2-}$ E° = -0.1 V vs SHE **Eq. (46)**

Overall: $2\,Li + O_2 \leftrightharpoons Li_2O_2$ E = 3.0 V **Eq. (47)**

Performance additional details:

Concepts such as capacity and C-rate are not relevant at this stage of Li-air battery development, as the technology is still largely studied in research laboratories. However, the C-rate is not likely to exceed that of LIBs due to the necessity of incorporating extra membranes within the cell to effectively filter out contaminants such as carbon dioxide and water.

Appendix B SWOT Analyses

A SWOT analysis is a strategic planning tool used to evaluate internal and external factors that can affect an organisation, a person, a project, or a situation. They help make informed decisions to develop an effective strategy. They are constituted by 4 categories:

- Strengths (positive internal factors, advantages)
- Weaknesses (negative internal factors, disadvantages)
- Opportunities (positive external factors that could be exploited)
- Threats (negative external factors that could cause issues).

B.1 LABs

LABs are a well-established technology that consumers tend to be familiar with. They present an overall good safety profile and low-temperature performance, which make them suitable for a wide range of applications. However, their limitations, such as weight, limited cycle life, and lower energy density, represent challenges when compared to battery technologies such as lithium-ion systems. While they continue to be strong in markets such as automotive and stationary energy storage, their future will likely involve niche applications and potential hybridisation with newer technologies to address their shortcomings.

B.2 LIBs

The LIB field benefits from continuous innovation and competition among various chemistries, as each of them is designed to fit specific needs of diverse applications. LIBs as a group, are currently considered the preferred solution to a wide range of energy storage challenges. While NMC and NCA offer high energy density, they face challenges in thermal stability and supply chain constraints as they involve critical minerals such as cobalt and nickel. On the other hand, LFP present a lower energy density, but offers enhanced safety and longer cycle life. LMO and LTO present opportunities in niche applications like medical device powering (LMO) or grid energy storage (LTO), where thermal stability and fast charging are required.

B.3 SIBs

The advantages of SIBs are primarily due to the abundance and low cost of sodium versus lithium, making them promising alternative to LIBs for large-scale energy storage applications. However, SIBs currently face challenges in terms of lower energy density and limited commercialisation. Despite these limitations, ongoing research and development efforts are focused on improving their performance via the design of novel materials.

To further improve performance and stability, researchers are exploring the use of additives like film-forming compounds and redox additives. Ongoing research aims to optimise electrolyte formulations by balancing conductivity, stability, and overall battery performance. The demand for sustainable and cost-effective energy storage solutions will position SIBs as a significant player in the energy storage market, particularly in grid-scale applications and electric vehicles.

B.4 Ni-MH batteries

Ni-MH batteries offer several advantages, including higher energy density than Ni-Cd, environmental safety due to the absence of toxic heavy metals, reduced memory effect, a wide operating temperature range, and a longer cycle life. However, they also have limitations, such as higher production costs compared to Ni-Cd batteries, the use of rare earth metals in the anode, relatively high self-discharge rates, higher weight and lower energy density when compared to LIBs, and complex recycling processes. While Ni-MH batteries offer a balance of performance and environmental friendliness, addressing these limitations is essential for their continued development and wider adoption.

B.5 Ni-H_2 batteries

Ni-H_2 batteries' high energy density, long cycle life, and safety advantages make them a promising candidate for large-scale energy storage systems. However, high cost and complex design currently limit their widespread adoption. Some recent advancements, such as the development of aqueous Ni-H_2 batteries, have shown promise in reducing costs and improving performance, making them more competitive with other stationary storage technologies like LIBs.

B.6 V-RFBs

V-RFBs possess key strengths in independent power/energy scaling, long cycle life, relatively high safety, and low environmental impact, making them well-suited for grid-scale storage. However, weaknesses include lower energy density when compared to LIBs for example, higher initial cost, and temperature sensitivity. Opportunities lie in the growing renewable energy market, potential vanadium price reductions, and technological advancements, while threats arise from competition with other storage technologies. Overall, V-RFBs offer a promising solution for large-scale energy storage, but must overcome cost and performance challenges to fully capitalise on market opportunities.

B.7 Fe-RFBs

Fe-RFBs' key strength reside in low material cost, high safety, long cycle life, and wide operating temperature range, making them attractive for long-duration energy storage. However, weaknesses include lower energy density or potential hydrogen evolution. Opportunities arise from the growing grid-scale storage market, cost competitiveness driven by abundant iron, and ongoing technological advancements. Threats include competition from other battery technologies, especially LIBs, and the challenges of scaling up production. Overall, Fe-RFBs present a promising cost-effective solution for large-scale storage.

