UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT


Technical and statistical report

# Changing battery chemistries and implications for critical minerals supply chains

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# Abbreviations

°C ............ degrees Celsius
EV ............ electric vehicle
GHG ......... greenhouse gas
kWh .......... kilowatt hour
LCO ......... lithium cobalt oxide
LFP .......... lithium iron phosphate
Li-S .......... lithium-sulfur
LIB ........... lithium-ion battery
LMB ......... liquid-metal battery
LMO ......... lithium manganese oxide
MAB ......... metal-air battery
MIB .......... metal-ion battery
NCA ......... nickel cobalt aluminium oxide
NMC ........ nickel manganese cobalt
PV ............ solar photovoltaics
R&D ......... research and development
RFB .......... redox flow battery
SIB ........... sodium-ion battery
SSB .......... solid-state battery
UNCTAD ... United Nations Conference on Trade and Development
US$ .......... United States dollar
VRFB ........ vanadium redox flow battery
Wh/kg ...... watt-hour per kilogram

# Symbols and formulas

Al .............. aluminium
Ca ............ calcium
CO2 ......... carbon dioxide
e- ............. electron
K .............. potassium
Mg ............ magnesium
Na ............ sodium
O2 ............ oxigen gas
Rb ............ rubidium
Zn ............. zinc

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# Key messages

**As the energy transition rapidly expands, demand for critical minerals used in battery technologies is expected to rise sharply.** These minerals include lithium, cobalt, nickel, phosphate and graphite – along with emerging materials like sodium, zinc, sulfur, and silicon. This increase is anticipated to expand supply in producing countries and potentially lead to higher export revenues, providing funds that governments can reinvest in other economic sectors.

**Developing countries with raw materials used for battery manufacturing can leverage this opportunity to spur industrial development** by investing in manufacturing facilities, and implementing value addition activities which will generate jobs in mining, processing and further downstream sectors, contributing to economic diversification and resilience.

**Innovations in battery technologies and chemistries are pivotal for the energy transition.** These advancements enhance energy storage capabilities, improve battery efficiency and performance, and utilize more sustainable and less environmentally damaging materials.

- Battery technologies provide advanced energy storage solutions, ensuring a stable and resilient energy grid, enhancing energy access in developing countries and fostering economic growth.
- Advancements in battery technologies and chemistries also have a significant impact on the global transportation sector, supporting longer ranges and faster charging times, making electric vehicles (EVs) more appealing to consumers.
- Evolving battery chemistries can reduce costs, mitigate supply chain risks, and potentially address ethical concerns related to mining the minerals used in these technologies, such as child labour.

**To fully realize the potential of new battery technologies and chemistries, governments should address challenges** such as safety, scalability, skills gap, and using less toxic materials to reduce environmental impact. Robust supply chains for alternative materials must also be established.

**Policy priorities** to support the sustainable development of industries centred around critical minerals should focus on:

- **Targeted education and training programmes** to develop a workforce capable of supporting the growing battery and energy storage sectors;
- **Infrastructure investment** to scale up industrial production and expand supply chains;
- **Reform extraction and processing regulations** to ensure sustainability, value addition and community benefits;
- **Strengthen transparency and accountability in supply chains**;
- **Support research and development (R&D)** to build upon new battery chemistries and improve existing ones; and
- **Foster collaboration between public and private sectors and promote international partnerships** to share knowledge and best practices.

Harnessing the opportunities in battery technologies and critical minerals supply chains can drive economic growth, create jobs, and foster a sustainable and equitable global energy future.

Chapter I

# Introduction

# Introduction

**Global carbon dioxide ($CO_2$) emissions from the energy sector are increasing despite ongoing global efforts to mitigate them. In 2023, energy-related $CO_2$ emissions reached a record high of 37.4 billion metric tons, a 1.3 per cent increase from the previous year.1 This rise highlights the imperative of energy transition, from polluting fossil fuels to the widespread adoption of clean energy technologies within the energy mix. Among these technologies, batteries and battery storage systems with improved or new battery chemistries will play a crucial role in the energy transition.**

Batteries and battery storage systems enhance the efficiency and reliability of renewable sources by storing excess energy generated from solar and wind power when available and releasing it when needed. This capability addresses the intermittency of these sources, ensuring a more stable and dependable energy supply. This flexibility is crucial for balancing supply and demand on the grid, ensuring reliable energy delivery. In regions with limited access to a stable grid, battery storage can complement local renewable sources, reducing reliance on fossil fuels and enhancing energy independence. Additionally, batteries and energy storage systems are vital for electrifying transportation, facilitating the adoption of EVs, and reducing GHG emissions in the transportation sector, which accounts for 16 per cent of global emissions.[2]

Given the wide range of benefits that improved and new battery chemistries bring to battery storage systems in driving the energy transition, greater focus must be placed on battery performance – the battery's ability to store and deliver energy efficiently and reliably, largely driven by their chemistries. Moreover, the scalability, efficiency,[3] and cost-effectiveness of battery technologies will be instrumental in building a more resilient and decarbonized energy system. As more consumers and industries transition to EVs and invest in renewable energy storage solutions, the demand for high-performance batteries will grow significantly in the coming years. This growth will likely exert significant pressure on the supply chain for raw materials essential to battery production, also known as critical energy transition minerals. It will also intensify efforts to develop chemistries that further enhance battery performance characteristics.

Policymakers and other stakeholders focused on mitigating climate change are exploring collaborative approaches to implement and enhance initiatives that promote clean energy technologies.

1 International Energy Agency (2024). CO2 Emissions in 2023: Executive Summary. Available at https://www.iea.org/reports/co2-emissions-in-2023/executive-summary

2 European Commission: Joint Research Centre (2024). GHG emissions of all world countries. Publications Office of the European Union. Available at https://data.europa.eu/doi/10.2760/4002897

3 Battery efficiency refers to the ratio of the energy output from the battery to the energy input required to charge it. It is a measure of how effectively the battery converts the stored energy int usable power with minimal losses.

These efforts include integrating renewable sources into the energy mix, adopting nature-based solutions (e.g. afforestation and reforestation),[4] advancing carbon capture and storage technologies, and scaling up the deployment of EVs and energy storage solutions.

## Objectives

This report analyses trends in battery chemistry development and the key chemistries driving energy storage and the energy transition, focusing on current and emerging technologies. It evaluates potential battery chemistries and the critical minerals that are required, examining the implications of these advancements.

## Structure

This report is organized into four chapters, including this introductory chapter. Chapter II discusses trends in battery technology and chemistries, potential breakthroughs, performance characteristics of selected battery technologies, and their respective strengths and weaknesses. Chapter III examines the opportunities and challenges that evolving battery chemistries present for stakeholders in the battery minerals sector, including governments, battery manufacturers, mining companies and consumers. Chapter IV examines the policy and regulatory landscape that has shaped the development of battery chemistries and highlights key policy areas to advance battery innovation.

[4] For an example, see: The White House (2023). Biden-Harris Administration Expands Use of Nature-Based Solutions to Better Protect Communities from the Impacts of Climate Change. Available at https://bidenwhitehouse.archives.gov/ostp/news-updates/2023/12/09/biden-harris-administration-expands-use-of-nature-based-solutions-to-better-protect-communities-from-the-impacts-of-climate-change/

Chapter II

# Battery technologies and chemistries

# Battery technologies and chemistries

**Innovation in batteries relies on the complex chemistry of the battery materials. Their specific combinations determine how electrical energy is stored and released, directly influencing a battery's performance, lifespan and suitability for various applications.**

## Batteries and chemistry

The core function of a battery lies in its chemistry — a combination of chemicals that facilitates reactions within the cells, transforming electrical energy into chemical energy during charging and reversing the process during discharge. The chemical composition within the cells dictates the power level and energy storage capacity of batteries, directly influencing their performance and ability to store excess energy during periods of low demand and discharge it when demand peaks, ensuring a consistent power supply. As various sectors increasingly depend on electric energy, battery technologies and chemistry are rapidly evolving. This evolution has led scientists, researchers, industries, and governments to explore new frontiers, aiming to develop a new generation of highly efficient electrical energy storage solutions that offer enhanced safety, use less toxic materials and address concerns over resource availability and cost.

This chapter examines lithium-ion technology, the cornerstone of modern energy storage solutions, and newer technologies and their chemistries, including metal-ion, metal-air, solid-state, liquid metal and flow batteries.

These newer technologies aim to overcome some of the limitations of lithium-ion technology, such as the reliance on scarce and expensive materials like cobalt and the environmental impact of mining these materials.

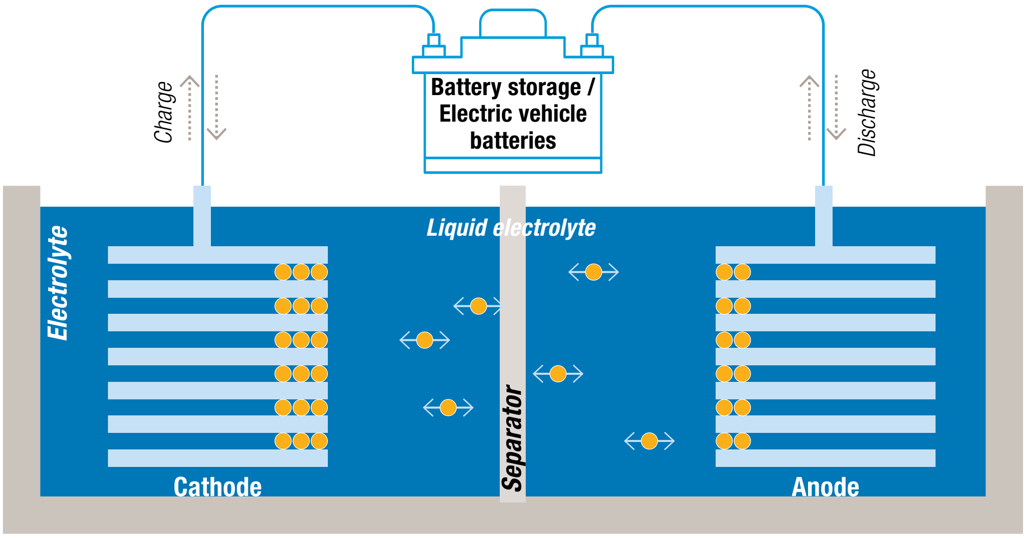
## Lithium-ion technology

Lithium-ion technology currently dominates the battery market, holding approximately half of the market share as of 2022.[5] Batteries using this technology comprise an anode (negative electrode), a cathode (positive electrode), an electrolyte as a conductor, and two current collectors (positive and negative). Electric current is generated by the movement of lithium ions intercalated within the cathode towards the anode, creating free electrons in the anode leading to a charge at the positive current collector.[6] The electrical current then flows from the current collector through the device being powered (e.g. cell phone, Battery storage, EV etc.) to the negative current collector. Figure 1 illustrates a schematic of a lithium-ion battery (LIB).

The common active material used in the LIB is lithium combined with other materials such as the cathode and graphite as the anode.

5 Statzon (2024). Global Battery Market Keeps Expanding to Reach USD 424 billion by 2030. Available at https://statzon.com/insights/global-battery-market
6 "Intercalation" refers to the reversible inclusion or insertion of a molecule (or ion) int compounds with layered structures. upsbatterycenter.com (2014). How Does Intercalation Work in Batteries? 8 May. Available at https://blog.upsbatterycenter.com/intercalation-work-batteries/

## Figure 1
### Schematic representation of a lithium-ion battery




*Source:* Adapted from Huang P, Wang Q, Li K et al (2015). The combustion behavior of large scale lithium titanate battery. Sci Rep 5, 7788 (2015). Available at: https://doi.org/10.1038/srep07788

LIB cathodes have evolved over time, and some examples include lithium manganese oxide (LMO), lithium cobalt oxide (LCO), nickel manganese cobalt (NMC), lithium iron phosphate (LFP) and nickel cobalt aluminium oxide (NCA). The diverse chemistries underscore lithium's versatility in creating batteries with varying characteristics tailored to meet the demands of a wide range of technological applications including EVs, renewable energy storage, consumer electronics and industrial equipment. Battery scientists also modify the proportions of active materials within existing lithium-ion chemistries to enhance efficiency and performance while reducing costs. For example, the NMC 811 chemistry, comprising 80 per cent nickel, 10 per cent manganese and 10 per cent cobalt (8:1:1), represents a significant advancement from the older NMC 111 and widely used NMC 622. With its higher nickel concentration and lower manganese and cobalt content, NMC 811 delivers batteries with enhanced energy density while maintaining cost-effectiveness.[7]

## Metal-ion battery

Battery scientists have explored alternative materials for use in lithium-ion technology, investigating potential substitutes for lithium. Elements such as sodium (Na), magnesium (Mg), aluminium (Al), calcium (Ca), zinc (Zn), potassium (K), and rubidium (Rb) have been considered owing to their high chemical energy potential. Batteries employing these materials are often called metal-ion batteries (MIBs). Their operating mechanisms are similar to LIBs, involving the intercalation of ions, which induces a flow of electrons in the external circuit to generate a current (see Figure 1). The use of these alternative raw materials in MIBs reflects ongoing efforts to diversify and optimize battery technologies, aiming for solutions that offer advantages in cost, material availability, and reduced environmental impact.

MIBs are in the technology-ready phase, gradually advancing towards commercialization, marking a significant shift in the energy storage technology landscape dominated by LIBs.

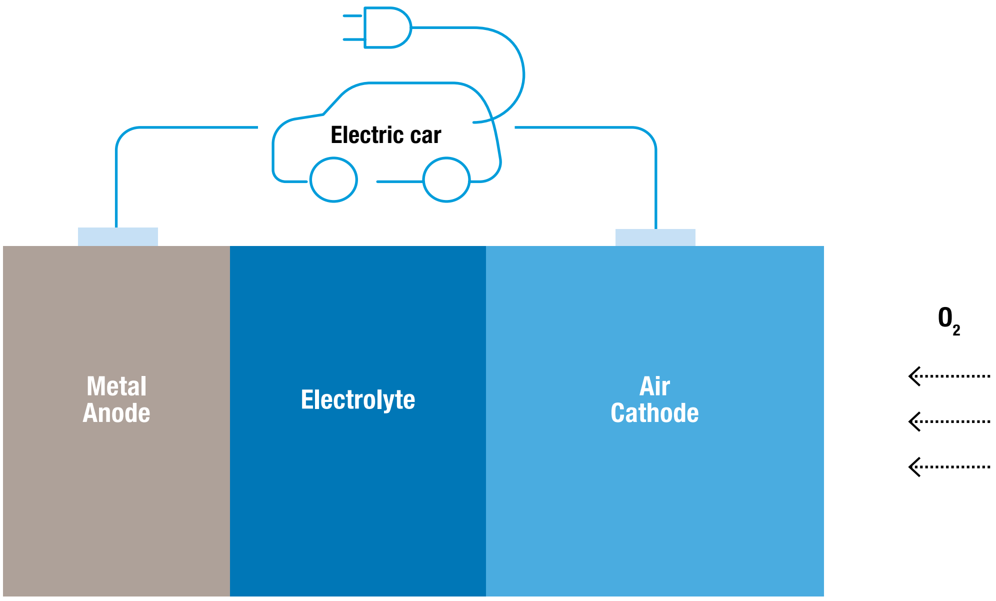
7 Nickel Institute (2024). Powering the future: advances in nickel-based batteries. 17 October. Available at https://nickelinstitute.org/en/blog/2024/october/powering-the-future-advances-in-nickel-based-batteries/

Among these, the sodium-ion battery (SIB) emerges as the most promising and attractive alternative to LIBs.[8] Several pilot plants are in operation, and smaller factories are commencing production, albeit at a scale of only a few gigawatt-hours per year.[9] Some forecasts indicate that by 2025, approximately 10 gigawatt-hours of SIBs will be installed.[10] To provide context to this estimate, one gigawatt-hour of energy is equivalent to the output of 2.469 million PV panels, each with a capacity of 405 watts, or enough power for 9,090 Nissan Leaf EVs.[11] This surge in capacity is expected as substantial manufacturing capabilities come online and existing lithium-ion production lines undergo conversion to sodium-ion production, underscoring the imminent impact of sodium-ion technology on the energy storage landscape.

## Metal-air battery

The metal-air battery (MAB) represents another frontier in battery technology that is undergoing extensive R&D to rival the energy density of LIBs. MABs operate by using a metal as the anode, a porous carbon cathode containing a catalyst, and an electrolyte. The anode materials may include alkali metals such as lithium, potassium or sodium; alkaline earth metals like calcium and magnesium; metalloids like silicon; aluminium; or transition elements like iron and zinc.[12] The electrolyte can be aqueous or non-aqueous, depending on the anode used.[13]

**Figure 2**
**Schematic representation of a metal-air battery**




*Source:* http://large.stanford.edu/courses/2016/ph240/abate1/

8 International Energy Agency (2023). Global EV Outlook 2023: Trends in batteries. Available at https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries
9 IDTechEx (2023). Cheaper and Safer Sodium-Ion Batteries on the Horizon. 14 July. Available at: https://www.idtechex.com/en/research-article/cheaper-and-safer-sodium-ion-batteries-on-the-horizon/29608
10 Ibid.
11 US Department of Energy (2024). How Much Power is 1 Gigawatt? 21 August. Available at https://www.energy.gov/eere/articles/how-much-power-1-gigawatt
12 Ahuja D.et al (2021), Journal of Physics and Conference Series, 1913 012065. Metal Air Battery: A sustainable and low cost material for energy storage. Available at: https://iopscience.iop.org/article/10.1088/1742-6596/1913/1/012065/pdf
13 European Association of Storage of Energy (undated). Metal-air battery: Electrochemical energy storage. Available at: https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_M-Air.pdf

MABs work by atmospheric oxygen diffusing through the porous carbon cathode, where a catalyst facilitates its reduction while the metal is oxidized in the anode.[14] In this process, the metal transforms into ions at the anode, while oxygen forms hydroxide ions at the cathode. This reaction generates electrons, and the metallic ions dissolve into the electrolyte.[15] This reaction is reversed during charging, illustrating the reversible nature of MABs.[16] Figure 2 shows a schematic representation of a MAB.

An emerging variant of MABs in development is the iron air battery, which uses a water-based electrolyte and stores energy using reversible rusting.[17] Iron, being an abundant material on Earth, makes this technology particularly promising. Its potential lies in achieving lower battery costs due to iron's abundance and affordability as a raw material.

## Solid-state batteries

Solid-state batteries (SSBs) employ the same technology as LIBs but have the flexibility to use a wide range of chemistries. The key difference is in the electrolyte: while LIBs and related chemistries use a liquid electrolyte to facilitate charge movement, SSBs use solid materials such as ceramics, sulfides (e.g. lithium sulfide), or solid polymers.[18]

The working mechanism of SSBs parallels that of LIBs, as both involve ion movement accompanied by the transfer of electrons; initiating oxidation-reduction reactions within the battery's materials. During discharge, the cathode undergoes reduction by gaining electrons, while the anode undergoes oxidation by losing electrons. This flow of electrons from the anode to the cathode generates the electric current that powers external devices, while the reverse process occurs during charging.[19]

Most cathode and anode materials used in LIBs can also be applied in SSBs, with only a few exceptions due to the intrinsic instability between electrodes and solid electrolytes.[20] Figure 3 shows a schematic of an SSB. Numerous variants of SSBs are in development and making their way to market.

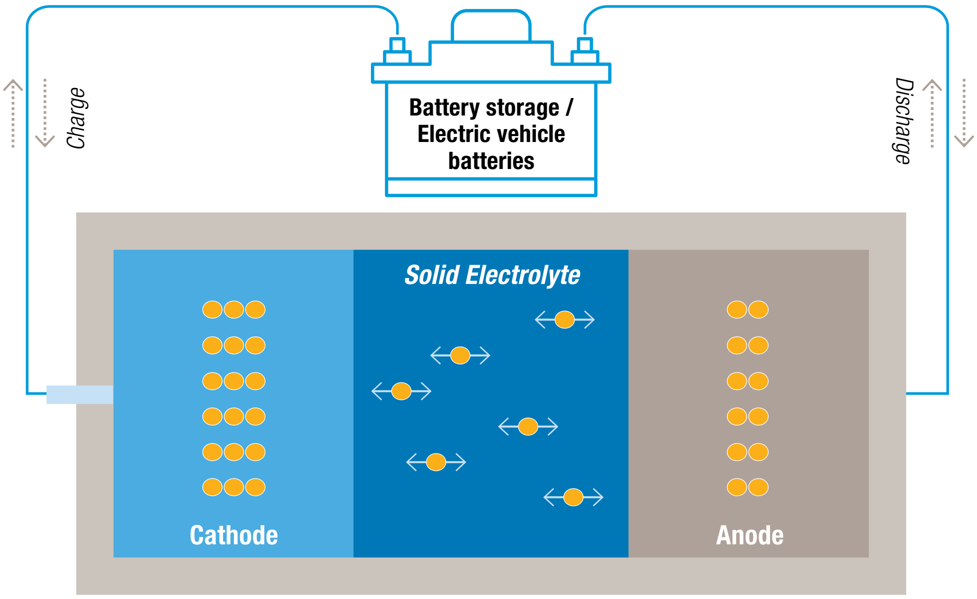
## Liquid metal battery

The liquid metal battery (LMB) technology employs a chemistry based on alloying and de-alloying different metals, typically involving molten electrodes and a molten salt electrolyte.[21] This concept involves reversible reactions within the battery during charging and discharging processes. An example consists of a dense molten metal cathode at the bottom, an intermediate density salt electrolyte, and a light metal alloy at the top.[22]

During discharge, the metal alloy breaks down into metal ions and electrons. The ions migrate towards the dense metal layer, while electrons flow through an external circuit, generating an electric current.

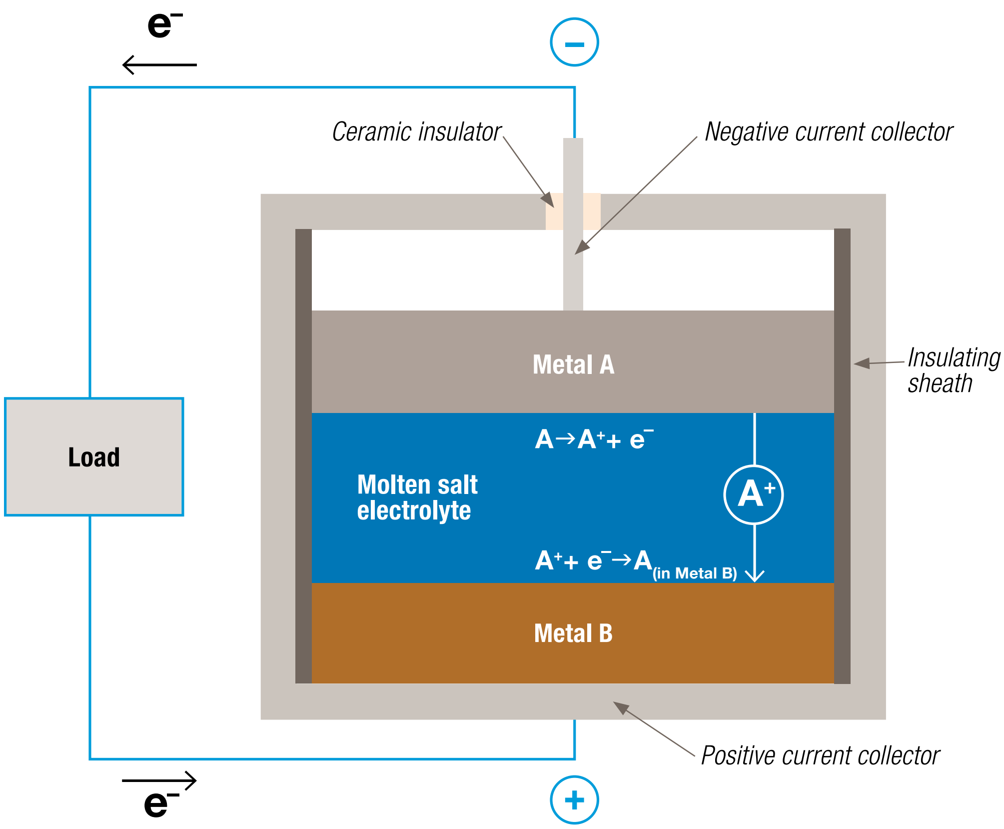
14 European Association of Storage of Energy (undated). Metal-air battery: Electrochemical energy storage. Available at: https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_M-Air.pdf
15 Sauer Energy International (2022). All About Metal-Air Batteries. 31 January. Available at https://www.saurenergy.com/solar-energy-news/all-about-metal-air-batteries
16 Ibid.
17 MIT Technology Review (2023). What's next for batteries. 4 January. Available at https://www.technologyreview.com/2023/01/04/1066141/whats-next-for-batteries/ /
18 Larsen J. (2024). What materials are in a solid state battery and their impact on performance and safety. Available at https://batteryspotlight.com/what-materials-are-in-a-solid-state-battery/
19 American Chemical Society (2022). Solid State Batteries Volume 1: Emerging Materials and Applications. Chapter 1. Solid-State Batteries: An Introduction. Available at https://pubs.acs.org/doi/pdf/10.1021/bk-2022-1413.ch001
20 Ibid.
21 IEEE Spectrum (2023). Liquid-Metal Battery Will Be on the Grid Next Year. 7 August. Available at https://spectrum.ieee.org/liquid-metal-battery
22 GreyB (Undated). Ambri's Liquid Metal Battery is Reshaping Energy Storage. Available at https://www.greyb.com/blog/ambri-liquid-metal-battery/#elementor-toc__heading-anchor-0