B.8 Zn/Br_2-RFBs

The strengths of Zn/Br_2-RFBs reside in higher energy density (compared to other RFBs), relatively low material cost, >5,000 cycle life, and technological maturity. Key weaknesses include challenges related to bromine management (handling, corrosion), lower efficiency than some alternatives, zinc dendrite formation, and self-discharge. Opportunities exist in the expanding grid-scale storage market, potential improvements in bromine management, and cost reductions through economies of scale. Threats stem from strong competition from LIBs, safety concerns surrounding bromine, and the emergence of alternative RFB chemistries. Overall, Zn/Br_2-RFBs offer a competitive energy density within the RFB landscape but must overcome bromine-related challenges and competition to achieve wider market adoption.

B.9 SNCBs

SNCBs' strengths primarily reside in a long lifespan with minimal maintenance, high power density, and robust tolerance to overcharging and overdischarging. Their modular design enables tailored performance to the specific applications. While operating at high temperatures and requiring higher initial investment than LABs for example, they perform well in grid-scale energy storage or 'off'-grid industrial applications. These systems offer a rapid solution for large-scale emergency power, thanks to their ease of transportation, a key advantage over lithium-ion systems. However, competition from evolving technologies like LIBs and RFBs poses a significant challenge.

B.10 Na-S batteries

Na-S batteries present high energy density, long cycle life, high efficiency, and a mature technology base. These strengths make them strong candidate for grid-scale energy storage and industrial applications (UPS or off-grid). However, their high operating temperature, safety concerns, and long startup time pose significant challenges exposing them to the threat of competition from evolving LIBs and RFBs, which are constantly improving in terms of performance and cost-effectiveness.

B.11 Fe-air batteries

Fe-air batteries appear to be one of the most promising candidates currently investigated with high theoretical energy density and based on abundant, inexpensive, and environmentally friendly materials. They offer high scalability and good safety. However, they suffer from low power density and limitations associated with the oxygen cathode, leading to high self-discharge and reduced efficiency. Furthermore, the technology is still nascent, requiring ongoing research and development. Opportunities lie in grid-scale energy storage and emerging markets for renewable energy integration. However, competition from established technologies like LIBs, RFBs, and pumped hydro storage, along with technological limitations related to rechargeability, cost, and cycle life, pose significant threats to their widespread adoption.

B.12 Li-air batteries

Li-air batteries present an exceptionally high theoretical energy density, readily available oxygen as one of the electrode materials, and have the potential for using environmentally friendly cathode materials. These factors, make them a very promising candidate for renewable energy storage solutions. Researchers will still have to overcome numerous challenges linked to the complex physiochemistry, their sensitivity to impurities in the air, safety concerns, anticipated low power density, and short cycle life. As all of the battery chemistries discussed in this report, they could suffer from the fierce competition with rapidly evolving LIBs technologies. However, the current main threats reside in manufacturing complexities, and potential cost increases associated with the use of noble metal as catalysts on the cathode side.

Appendix C Terminology

C.1 Performance factors driving the best market segment

When assessing the commercial viability of the 12 battery chemistries reported herein, section *2.2.2 Scale of application* details the scale of development of BESS when integrated with renewable energy solar generation. The specific application of a chemistry for residential, community, commercial or industrial market segment is based on several performance drivers:

- **Cost:** The cost of battery systems is a critical factor in determining their feasibility for grid-connected applications. LIBs are currently the most cost-effective option for many residential and commercial applications, but costs are declining for other technologies, such as SIBs and RFBs.
- **Energy Density and Power Density**: Energy density determines the amount of energy stored per unit volume or weight, while power density determines the rate at which energy can be delivered. These factors are essentials to determine the suitability of a battery chemistry for specific applications.
- **Lifespan and Cycle Life**: The lifespan and cycle life of a battery determine its longevity and overall performance.
- **Safety**: Safety considerations are a required for all battery chemistries.
- **Environmental Impact:** The environmental impact of battery production, operation, and disposal must be carefully considered.