## Figure 3
**Schematic representation of a solid-state battery**




*Source:* Adopted from Sousa R, Sousa JA, Ribeir JF, Goncalves LM, Correia JH (2013). All-solid-state batteries: An overview for bi applications. Available at https://ieeexplore.ieee.org/document/6518400

## Figure 4
**Schematic representation of a liquid metal battery**




*Source:* Adopted from MIT Energy Initiative. MIT News (2016). A battery made of molten metals. 12 January. Available at https://news.mit.edu/2016/battery-molten-metals-0112 /

This discharge process culminates in the formation of a homogeneous new alloy inside the battery, located beneath the electrolyte layer.[23] One example is the Ambri Liquid Metal Battery, which uses antimony as the heavy metal, calcium alloy as light metal, and a molten salt as the electrolyte. Figure 4 shows a schematic diagram of the LMB.

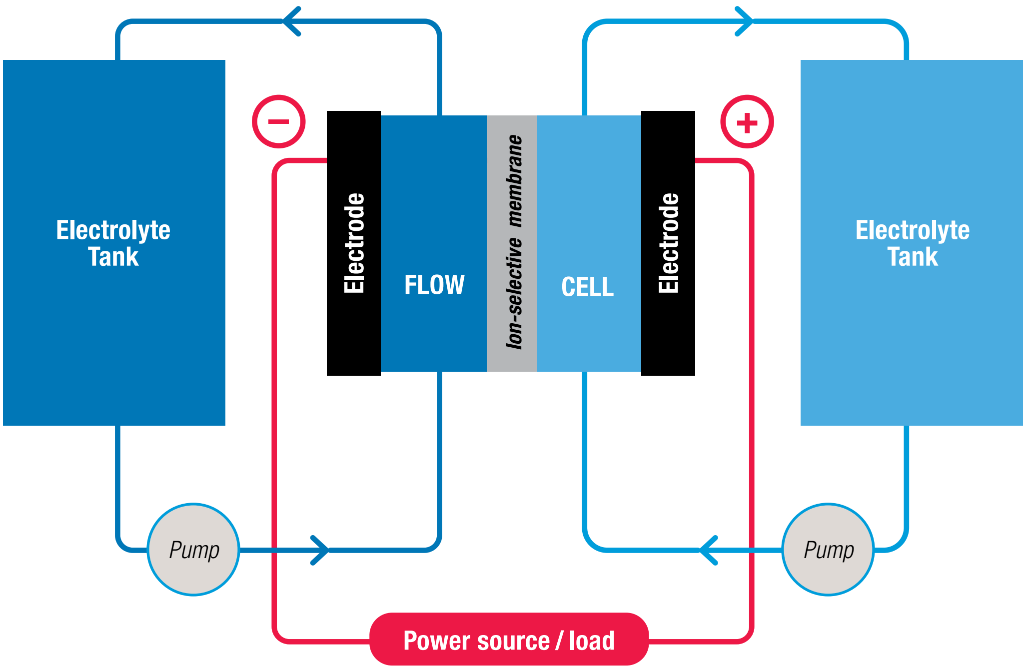
The reactions in LMBs are initiated at high heat so that the components are in a molten state, but generate their own heat to sustain the reactions.[24] To recharge, an electrical current is applied, reversing the reaction. This process returns the calcium alloy and antimony to their original positions, resetting the system for reuse.[25]

## Flow battery

Flow batteries offer a distinct energy storage solution. Unlike conventional batteries that store energy in solid electrodes, flow batteries use liquid electrolytes containing chemicals that change state during charge and discharge cycles. This allows for independent scaling of energy capacity, which is related to electrolyte volume, and power output, determined by electrode surface area. Figure 5 shows a schematic diagram of a flow battery.

Redox flow batteries using vanadium (VRFBs) in different oxidation states as the electrolyte on both sides of the system is the most widely used configuration.[26]

**Figure 5**
**Schematic representation of a flow battery**




*Source:* Adopted from International Flow Battery Forum (undated). What is a flow battery? Available at https://flowbatteryforum.com/what-is-a-flow-battery/

[23] GreyB (Undated). Ambri's Liquid Metal Battery is Reshaping Energy Storage. Available at https://www.greyb.com/blog/ambri-liquid-metal-battery/#elementor-toc__heading-anchor-0
[24] Ibid.
[25] Ibid
[26] MIT News (2023). Flow batteries for grid-scale energy storage. 7 April. Available at https://news.mit.edu/2023/flow-batteries-grid-scale-energy-storage-0407

During charging, electrons are transferred from one vanadium ion to another, changing oxidation state and storing energy as chemical potential energy within the vanadium ions. During discharge, the reverse process occurs, releasing stored energy.[27] Other flow battery chemistries employ materials like zinc-bromine or iron-chromium.[28]

## Anode chemistries

Future anode chemistries hold the potential to revolutionize next-generation batteries, offering both enhanced performance and greater sustainability, thereby reshaping the battery technology landscape.

Graphite-based anodes are a common choice in many battery technologies due to their excellent conductivity, structural suitability for intercalation, and ability to withstand repeated charge and discharge cycles without significant degradation. However, there is a growing trend of incorporating small quantities of silicon into graphite anodes. This innovation leverages silicon's higher theoretical capacity to store lithium ions, presenting potential advancements in energy storage capabilities and overall battery performance.[29]

Researchers are also investigating replacing graphite anodes with only silicon to further enhance battery performance. However, this approach presents challenges as silicon anodes are prone to swell and shrink during charge and discharge cycles, leading to mechanical degradation and reduced battery stability.[30]

Researchers are exploring ways to overcome these challenges and harness silicon's full potential. For example, silicon can be processed into micro/nanometer-sized particles and fine-tuned with polymer and metal coatings, allowing expansion and contraction in a controlled manner.[31]

Polymers have also been successfully used in LIBs due to their outstanding properties. Their low density helps reduce the overall weight of batteries, they are easy to process, and they have excellent thermal, mechanical and electrical properties, making them versatile for battery applications.[32]

## Implications of changing battery chemistries

The new frontiers in battery chemistry are likely to reshape demand patterns for raw materials, diversify material requirements, drive innovation in sourcing and recycling, and impact trade dynamics. These shifts arise from the varying types and volumes of minerals needed across different clean energy technologies, and even within a particular technology (e.g. electric vehicles and battery storage). For example, new battery chemistries could alter the minerals used to manufacture electrodes (anode and cathode) within the dominant lithium-ion technology. Additionally, the adoption of advanced technology to replace LIBs may introduce demand for materials that were not previously integral to rechargeable battery technologies.

New battery chemistries have significant implications for resource-rich countries.

27 Ruiyong C, Sangwon K and Zhenjun C (2017). Redox Flow Batteries: Fundamentals and Applications. Available at DOI: 10.5772/intechopen.68752

28 International Flow Battery Forum (Undated). What is a flow battery? Available at https://flowbatteryforum.com/what-is-a-flow-battery/

29 IEEE Spectrum (2023). The Age of Silicon Is Here…for Batteries: The mainstay material of electronics is now yielding better energy storage. 4 May. Available at https://spectrum.ieee.org/silicon-anode-battery

30 Ibid.

31 Cleantech Group (2023). Silicon Anodes Can Improve EV Battery Density and Extend Range Without Cost Increase. Available at https://www.cleantech.com/silicon-anodes-can-improve-ev-battery-density-and-extend-range-without-cost-increase/

32 Costa CM, Lizundia E, Lanceros-MÃ©ndez S (2020). Polymers for advanced lithium-ion batteries: State of the art and future needs on polymers for the different battery components. Progress in Energy and Combustion Science, Volume 79, 2020, 100846, ISSN 0360-1285. Available at https://doi.org/10.1016/j.pecs.2020.100846

On the one hand, increased demand for raw materials can attract investments in the extractive sector, expanding their mining operations. This can potentially boost export revenues, job creation and poverty reduction. It could also foster infrastructure development that benefits various industries and local communities and the development of related downstream industries, contributing to overall economic development.

On the other hand, the emergence of new chemistries brings challenges, such as ensuring the supply of newly demanded minerals while addressing bad mining practices, human rights issues, and ecosystem impacts. Moreover, the reduced demand for minerals that previously dominated markets can lead to economic challenges for regions and industries that rely heavily on the extraction and processing of these minerals. Additionally, competition between suppliers of raw materials and new entrants for market share may intensify. The complexity of global supply chains and the integration of multiple raw materials would require effective supply chain management to ensure consistent and timely delivery to end users.

To address these challenges, the United Nations Secretary-General's Panel on Critical Energy Transition Minerals has developed Principles applicable to the entire value chain and life cycle of these minerals. These Principles aim to guide the exploitation of these minerals towards equity and justice by spurring sustainable development, respecting human rights, protecting the environment, and driving prosperity in resource-rich developing countries.[33]

## Performance characteristics of selected battery technologies and chemistries

Battery chemistries are the catalysts behind the pursuit of higher efficiencies in battery performance. Each breakthrough in material science brings researchers closer to unlocking the full potential of energy storage solutions, powering the transition to cleaner and more sustainable energy sources. The performance of batteries varies significantly due to the distinct characteristics of their specific chemistries, which influence key performance indicators such as energy density, nominal voltage, charge cycle life, charge time and safety features. These factors enable the customization of batteries to meet the specific needs of various applications, highlighting their versatility and adaptability.

For example, high energy density — the amount of energy stored in a battery relative to its weight or volume — is essential for applications requiring lightweight and compact power sources, such as EVs and portable electronics. Long charge cycle life, the number of charge and discharge cycles a battery can undergo before significant capacity degradation, is critical for reducing the frequency of battery replacements, which is a key factor in the total cost of ownership.

Fast charging and discharging capabilities are important for applications requiring rapid energy replenishment or delivery, such as grid storage and fast-charging EVs. Safe battery chemistries are crucial to prevent accidents and ensure user safety, particularly in consumer electronics and EVs. Lastly, nominal voltage is important as it determines the compatibility of the battery with various devices and systems.

[33] UN Secretary-General's Panel on Critical Energy Transition Minerals (2024). Resourcing the energy transition. Principles to guide critical energy transition minerals towards equity and justice. Available at https://www.un.org/sites/un2.un.org/files/report_sg_panel_on_critical_energy_transition_minerals_11_sept_2024.pdf

## Table 1

### Summary of performance characteristics of selected current and emerging rechargeable batteries

| Technology/Chemistry | Energy density (Wh/kg) | Nominal Voltage (Volts) | Charge cycle Cycle life | Charge time (hr) | Cost (US$ per kWh) |
|---|---|---|---|---|---|
| **Lead-acid** | 30-50 | 2 | 200-300 | 8-16h | 65-100 |
| **Nickel metal hydride** | 60-120 | 1.25 | 300-500 | 8h | 83-530[34] |
| **Lithium-ion batteries** | | | | | |
| **Lithium cobalt oxide** | 150-200 | 3.7-3.9 | 500-2 000 | 3h | 150-300 |
| **Nickel manganese cobalt** | 130-241 | 3.65-4.0 | 1 000-2 000 | 3h | 112.7 |
| **Lithium iron phosphate** | 90-130 | 3.2-3.3 | 2 000-7 000 | 1-2h | 98.5 |
| **Nickel cobalt aluminium** | 200-310 | 3.0-3.65 | 1 000-2 000 | 3h | 120.3 |
| **Metal-ion batteries** | | | | | |
| **Magnesium/Sodium** | 300-500 | 2.3-2.5 | 500-4 000 | 0.25h[35] | 40-80[36] |
| **Metal-air batteries** | | | | | |
| **Iron/Lithium/zinc/ aluminium/Magnesium air** | ~400-2 000 | 3 | 500 | 0.5h | 20-60 |
| **Solid-state batteries** | | | | | |
| **Lithium cobalt oxide aluminium** | >400 | | 3 000 | 0.17-0.25h | 200-300 |
| **Sodium-sulfur** | 250-1 700 | 2.1-2.2 | 100-500 | 4-5h[37] | 300-500 |
| **Liquid metal batteries** | | | | | |
| **Calcium Antimony** | 505-1 023 | 0.94-1.04 | 1000 | 4h | 180-250 |
| **Flow batteries** | | | | | |
| **Vanadium Redox Flow**[38] | 15-25 | 1.15-1.55 | 20 000 | n/a | 350-600[39] |

*Source:* Estimates based on Statista,[40] BloombergBNEF[41-42] Battery chemistry,[43] Frost and Sullivan,[44] GME,[45] Elements,[46] BEPA.[47]

34 Salehi H, Maroufi S, Mofarah SS, Nekouei RK, Sahajwalla V (2023). Recovery of rare earth metals from Ni-MH batteries: A comprehensive review. Renewable and Sustainable Energy Reviews, Volume 178, 2023, 113248, ISSN 1364-0321. Available at https://doi.org/10.1016/j.rser.2023.113248

35 Ruiz C, Lyons M, Garcia I. E., Wu Z (2023). Sodium-ion batteries ready for commercialisation: for grids, homes, even compact EVs. Available at https://www.sibattery.com/t/sodium-ion-batteries-ready-for-commercialisation-for-grids-homes-even-compact-evs/157

36 Ibid.

37 Aktas A. and Kircikek Y. (2021). Chapter 5 - Solar hybrid systems and energy storage systems, Academic press, pages 87-125. Available at: https://doi.org/10.1016/B978-0-323-88499-0.00005-7 https://www.sciencedirect.com/science/article/pii/B9780323884990000057

38 González-González J. M. et al (2023). Chemical energy storage technologies, Encyclopedia of Electrical and Electronic Power Engineering, Elsevier, 2023, Pages 426-439, ISBN 9780128232118 Available at https://doi.org/10.1016/B978-0-12-821204-2.00100-8; https://www.sciencedirect.com/science/article/pii/B9780128212042001008

39 Tang L, Leung P, Mohamed MR, Xu Q, Dai S, Zhu X, Flox C, Shah AA, Lia Q (2023). Capital cost evaluation of conventional and emerging redox flow batteries for grid storage applications, Electrochimica Acta, Volume 437, 2023, 141460, ISSN 0013-4686. Available at: https://doi.org/10.1016/j.electacta.2022.141460

40 Statista Research Department (2024). Lithium-ion battery price worldwide 2013-2024. Available at https://www.statista.com/statistics/883118/global-lithium-ion-battery-pack-costs/

41 Bloomberg (2024). China's Batteries Are Now Cheap Enough to Power Huge Shifts. 9 July. Available at https://www.bloomberg.com/news/newsletters/2024-07-09/china-s-batteries-are-now-cheap-enough-to-power-huge-shifts

42 BloombergNEF (2023). Lithium-Ion Battery Pack Prices Hit Record Low of $139/kWh. 26 November. Available at https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/

43 Battery University (2021). BU-107: Comparison Table of Secondary Batteries. Available at https://batteryuniversity.com/article/bu-107-comparison-table-of-secondary-batteries

44 Frost and Sullivan (2023). Advanced Lithium Batteries and New Battery Chemistries on Track to Transform Electric Vehicle Landscape. Available at https://www.frost.com/growth-opportunity-news/mobility-automotive-transportation/advanced-lithium-batteries-and-new-battery-chemistries-on-track-to-transform-electric-vehicle-landscape/

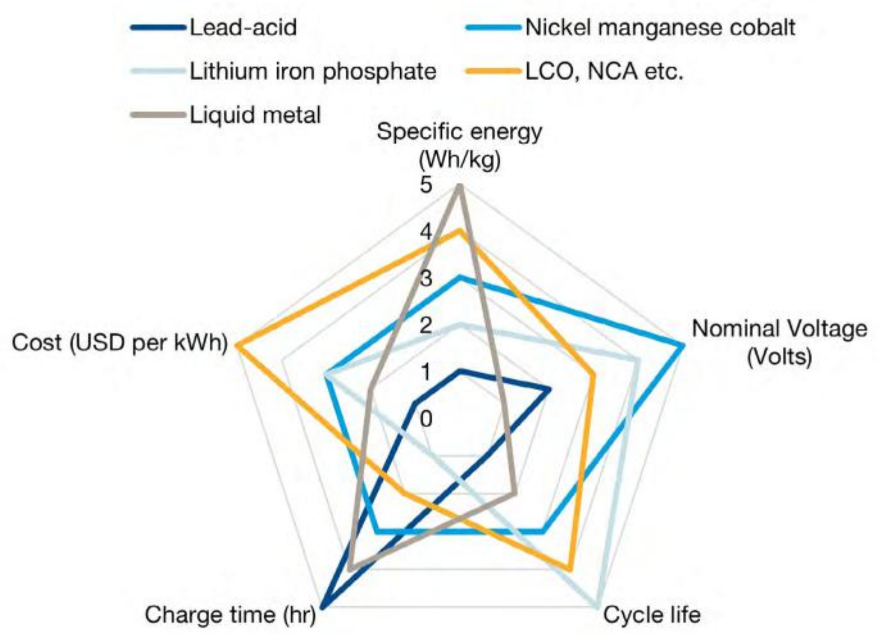
45 Gianni Mori Engineering S.r.l. (2023). What is the difference between lead acid and lithium batteries. Available at https://www.gme-recycling.com/what-is-the-difference-between-lead-acid-and-lithium-batteries/

46 Elements (2023). Visualized: What is the Cost of Electric Vehicle Batteries? 14 October. Available at https://elements.visualcapitalist.com/cost-of-electric-vehicle-batteries/

47 BATT4EU (2022). The case for solid-state batteries. 28 October. Available at https://bepassociation.eu/the-case-for-solid-state-batteries/

**Figure 6**

**Graphical representation of performance characteristics of selected current and emerging rechargeable batteries**




*Source:* UNCTAD using data from Table 1.

Advanced battery technologies showcase a range of capabilities and limitations, enabling strategic decision-making in energy storage applications.

An examination of selected battery technologies and their chemistries reveals varying performance levels that cater to diverse applications. For example, LIBs and their different chemistries produce energy densities ranging from 90 to 310 Wh/kg. Emerging technologies such as SSBs and MABs can achieve energy densities exceeding 400 Wh/kg and fast-charging capabilities, making them well-suited for automotive applications. Magnesium- and sodium-ion batteries achieve high energy densities between 300 and 500 Wh/kg, with a high charge cycle life of up to 4,000 cycles and reduced charging times. These technologies also stand out for their significantly lower costs, primarily due to the abundance of raw materials used in their chemistry. Table 1 provides a comparative overview of key performance indicators for select battery technology and chemistries, as well as their estimated cost per kWh.

# Strengths and weakness of selected battery types

The performance characteristics of various rechargeable battery types are crucial in guiding decision-making and ensuring the optimal alignment of battery types with their intended applications. To make well-informed choices, it is essential to weigh the strengths and weaknesses of different battery technologies. Strengths such as high energy density, long cycle life, safety features, and cost-effectiveness enable the selection of the right energy storage solution, whether for EVs, renewable energy systems, or portable electronics (Table 2).

## Table 2

### Balancing strengths and weakness in battery technology for targeted use

| Battery Type | Strengths | Weaknesses | Best use |
|---|---|---|---|
| **Lithium-ion (LIB)** | High energy density, high efficiency, low weight-to-power ratio, long cycle life, low self-discharge rate | Safety concerns (thermal runaway), reliance on expensive materials (e.g., cobalt), environmental risks during extraction | Portable electronics (smartphones, laptops), electric vehicles (EVs), renewable energy storage systems |
| **Metal-ion (MIB)** | Utilizes widely available materials (e.g., sodium, magnesium), lower environmental impact, broadens resource pool | Lower energy density (e.g., sodium-ion), slower charge rates (e.g., magnesium-ion), potential interactions with surrounding materials affecting lifespan | Renewable energy storage, large-scale grid storage, applications requiring lower-cost and abundant materials |
| **Metal-air (MAB)** | High energy density, cost-effectiveness due to use of materials like zinc and iron, lightweight design | Limited cycle life, sensitivity to moisture, corrosion issues, and safety concerns with reactive metals | Long-duration energy storage, grid stabilization, backup power systems |
| **Solid-state (SSB)** | High energy density, longer cycle life, improved safety (non-flammable solid electrolyte), higher thermal stability | High manufacturing costs, scaling production challenges, dependence on scarce materials | High-performance electric vehicles (extended range), aerospace applications, advanced portable electronics |
| **Liquid Metal (LMB)** | High scalability, fast charging/discharging, cost-effectiveness for grid-scale storage | High operating temperatures (300°C–700°C), material degradation at elevated temperatures, safety risks if improperly managed | Utility-scale energy storage, renewable energy integration, grid stabilization |
| **Redox Flow (RFB)** | Scalability (independent energy and power scaling), long cycle life, environmental advantages (e.g., reusable vanadium) | Low energy density, high material costs (e.g., vanadium), lower charge/discharge rates | Large-scale grid storage, renewable energy integration, industrial energy backup |

*Source:* UNCTAD.

At the same time, awareness of key weaknesses — such as flammability risks, limited scalability of production for some emerging technologies, or environmental challenges associated with exploiting certain battery materials — prompts researchers to innovate. This could result in the development of efficient recycling methods for spent batteries, overcoming technical hurdles in advanced battery development, and fostering sustainable practices in material sourcing and production.

## Lithium-ion battery

The LIB has several advantages over other types of batteries. They provide high energy density, allowing them to hold more energy relative to their size compared to most other battery models. LIBs' energy density is approximately three to four times higher than that of lead-acid batteries, making them a more efficient solution for energy storage.[48]

LIBs are also highly efficient, converting, on average, an estimated 95 per cent of the energy they store into usable power.

[48] Fan T, Liang W, Gu W, Feng T, Li W (2023). Life cycle assessment of electric vehicles' lithium-ion batteries reused for energy storage, Journal of Energy Storage, Volume 71, 2023, 108126, ISSN 2352-152X. Available at https://doi.org/10.1016/j.est.2023.108126

This efficiency exceeds that of lead-acid batteries, which typically operate at around 80 to 85 per cent efficiency.[49] This efficiency advantage enables faster charging times and enhances the overall effectiveness and performance of LIBs in various applications.[50]

On average, LIBs are five times lighter than standard lead-acid batteries.[51] A LIB weighing 6 kg will deliver one kilowatt-hour of energy compared to a 30 kg lead acid battery for the same amount of power.[52] This favourable low weight to power output ratio is specially importat in the transportation sector, where weight is a critical consideration.