C.2 Glossary

Anion	A negatively charged ion
Anode	The electrode where oxidation occurs (loss of electrons)
Anolyte	In RFBs, the electrolyte containing redox-active chemical species surrounding the anode
Battery	A device that converts chemical energy into electrical energy
Capacity	The amount of electric charge a battery can deliver, expressed in Ah
Catalyst	A chemical that accelerates a chemical reaction without being consumed
Cathode	The electrode where reduction occurs (gain of electrons)
Catholyte	In RFBs, the electrolyte containing redox-active chemical species surrounding the cathode
Cation	A positively charged ion
Cell	A basic electrochemical unit making up a battery
Coin cell	A small, disc-shape form factor for a battery
C-rate	The rate at which a battery is discharged or charged relative to its capacity
Current collector	A conductive component that facilitates the electron flow from the battery to the external circuit
Cycle life	The number of charge and discharge cycles a battery can endure
Cylindrical cell	A cylinder-shape form factor for a battery
Distributed storage	A system where energy is stored in decentralised systems located near the point of consumption, as opposed to centralised large-scale storage
Electrode	A component of a battery where redox reaction occurs
Electrolyte	A ‘bath’ containing free ions that conducts electricity. It can be under a solid or liquid state
Energy density	The amount of energy stored per unit of mass or volume, expressed in Wh/kg or Wh/L, respectively
Form factor	The physical shape and size of a battery
Intercalation	The reversible insertion of ions into an electrode material's lattice structure
Ion	An atom or molecule with an electrical charge
Lattice	The regular arrangement of atoms or ions in a crystalline solid
Levelised Cost of Storage	The total lifetime cost of an energy storage system, expressed per unit of energy delivered
Membrane	*see Separator*
Nominal voltage	The typical operating voltage of a battery's cell
Pouch cell	A flexible, laminated pouch-shape form factor for a battery
Power density	The rate at which a battery can deliver energy per unit of mass or volume, expressed in Wh/kg or Wh/L, respectively. It can be expressed in a surfacic form, in W/cm^2, if the surface of the electrode is the meaningful parameter (in RFBs)
Primary battery	A non-rechargeable battery
Prismatic cell	A flat- or rectangular-shape form factor for a battery
Salt	A neutral compound formed by the association of cations and anions
Secondary battery	A rechargeable battery
Self-discharge	The gradual loss of charge in a battery when not in use
Separator	A porous material that prevents direct contact between electrodes
Specific energy	*see Energy Density*
Specific power	*see Power Density*
Stack	Multiple electrochemical cells or batteries connected in a pack
Voltage	The electrical potential difference between 2 electrodes
Zebra battery	Branded name for sodium-nickel chloride batteries (SNCBs)

C.3 Abbreviations

Ah	Amper hour	**m^2**	Square meter
Zn/Br$_2$-RFB	Zinc Bromine Redox-Flow Battery	**min**	Minute
ARENA	Australian Renewable Energy Agency	**MO**	Metal Oxide
BESS	Battery Energy Storage System	**MW**	Megawatt
BMS	Battery Management System	**Na-S**	Sodium-Sulfur Molten Salt (battery)
CCS	Carbon Capture and Storage	**NCA**	Nickel Cobalt Aluminium (a type of lithium-ion battery)
CCUS	Carbon Capture, Utilisation and Storage	**NEM**	National Energy Market
cm^2	Square centimetre	**Ni-Cd**	Nickel Cadmium (battery)
CRI	Commercial Readiness Index	**Ni-H$_2$**	Nickel-Hydrogen (battery)
CSIRO	Commonwealth Scientific and Industrial Research Organisation	**Ni-MH**	Nickel Metal Hydride (battery)
CST	Concentrated Solar Thermal	**NMC**	Nickel Manganese Cobalt (a type of lithium-ion battery)
DES	Deep Eutectic Solvent	**°C**	Celsius degree
e$^-$	Electron	**PV**	Photovoltaic
ESS	Energy Storage Systems	**R&D**	Research and Development
EU	European Union	**RE**	Renewable Energy
Fe-air	Iron-air battery	**RFB**	Redox-Flow Battery
Fe-RFB	Iron Redox-Flow Battery	**s**	Second (unit of time)
FiT	Feed-in-Tariff	**SDG**	Sustainable Development Goals
GDP	Gross Domestic Product	**SEDA**	Sustainable Energy Development Authority Malaysia
GHG	Greenhouse Gas	**SEI**	Solid-Electrolyte Interphase
GW	Giga Watt	**SHE**	Standard Hydrogen Electrode
h	Hour	**SIB**	Sodium-Ion Battery
HECO	Hawai'ian Electric Co	**SNCB**	Sodium-Nickel Chloride Battery
IEA	International Energy Agency	**SWOT**	Strengths, Weaknesses, Opportunities and Threats
kg	Kilogram	**TNB**	Tenaga Nasional Berhad
KPI	Key Performance Indicator	**TRL**	Technology Readiness Level
kWh	kilo Watt hour	**UK**	United Kingdom
L	Liter	**UN**	United Nations
LAB	Lead-Acid Battery	**UNFCC**	United Nations Framework Convention on Climate Change
LCO	Lithium Cobalt Oxide (a type of lithium-ion Battery)	**UPS**	Uninterruptible Power Supply
LCOS	Levelised Cost of Storage	**V**	Volt
LFP	Lithium Iron Phosphate (a type of lithium-ion Battery)	**VPP**	Virtual Power Plant
Li-air	Lithium-air battery	**VRE**	Variable Renewable Energy (generation)
LIB	Lithium-Ion Battery	**V-RFB**	Vanadium Redox-Flow Battery
LMO	Lithium Manganese Oxide (a type of Lithium-ion battery)	**VRLA**	Valve-Regulated Lead-Acid
LTO	Lithium Titanate Oxide (a type of lithium-ion battery)	**Wh**	Watt hour
M	Metal	**wt%**	Percentage per weight

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