LIBs also exhibit a longer charging cycle life when compared to other batteries.[53] They can be charged and discharged multiple times before their capacity significantly degrades.[54] Estimates suggest that most LIBs can last 10-15 years, almost three times as long as cheaper lead-acid batteries, which only last five to seven years.[55] This extended cycle life enhances their durability and longevity.

LIBs also have a low self-discharge rate — they can hold their charge for an extended period when not in use.[56] This feature makes them suitable for devices that are intermittently used, like remote controls and emergency backup systems.

Furthermore, LIBs have faster charging times than lead-acid batteries. While the latter takes more than 10 hours to charge, LIBs can take from three hours to as little as a few minutes, depending on the size of the battery.[57]

The main disadvantage of LIBs lies in safety concerns, notably the potential for thermal runaway — an uncontrollable, self-heating state within the lithium-ion cell that can lead to dangerously high temperatures and fire.[58] This risk arises from the liquid electrolyte typically employed in LIBs, consisting of lithium salt dissolved in volatile and flammable organic solvents like ether or carbonate. These properties make LIBs susceptible to fire or explosion, especially in high-temperature conditions.[59]

LIBs also face cost and resource challenges. They rely on the use of expensive materials like cobalt and resources required for LIBs are often concentrated in specific regions, making the supply chain vulnerable to disruptions.

Environmental concerns further compound the disadvantages of LIBs. Their chemistries include chemicals such as manganese, cobalt, and nickel, which can pose environmental risks during extraction, processing and disposal. For example, mining activities may result in habitat destruction, soil erosion, and water pollution.[60]

49 Pilot group (undated). Lithium ion battery vs lead acid battery. Available at https://www.thepilotgroup.co.uk/lithium-ion-battery-vs-lead-acid-battery/
50 Ibid.
51 Flash battery (undated). Why change from a lead-acid battery to a lithium battery? Available at https://www.flashbattery.tech/en/why-switch-from-lead-acid-battery-to-lithium-battery/
52 Ibid.
53 Renogy (2022). Everything You Need to Know About Lithium Battery Charging Cycles. 19 July. Available at https://au.renogy.com/blog/everything-you-need-to-know-about-lithium-battery-charging-cycles/
54 Ibid.
55 Ibid
56 Ec Tree Lithium (2022). Lead Acid vs. Lithium Batteries – Which One Utilize the Better Technology. 23 November. Available at https://ecotreelithium.co.uk/news/lead-acid-vs-lithium-batteries/
57 Cummins (2019). Spot the Difference: Lithium Ion Versus Lead Acid Battery Electric Technology. 17 June. Available at https://www.cummins.com/news/2019/06/17/spot-difference-lithium-ion-versus-lead-acid-battery-electric-technology
58 UL Research Institutes (2021). What Is Thermal Runaway? 24 August. Available at https://ul.org/research-updates/what-is-thermal-runaway/
59 Mining.com (2022). New electrolyte allows Li-ion batteries to heat up without risk of fire. 12 December. Available at https://www.mining.com/new-electrolyte-allows-li-ion-batteries-to-heat-up-without-risk-of-fire/
60 UN Secretary-General's Panel on Critical Energy Transition Minerals (2024). Resourcing the energy transition. Principles to guide critical energy transition minerals towards equity and justice. Available at https://www.un.org/sites/un2.un.org/files/report_sg_panel_on_critical_energy_transition_minerals_11_sept_2024.pdf

Runoff from mining sites may carry harmful substances into nearby ecosystems, affecting aquatic life and vegetation. Processing of these minerals can further release pollutants into the air, water bodies, as well contribute to GHG emissions, depending on the energy sources.

Other types of LIBs have their own unique problems even though they offer great promise. For example, lithium-sulfur (Li-S) batteries encounter technical issues related to the chemical reactions that occur inside them during the charge and discharge cycles. Specifically, sulfur goes from a solid to a liquid state and back to solid during these cycles. In this process, some of the sulfur stays in the electrolyte causing an irreversible loss of capacity, dramatically reducing the charge capacity with each cycle.[61]

## Metal-ion batteries

A significant advantage of MIBs is their ability to harness chemical energy from a wide range of metals, including sodium, zinc, magnesium, calcium and aluminium, avoiding reliance on critical raw materials such as lithium and cobalt. Using these widely available materials expands the pool of available raw resources, reducing supply chain vulnerabilities. Their abundance mitigates depletion risks and contributes to lower-cost production. Additionally, these materials are less environmentally harmful than elements such as cobalt used in LIBs.

Magnesium- and aluminium-ion batteries offer potential advantages over most lithium-ion counterparts regarding energy density and charge time (see Table 1). These attributes make them suitable for applications requiring high energy storage, such as EVs and renewable energy storage systems.

A promising variant, SIBs, offers distinct advantages. SIBs do not require extensive extraction processes, resulting in a smaller carbon footprint and reduced environmental impact.[62] They rely on lower-cost materials compared to LIBs, leading to cheaper batteries, and they completely avoid the need for critical minerals. Another key advantage of SIBs is that they can be produced on existing LIBs lines, enabling a smoother transition to this technology with minimal adjustments to production infrastructure.[63]

MIBs, such as the magnesium-ion battery, are generally considered safer than lithium-metal batteries due to reduced risks of dendrite[64,65] This improved safety profile is crucial for EVs and other applications where safety is a top priority.

However, the disadvantages of MIBs depend on the raw materials used in their construction. For example, sodium ions are heavier than lithium ions, which contributes to a lower energy density in SIBs compared to LIBs, limiting the energy storage capacity of SIBs.[66] Magnseium-ion batteries produce interactions with surrounding materials that compete with the process of storing charge, reducing battery lifespan.

[61] Coherent (2023). Securing the Battery Supply Chain. 20 October. Available at https://www.coherent.com/news/blog/li-s-battery-technology

[62] Mobility outlook (2023). Sodium-Ion Batteries Make Strong Pitch For Electric Vehicles. 30 June. Available at https://www.mobilityoutlook.com/features/sodiumion-batteries-make-strong-pitch-for-electric-vehicles/

[63] The Faraday Institution (2023). Developments in Lithium-Ion Battery Cathodes, Faraday Insights - Issue 18: September. Available at https://www.faraday.ac.uk/wp-content/uploads/2023/09/Faraday_Insights_18_FINAL.pdf

[64] Dendrites are metallic microstructures that form typically on the negative electrode during the charging process. As dendrites grow, they can create a direct pathway for electric current from anode to cathode, causing short circuits and triggering potential hazards such as fires and explosions.

[65] Liu Y., Holze R. (2022), Metal-Ion Batteries, Encyclopedia 2022, 2(3), 1611-1623; Available at: https://doi.org/10.3390/encyclopedia2030110

[66] Physics (2024). Sodium as a Green Substitute for Lithium in Batteries. 25 April. Physics 17, 73. Available at https://physics.aps.org/articles/v17/73

Additionally, charge rates are limited due to the slow movement of magnesium ions through all materials, which can impact their overall performance.[67]

## Metal-air battery

MABs have distinct advantages, notably their lightweight design, as the cathode is made from porous carbon. One of their key benefits is their high energy density, surpassing that of LIBs,[68] which makes MABs particularly attractive for applications requiring extended power supply, such as in EVs and renewable energy storage systems.

Additionally, MABs often use materials like zinc and iron, which are abundant and relatively cheaper than some materials used in LIBs. This contributes to their cost-effectiveness and sustainability,[69] making large scale production feasible without facing significant risks of material shortages or high costs, and enabling their deployment in both small-scale applications and large-scale grid storage. Furthermore, MABs have fewer components compared to other battery types, further reducing potential manufacturing costs.

As R&D in MAB technology progress, variants such as the iron air battery hold promise for revolutionizing energy storage. These batteries are advantageous for stabilizing the grid due to their high energy density, cost-effectiveness and lower environmental impact.[70]

The main disadvantage of MABs lies in their limited cycle life due to electrode degradation. They are also sensitive to moisture, which can affect performance. Safety concerns arise due to the highly reactive nature of the metals involved, increasing the risk of instability. Additionally, MABs require air access to the cathode, which can lead to issues with corrosion and electrolyte drying, further impacting their durability and efficiency.[71]

## Solid-state battery

The technology used in SSBs is still evolving, but they have the potential for higher energy density compared to liquid electrolyte batteries. This can lead to longer-lasting devices and extended driving ranges in EVs. For example, while current EVs can travel about 483 kilometres per charge, SSBs could potentially double that range or enabe EV batteries to weigh half as much as the lithium-ion-powered equivalent.[72] This could either lead to smaller and lighter EVs or extend their ranges without increasing their size and weight, making them more efficient.

SSBs typically offer longer cycle lives, allowing them to be charged and discharged more times before experiencing significant capacity degradation. This makes them particularly suitable for applications where longevity is crucial, such as EVs.

SSBs also provide notable safety advantages. By using a solid electrolyte instead of a liquid one, SSBs are more chemically stable, reducing the likelihood of degradation over time and under extreme conditions.

[67] Argonne National Laboratory (2022). Q&A: Could magnesium be a battery future? Argonne chemist Brian Ingram weighs in. 15 February. Available at https://www.anl.gov/article/qa-could-magnesium-be-a-battery-future-argonne-chemist-brian-ingram-weighs-in

[68] Ahuja D et al (2021). Metal air battery: A sustainable and low cost material for energy storage. Journal of Physics: Conference Series 1913 012065. Available at http://dx.doi.org/10.1088/1742-6596/1913/1/012065

[69] Ibid.

[70] Environment+Energy Leader (2024). Will Iron-Air Batteries Revolutionize Renewable Energy Storage? 19 August. Available at https://www.environmentenergyleader.com/stories/will-iron-air-batteries-revolutionize-renewable-energy-storage,48339

[71] Babu M, Bhanu U (2023). Metal Air Battery. International Journal of Research Publication and Reviews, Vol 4, n 5, pp 2119-2122, May 2023. Available at https://ijrpr.com/uploads/V4ISSUE5/IJRPR12952.pdf

[72] The Energy Mix (2023). Solid-State Battery Breakthrough Could Double EV Range. 30 November. Available at https://www.theenergymix.com/solid-state-battery-breakthrough-could-double-ev-range/

Additionally, the absence of flammable liquid electrolytes significantly reduces the risk of fire incidents.[73] SSBs also present higher thermal stability, enabling them to tolerate higher temperatures, further enhancing their safety and reliability in demanding applications.[74]

The main disadvantage of SSBs is their high manufacturing costs. The materials used as electrolyte to transfer energy between the cathode and anode are still scarce and expensive. For comparison, some estimates put SSBs at three to four times the price of traditional LIBs.[75]

Additionally, scaling up production while maintaining quality and performance is a significant challenge. The intricate manufacturing techniques required are not yet optimized for large-scale production. These processes need to be streamlined and made more efficient to produce batteries at a higher volume and reduced costs.

## Liquid metal battery

LMBs hold substantially more energy in the same volume and charge much faster when compared to LIBs. The unique composition of LMBs allows for higher energy density in combination with high efficiency, enabling them to store more power within a given space and minimize energy loss when discharging. LMBs have significantly faster diffusion of ions than traditional LIBs because their electrodes and electrolytes are in a molten state, making them ideal for applications that require fast charging and discharging.[76] Additionally, LMBs are highly scalable, allowing them to be tailored for various applications, from residential to utility-scale energy storage.

With their scalability and cost-effectiviness, LMBs have a potential to emerge as transformative solution for grid-scale energy storage. They can help address the intermittency of renewable energy generation and facilitate the management of peak loading requirements, supporting a more stable and reliable energy infrastructure.

The main disadvantage of LMBs is that they require high temperatures to operate, typically between 300°C and 700°C, depending on the specific design and materials used.[77] These high temperatures are necessary for keeping the liquid metals and molten salts in a fluid state, enabling efficient charge and discharge cycles. However, they can pose a risk of fire or explosion if not properly managed. Additionally, the high temperatures can limit the choice of materials that can be used in the battery's construction because many materials break down or degrade at elevated temperatures, which can reduce the battery's lifespan and performance.[78]

73 NewScientist (2023). What are solid-state batteries and why do we need them? 24 October. Available at https://www.newscientist.com/article/2398896-what-are-solid-state-batteries-and-why-do-we-need-them/

74 Centre for Process Innovation Limited (2023). 6 ways solid-state batteries are better than lithium-ion alternatives in electric vehicles. 24 August. Available at https://www.uk-cpi.com/blog/6-ways-solid-state-batteries-are-better-than-lithium-ion-alternatives-in-electric-vehicles

75 Topspeed (2023). The Pros And Cons Of Solid-State Batteries. 16 June. Available at https://www.topspeed.com/solid-state-batteries-pros-and-cons/

76 Zhou X, Yan S, He X, Zhou H, Ning J, Li H, Wang K, Jiang K (2023). Low-temperature, high cycling stability, and high Coulombic efficiency liquid metal batteries enabled by lithium halide-potassium halide molten salt electrolytes. Energy Storage Materials, Volume 61, 2023, 102889, ISSN 2405-8297. Available at https://doi.org/10.1016/j.ensm.2023.102889

77 Wu S, Zhang X, Wang R, Li T (2023). Progress and perspectives of liquid metal batteries. Energy Storage Materials, Volume 57, 2023, Pages 205-227, ISSN 2405-8297. Available at https://doi.org/10.1016/j.ensm.2023.02.021

78 Weber N et al. (2024). Risk assessment for Na-Zn liquid metal batteries. Available at https://open-research-europe.ec.europa.eu/articles/4-236

## Redox Flow batteries

The scalability of redox flow batteries (RFBs) is a key advantage, as their capacity can easily be adjusted by modifying the size of the electrolyte tanks and the power conversion components. This flexibility makes them suitable for various applications, from small-scale energy storage to grid-level systems.

RFBs also have longer cycle lives compared to other battery technologies, as they undergo minimal degradation over multiple charge-discharge cycles. Moreover, they can store energy for extended durations without degradation, making them suitable for applications requiring long-duration energy storage, such as renewable energy integration and grid stabilization.

RFBs are considered safer than some other battery technologies, as they use non-flammable and non-toxic electrolytes. They also offer environmental advantages over LIBs, including lower $CO_2$ emissions, largely due to less energy-intensive production processes and the use of more sustainable materials.[79] Vanadium, the primary material used in RFBs, is fully reusable at the end of the battery's life cycle, further enhancing their environmental benefits.[80]

One of the main disadvantages of RFBs is their low energy density and low charge-discharge rates, which may limit their suitability for applications requiring high energy storage capacity in a compact space.[81] However, RFBs such as the vanadium type are well-positioned to capture a significant share of the stationary energy storage market, given their unique advantages for long-duration applications.[82]

Another disadvantage is the high cost of materials in manufacturing RFBs such as vanadium, which can increase upfront costs and impact their competitiveness in certain markets.[83]

## Main actors in battery technology and market size

The development of battery technologies and their chemistries is being driven by several key players located in North America, Europe, and Asia (Table 3).

In North America, Tesla leads in EV batteries and energy storage solutions, with Panasonic partnering to invest heavily in battery technology R&D. The American companies QuantumScape and Solid Power are making significant strides in developing SSBs, while Sion Power (United States of America), Oxis Energy (United Kingdom of Great Britain and Northern Ireland), and PolyPlus Battery Company (United States of America) are exploring Li-S batteries, which offer higher energy density and lower costs. Research institutions like the MIT Materials Research Laboratory and Argonne National Laboratory, both located in the United States of America, have been instrumental on advancing research on LMBs and their chemistries.[84]

In Europe, Leclanché SA develops and produces advanced battery storage solutions, covering the full technology chain from cells to energy optimization systems. Its strong production capacity, expertise in battery materials, and focus on energy density, alongside collaborations with European cell manufacturers, position it as a leading player in the market[85].

79 Bushveld Minerals (undated). Vanadium Redox Flow Batteries. Available at https://www.bushveldminerals.com/energy/vrfb-technology/
80 Ibid.
81 Low energy density batteries mean bulkier and heavier batteries. This can be a significant drawback for applications where weight and size are crucial factors.
82 Bushveld Minerals (undated). Vanadium Redox Flow Batteries. Available at https://www.bushveldminerals.com/energy/vrfb-technology/
83 Batteries International (2022). Keeping the price of vanadium down — and steady too. Issue 124, Summer. Available at https://issuu.com/rizzo48/docs/bat124issuu3/s/16626006
84 MIT News (2022). Donald Sadoway wins European Inventor Award for liquid metal batteries. 23 June. Available at https://news.mit.edu/2022/sadoway-wins-european-inventor-award-liquid-metal-batteries-0623
85 Leclanché SA (2024). Available at https://www.leclanche.com/

## Table 3
### Selected actors in battery technology

| Region | Key Players | Focus/Contribution |
|---|---|---|
| North America | Tesla | Leading in EV batteries and energy storage solutions. |
| | Panasonic | Investing in battery technology R&D, in partnership with Tesla. |
| | QuantumScape, Solid Power | Developing solid-state batteries. |
| | Sion Power, Oxis Energy, PolyPlus Battery Company | Exploring Li-S battery chemistries with higher energy density and lower costs. |
| | MIT Materials Research Laboratory, Argonne National Laboratory | Advancing research on liquid metal batteries and their chemistries. |
| Europe | Leclanché SA | Specialized in lithium-ion battery technology for electric mobility and energy storage applications. |
| | Volkswagen Group | Investing in battery technology and EV production. |
| | Faraday Institution (UK) | Contributing significantly to advancements in battery technologies and chemistries. |
| Asia | Panasonic (Japan), CATL (China), LG Chem (Republic of Korea), Samsung SDI (Republic of Korea) | Leading innovation in LIB chemistries. |
| | BYD, SVOLT, HiNa Battery Technology Company Limited (China), Reliance New Energy Solar (India) | Developing chemistries using sodium, promoting alternative battery solutions. |

*Source:* UNCTAD.

The Volkswagen Group is investing in battery technology and EV production[86], while research initiatives such as the Faraday Institution (United Kingdom of Great Britain and Northern Ireland) play a crucial role in advancing battery technologies and chemistries.

In Asia, companies like Panasonic (Japan)[87], Contemporary Amperex Technology Co., Limited – CATL (China), LG Chem (Republic of Korea) and Samsung SDI (Republic of Korea) are leading the way in innovating LIB chemistries. Chinese firms such as CATL, BYD Company Limited (BYD), SVolt Energy Technology Company Limited (SVOLT), and HiNa Battery Technology Company Limited (HiNa), along with Reliance New Energy Solar (RNES) (India), are working in developing chemistries using sodium.

These pioneers and institutions are at the forefront of developing battery technology and chemistries, which could play a crucial role in the transition to sustainable energy storage solutions.

The global battery market is projected to grow significantly in the coming years. By 2030, the market size for LIBs alone is expected to reach 4.7 TWh, with a value of over US$400 billion.[88] One TWh is commonly used to describe significant energy production or consumption.[89] To put this into perspective, in 2023, Africa as a whole generated a total 820 TWh of electricity.[90]

[86] Volkswagen Group (2021). Volkswagen enters into strategic partnerships for the industrialization of battery technology. Available at https://www.volkswagen-group.com/en/press-releases/volkswagen-enters-into-strategic-partnerships-for-the-industrialization-of-battery-technology-16801

[87] Battery Power (2024). Battery Innovator Award and Panasonic's Cylindrical Cell Preferences. 9 April. Available at https://www.batterypoweronline.com/news/battery-innovator-award-and-panasonics-cylindrical-cell-preferences/

[88] McKinsey & Company (2023). Battery 2030: Resilient, sustainable, and circular. 16 January. Available at https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular#/

[89] Energy Theory (2023). What is Terawatt-Hour (TWh)? 17 November. Available at https://energytheory.com/what-is-terawatt-hour-twh/

[90] Bloomberg NEF (2024). Africa Power Transition Factbook 2024 – Record clean energy investment boosts progress towards 2030 goals. 23 September. Available at https://assets.bbhub.io/professional/sites/24/Africa-Power-Transition-Factbook-2024.pdf

The overall battery market, including various chemistries, is expected to grow at a compound annual growth rate of 16.1 per cent from 2024 to 2030.[91] This rapid growth and the huge market potential are expected to drive significant advancements in battery technologies and increase the demand for raw materials. It is therefore crucial to explore sustainable methods for sourcing these materials such as recycling and developing alternative chemistries, to meet this demand while minimizing environmental impact.

The various battery technologies discussed in this chapter, along with their performance characteristics, provide insights for selecting appropriate energy storage solutions across different sectors. Ongoing R&D promise transformative advancements, paving the way to new, more sustainable, and cost-effective battery chemistries. However, these advancements may require different, and potentially greater quantities of raw materials than those used in current lithium-ion batteries, raising concerns about material availability and production capacity to meet rising demand.

91 Grand View Research (undated). Battery Market Size, Share & Trends Analysis Report By Material (Lead Acid, Lithium Ion, Nickel-based, Sodium-ion, Flow Battery), End-use (Aerospace, Automobile, Consumer Electronics, Telecom), By Application, By Type, By Region, And Segment Forecasts, 2025 – 2030. Available at https://www.grandviewresearch.com/industry-analysis/battery-market

Chapter III

# Opportunities and challenges

# Opportunities and challenges

**The energy storage landscape is changing rapidly, driven by advancements in battery technologies and their chemistries, along with an increased focus on sustainability. These innovations are opening doors for a wide range of stakeholders in the battery industry. However, they also present several challenges in developing, adopting and commercializing battery technologies and their chemistries that must be addressed to facilitate widespread adoption.**

## Opportunities

### Sustainable energy

New battery technologies have the potential to significantly enhance energy storage capacities, which is crucial for effectively harnessing renewable energy sources like solar and wind. Advanced battery chemistries, such as Li-S or sodium-ion, which use less expensive and more abundant raw materials, can reduce the costs of energy storage solutions, making them more accessible and scalable.

For many developing countries, these technologies present a significant opportunity to integrate more renewable energy into their energy mix, stabilize power grids, and reduce reliance on fossil fuels. This advancement can provide more reliable electricity access to remote and underserved areas, fostering socioeconomic development. A reliable and consistent electricity supply improves productivity across sectors in agriculture, manufacturing, and services, by preventing power outages and enabling uninterrupted operation of machinery and equipment.

By adopting advancements in battery technology and chemistries, developing countries can accelerate their transition to sustainable energy systems, mitigate climate change impacts, and ensure energy security and resilience in the face of growing energy demands. These efforts lay the groundwork for a more sustainable and equitable energy future.

### Diversification, value addition, industrialization

New battery chemistries present a valuable opportunity for resource owners through the use of alternative raw materials. For example, the production of raw materials for the dominant LIB technology — such as lithium, cobalt, nickel and graphite — is concentrated in a few countries, intensifying vulnerability to supply disruptions. A shift towards alternative raw materials reduces reliance on a limited set of resources and helps mitigate associated geopolitical vulnerabilities.

By diversifying raw material requirements, new battery chemistries offer opportunities for resource-endowed developing countries to engage in new supply chains. At the same time, they provide import-dependent countries with a strategy to offset the risks of excessive reliance on single sources of critical materials. Abundant raw materials such as sodium and silicon, which are widely available in the Earth's crust, hold the potential to mitigate supply constraints, provided they can be mined and processed economically.

If these pioneering chemistries prove cost-competitive and gain traction among battery manufacturers and the automotive industry, they could significantly reshape global markets and supply chain dynamics.

The anticipated increase in demand for raw materials in battery technology offers significant economic opportunities through value addition. By investing in refining and processing facilities to produce high-purity chemicals instead of just extracting raw materials, countries can add value to exports, boost revenues, and support local industry development, creating jobs and stimulating economic growth. Establishing local industries to use these raw materials can stimulate growth in other sectors, foster involvement in higher value-added activities, and reduce dependency on imports. This includes manufacturing batteries, electronics, and other high-tech products, which support job creation, build technical expertise, and drive innovation, strengthening the host country's technological capabilities. For example, lithium-rich countries can leverage their steady lithium supply to develop LIB manufacturing facilities, producing battery cells and packs to capture higher value along the value chain. Box 1 illustrates the value created and potential jobs generated at various stages of the lithium value chain.

However, pursuing this industrialization strategy requires substantial investment in infrastructure, skilled labour, and technological expertise.

## Box 1
### Lithium value chain

Australia is the largest exporter of spodumene, a key raw material used to produce lithium chemicals. In 2022, Australia's lithium spodumene exports were valued at approximately US$ 7.9 billion or approximately 74 per cent of the global value of lithium ore exports.[a] However, the country's limited processing and refining activities, from spodumene to battery chemicals, reduce its ability to generate additional revenue, create jobs and diversify the country's lithium raw materials industry.

To address this limitation, Australia is exploring a new model that extends beyond the export of unprocessed spodumene. The aim is to localize the entire lithium value chain, spanning from the mining of spodumene to the processing of battery active materials and, ultimately, to the manufacture of battery cells and packs — a domain currently dominated by China. Estimates suggest that investing in local lithium processing and manufacturing facilities could add 7.4 billion Australian dollars annually to the national economy and support 34,700 jobs by 2030.[b]

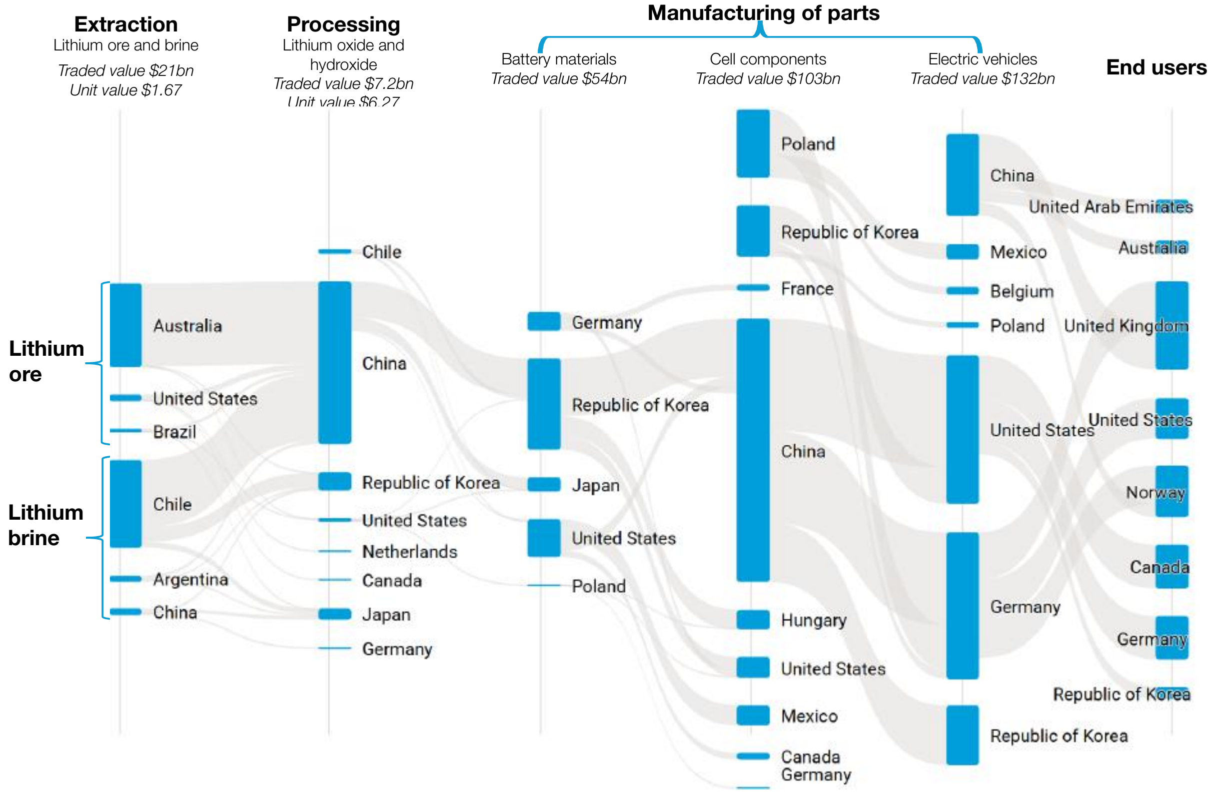
As the market for battery cells and packs continues to grow — it was estimated at US$103 billion in 2022— this strategy positions Australia to capture a larger share of the economic benefits from its lithium resources. By localizing the lithium value chain, Australia can maximize value addition, drive economic growth, and establish itself as a leader in the rapidly expanding battery industry.

Chile on the other hand, produces lithium from brine, which is a different process from rock mining. While some initial refining of brine concentrates to lithium chemicals occurs within Chile, yielding significant revenue, the country has not fully capitalized on the strong foundation it has established in lithium production and refining. Figure 7 shows revenues earned from lithium exports by major stakeholders in 2022, highlighting the potential for Chile to further capitalize on its lithium industry.

a See UN Comtrade Database on Lithium ore exports. Available at: https://comtradeplus.un.org/

b CSIR (2022). Surge in demand for Australian lithium-ion batteries. 20 April. Available at https://www.csiro.au/en/news/all/articles/2022/april/lithium-ion-battery-industry

## Figure 7
### Lithium value chain, export value, 2022, in United States dollars




*Source:* UNCTAD secretariat based on calculations from UN Comtrade

Developing a skilled workforce is crucial for raw material exporting countries to gain a competitive edge in downstream industries, driving industrialization and economic diversification. Establishing strong regulatory frameworks and fostering partnerships with established battery manufacturers can facilitate technology transfer and knowledge sharing, enabling countries to enter and excel in high-growth sectors. This industrialization process enhances economic complexity and resilience, reducing dependency on a single sector and shielding economies from extreme market volatility.

New battery chemistries offer opportunities for emerging players in battery development to establish themselves as key players in the global energy market.

By investing in R&D focused on advanced battery materials and innovative, niche technologies, these players can develop unique solutions that set them apart from established competitors.

For example, China's development of LFP battery chemistry has propelled the country to dominate about one-third of the market, significantly boosting the country's prominence in the global battery market. This breakthrough in battery technology has positioned China as a major player in the clean energy sector, as a global leader in the EV and EV battery industries.[92]

[92] Ezell S (2024). How Innovative Is China in the Electric Vehicle and Battery Industries? July 2024. Available at https://www2.itif.org/2024-chinese-ev-innovation.pdf /

Today, Chinese firms account for more than two-thirds of global EV battery production capacity.[93]

This success is attributed to substantial investments in R&D, forward-thinking policies and a strategic focus on developing advanced battery technologies, underscoring the potential for other countries and companies to follow a similar path to prominence in the evolving energy landscape.[94]

## Lower environmental impact

Some new battery chemistries use materials that are more environmentally friendly, reducing their carbon footprint and minimizing the ecological impact of production and disposal. For example, SIBs pose lower environmental and health risks compared to LIBs,[95] which use active materials such as cobalt that have raised ecological concerns.[96]

Mining companies can adopt more responsibility in mining practices with these new chemistries, as the extraction processes for materials like sodium are generally simpler and pose lower risk of environmental harm, such as water contamination, soil erosion and air pollution. In contrast, lithium mining can severely deplete water in arid regions, while cobalt mining often contributes to deforestation and soil degradation.[97] These mining operations can also release toxic substances, polluting air and water and harming local ecosystems.

By shifting to these environmentally friendly materials, battery manufacturers can avoid being associated with environmental damage often linked to traditional battery supply chains. Additionally, batteries using fewer hazardous materials compared to some cobalt-based batteries may be safer to dispose of at the end of their lifecycle, further reducing their environmental impact.

## Electric mobility and electrical utilities

The development of efficient, high-performance batteries is enabling the growth of the EV market, providing cleaner and more sustainable transportation options. Advancements in battery chemistries are making EVs more viable by delivering longer ranges, shorter charging times, and better overall performance. These improvements significantly reduce GHG emissions and reliance on fossil fuels compared with traditional internal combustion engine vehicles. As battery technologies continue to evolve, they will further enhance EV performance and make electric mobility more accessible, practical, and sustainable.

Evolving battery chemistries also have the potential to revolutionize energy storage for utilities by enhancing the efficiency and reliability of power grids. Innovations in materials, particularly solid-state electrolytes, are enabling significant improvements in energy density, longevity, and charging speed of storage systems, making them ideal for large-scale storage solutions.

93 Reuters (2024). Chinese EV battery maker CATL unveils LFP battery with 1,000 km range. 25 April. Available at https://www.reuters.com/business/autos-transportation/chinese-ev-battery-maker-catl-unveils-lfp-battery-with-1000-km-range-2024-04-25/

94 Ezell S (2024). How Innovative Is China in the Electric Vehicle and Battery Industries? July 2024. Available at https://www2.itif.org/2024-chinese-ev-innovation.pdf

95 Environmental Health News (2024). Sodium-ion batteries could offer cheaper, greener option over lithium. 5 November. Available at https://www.ehn.org/sodium-ion-batteries-could-offer-cheaper-greener-option-2669585346.html

96 International Institute for Environment and Development (2021). Mining cobalt better. 29 September. Available at https://www.iied.org/mining-cobalt-better

97 Mining Technology (2023). The cost of green energy: lithium mining's impact on nature and people. 30 October. Available at https://www.mining-technology.com/analyst-comment/lithium-mining-negative-environmental-impact/

Additionally, they provide more stable and sustainable energy storage, reducing reliance on less abundant or costly materials and enhancing the resilience of power grids against fluctuations in renewable energy generation.

These technologies not only address growing energy demands but also facilitate the integration of more renewable sources like wind and solar into the energy mix, supporting a cleaner and more sustainable energy future. Enhanced energy storage enables utilities to better manage supply and demand, minimize energy losses, and provide more reliable service to consumers. This shift also catalyzes environmentally friendly practices and reinforces a collective commitment to a more environmentally responsible future.

### Recycling

Demand for battery raw materials is projected to rise sharply as EVs become a mainstream mode of transportation. Estimates suggest each EV will consume about six times more minerals than internal combustion engine vehicles,[98] potentially leading to critical mineral shortages, posing challenges for various markets. To meet this growing demand, the production and processing of mineral resources are expected to increase sharply.

At the same time, more than 12 million metric tons of LIBs are projected to retire between 2021 and 2030,[99] presenting a valuable opportunity for companies to scale up existing recycling initiatives or establish new recycling facilities. Such efforts will not only address the supply challenges but also promote the development of a sustainable circular economy across multiple sectors, contributing to environmental conservation.

Recycling plays a pivotal role in enhancing the circularity and sustainability of critical raw materials. It offers a practical and responsible solution to mitigate the pressures of rising demand while fostering the evolution of cleaner and more sustainable technologies. By reducing reliance on newly extracted materials and maximizing resource efficiency, recycling supports both economic growth and environmental stewardship.

## Challenges

### Insufficient R&D investments for advancing battery chemistry

Developing advanced battery technologies and their chemistries requires substantial R&D investments. This can be particularly challenging for developing countries, though China constitutes an important exception. Insuficient funding for R&D limits the exploration and adoption of innovative battery technologies, hampering the ability of developing countries to establish and expand downstream industries. As a result, they miss opportunities to fully benefit from new battery chemistries and struggle to move up the value chain, remaining dependent on importing advanced battery technologies— an expensive dependency that can stifle economic growth potential.

By investing in battery R&D, developing countries can leverage their role as suppliers of critical minerals to position themselves as global players in the clean energy sector. This leadership can foster international partnerships, and create economic opportunities. Furthermore, local R&D investment can create jobs, drive technological advancements, and enhance global competitiveness.

98 Elements (2022). EVs vs. Gas Vehicles: What Are Cars Made Out Of? 30 May. Available at https://elements.visualcapitalist.com/evs-vs-gas-vehicles-what-are-cars-made-out-of/

99 The Guardian (2021). Millions of electric car batteries will retire in the next decade. What happens to them? 20 August. Available at https://www.theguardian.com/environment/2021/aug/20/electric-car-batteries-what-happens-to-them

Without these investments, mineral-rich developing countries risk being left behind in the rapidly evolving battery market, missing out on the long-term benefits of innovation and industrial growth.

## Limited access to finance

Limited access to finance is a major obstacle to the adoption and development of new battery chemistries, as significant investment is required to fund R&D, infrastructure and skilled labour. For example, advancing battery chemistries requires funding for laboratory facilities, equipment and materials, as well as for hiring and training skilled researchers and engineers. Financial constraints can limit the scope and scale of research activities, slowing the discovery of efficient and cost-effective battery solutions.

Furthermore, the establishment of sophisticated infrastructure—such as state-of-the-art processing facilities, manufacturing plants and quality control systems— requires considerable capital. These elements are essential for producing advanced batteries at scale and maintaining high-quality standards. Limited financial resources often prevent the development of such infrastructure, halting progress in building robust battery manufacturing ecosystems.

Commercialization and scaling of new battery technologies also involve significant financial risks. From prototyping and testing to market deployment, each stage demands substantial funding and carries uncertainties about market acceptance and profitability. These financial challenges can restrict the ability of developing countries to establish robust supply chains for new battery chemistries. Without access to finance, many promising battery technologies may never reach the market.

## Safety concerns

The safety of rechargeable batteries has been a persistent concern for manufacturers, often serving as a barrier to the commercialization of promising battery chemistries that could otherwise meet performance benchmarks. Early batteries were marred by safety risks such as thermal runaway. Operating in high temperatures also led to frequent failures. These safety concerns continue to affect advanced battery chemistries, hindering commercialization and widespread adoption.

For example, Li-S batteries, while offering high energy density, are susceptible to thermal runaway if the sulfur cathode undergoes unexpected reactions, leading to overheating and gas release. SIBs, considered a safer alternative to lithium-ion, can still exhibit overheating if subjected to harsh conditions or if the cathode materials are not well-optimized. SSBs are touted for their enhanced safety compared to liquid electrolyte batteries, but the choice and compatibility of solid-state materials, as well as the precision in manufacturing processes are critical to preventing overheating.

Addressing these safety issues requires significant advancements in materials science and engineering. Enhancing the thermal stability of battery components, and developing robust thermal management and monitoring systems can mitigate risks associated with overheating and short-circuiting.

## Price volatility

Mineral prices can be highly volatile, influenced by factors like geopolitical events and global economic conditions. The emergence of new battery chemistries is likely to reshape consumption patterns of raw materials like cobalt, lithium and nickel, which are integral components in various battery formulations.

As the demand for rechargeable batteries increases, the use of these commodities in new chemistries is set to surge, potentially leading to fluctuations in commodity prices if not matched with increased production.

While advancements in alternative chemistries, such as sodium-ion or SSBs, aim in part to mitigate dependence on costly materials, market dynamics and supply chain disruptions can still contribute to uncertainties in pricing. These price instabilities present challenges for battery manufacturers in accurately forecasting costs. Such uncertainties may delay the rollout of new, more affordable battery technologies for consumers.

## Environmental and societal risks

The extraction of raw materials carries a multitude of environmental risks. These include the destruction of natural habitats, leading to biodiversity loss; land degradation marked by soil erosion, compaction and reduced land productivity; air pollution from dust and emissions from machinery and transportation; and water pollution from the release of contaminants like heavy metals, acids, and other pollutants into nearby water bodies, causing harm to aquatic life.[100]

As the demand for battery raw materials surges, the intensity of mining operations is projected to increase significantly, amplifying these environmental risks. For example, lithium and cobalt extraction methods are highly energy intensive, often leading to air and water pollution, land degradation, and potential for groundwater contamination, affecting entire ecosystems and drinking water sustainability in the long term.[101]

The environmental risks associated with the extracting battery raw materials are likely to intensify as demand increases, particularly in the absence of stringent environmental regulations. In such scenarios, extraction operations may prioritize maximum output and profitability over sustainable practices, increasing the prevalence of unsustainable and environmentally harmful practices. This could potentially jeopardize efforts to mine minerals essential for certain battery technologies and their chemistries.

Without effective regulations, there is little incentives for industry players to invest in cleaner and responsible extraction technologies. Consequently, the cumulative environmental impact of raw material extraction may intensify. The implementation of stringent regulations could foster greater oversight and accountability, mitigating the likelihood of shortcuts in environmental protection measures.

Beyond environmental risks, the extraction of critical raw materials for battery technologies, such as lithium and cobalt, is linked to significant societal risks. In regions with weak regulatory frameworks, mining operations often raise alarming human rights concerns. For example, issues such as child labor, hazardous working conditions, and inadequate wages are frequently associated with cobalt mining activities in the Democratic Republic of the Congo.[102] Concerns have also been raised about lithium mining operations in Chile, occuring on land traditionally owned by indigenous communities. This can lead to conflicts over land rights, as indigenous populations may face displacement or experience disruptions to their traditional ways of life.[103]

[100] International Energy Agency (2021). The Role of Critical Minerals in Clean Energy Transitions. IEA, Paris Available at https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[101] Zheng M. (2023), The environmental impacts of lithium and cobalt mining. Available at: https://earth.org/lithium-and-cobalt-mining/

[102] Wilson Center (2021). The DRC Mining Industry: Child Labor and Formalization of Small-Scale Mining. 1 September. Available at https://www.wilsoncenter.org/blog-post/drc-mining-industry-child-labor-and-formalization-small-scale-mining

[103] Natural Resources Defense Council (2022). Lithium Mining Is Leaving Chile's Indigenous Communities High and Dry (Literally). 26 April. Available at https://www.nrdc.org/stories/lithium-mining-leaving-chiles-indigenous-communities-high-and-dry-literally

## Shortage of skills

A shortage of skills and insufficient investment in education and training significantly hinder the ability of developing countries to adopt and develop new battery chemistries. Advanced battery technologies, such as SSBs, Li-S batteries and next-generation LIBs, require a highly skilled workforce, including scientists, engineers, and technicians specialized in materials science, chemistry, and battery manufacturing processes. Without adequate investment in educational programmes and vocational training, there is a substantial gap in the expertise necessary to drive innovation and implementation.

The continuous evolution of battery technologies further exacerbates this challenge. Advanced chemistries demand ongoing R&D to overcome limitations and unlock their full potential. This dynamic field requires a workforce that is not only skilled but also adaptable and innovative. Insufficient training and education programmes in these specialized fields contribute to a shortage of skilled labor, impeding the development of downstream industries and limiting the economic benefits that could be derived from mineral resources.

This skill gap also prevents the establishment of robust R&D ecosystems and manufacturing capabilities, leaving countries dependent on imported technology and expertise. Consequently, these countries struggle to keep pace with global advancements, missing opportunities to capitalize on the economic and environmental benefits of new battery technologies.

## Inadequate legal frameworks

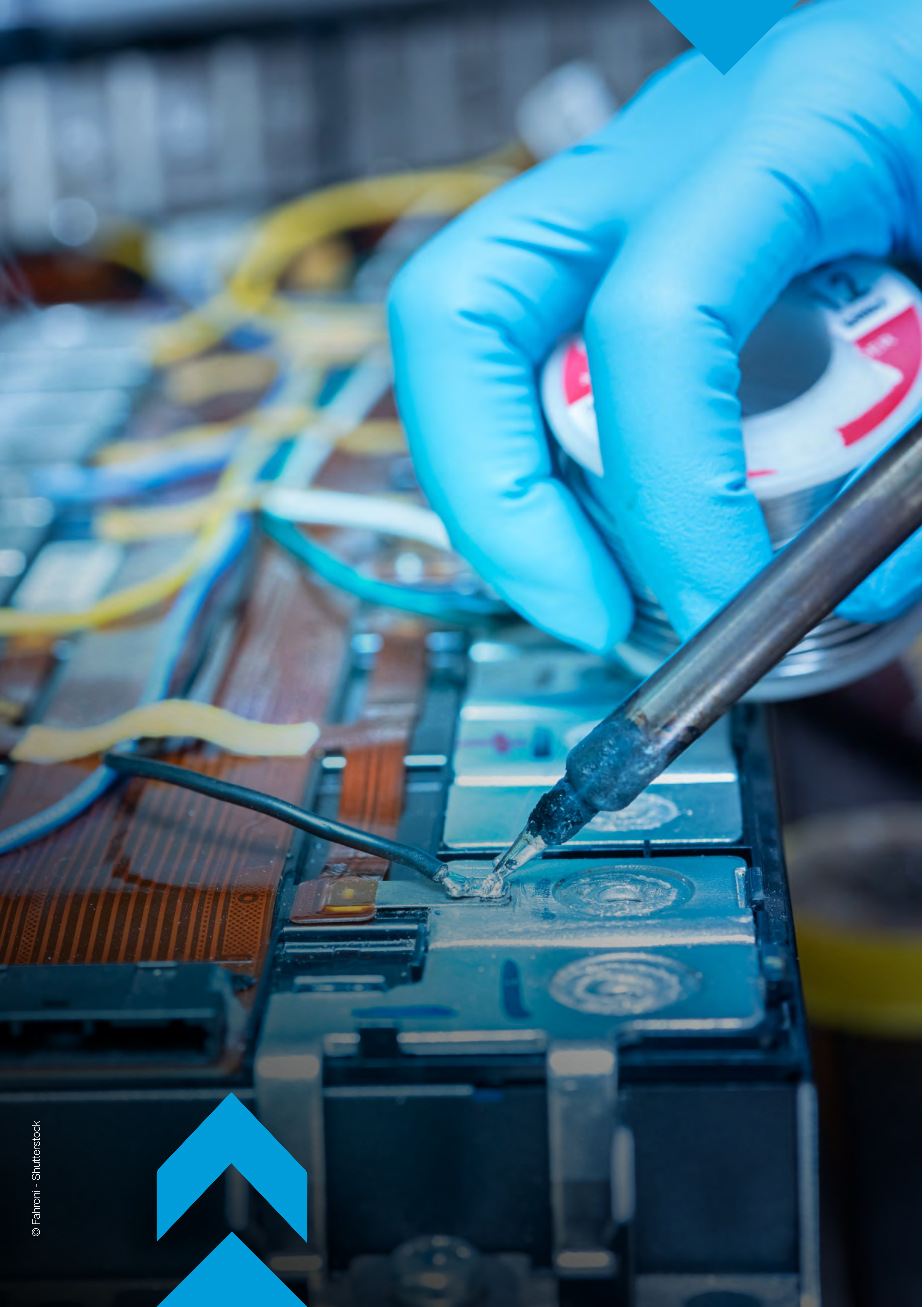
The absence of robust legal frameworks can significantly hinder the adoption and development of battery technologies and their chemistries in several ways. Without clear regulations, companies may face uncertainty about compliance requirements, including environmental standards, making it challenging to invest in new technologies and scale up production. Weak or ambiguous legal frameworks may also result in inadequate enforcement, leading to environmental degradation and health risks for local communities during the extraction of raw materials critical for battery production. This, in turn, can erode consumer trust and slow the adoption of advanced battery technologies.

Well-designed legal frameworks facilitate technology transfer and collaboration between companies, research institutions, and governments. Without clear guidelines, partnerships may become less effective or discouraged altogether. The lack of legal clarity may also make companies and research institutions hesitant to share proprietary technologies and innovations, slowing the dissemination of new battery chemistries and hindering collaborative development efforts. Investors are also less likely to fund projects in regions with ambiguous or underdeveloped legal frameworks due to perceived risks and uncertainties. This lack of financial support can limit the resources needed to develop and scale new battery chemistries.

Developing countries, in particular, need support in building their regulatory capacities to enforce these frameworks effectively. This includes technical assistance, capacity-building initiatives, and financial aid to implement and monitor compliance. By strengthening legal frameworks, countries can ensure that the growth of the battery industry aligns with sustainable practices, protecting both the environment and public health.

Chapter IV

# Policy considerations



# Policy considerations

**The successful development and deployment of advanced battery technologies hinge on the implementation of comprehensive and effective policy frameworks that facilitate innovation and market adoption while ensuring that environmental, economic, and social risk factors are adequately addressed.**

## Policy areas for advanced battery development

### Attracting investment to local value-addition activities

The distinct manufacturing processes and material requirements of different battery chemistries present a significant opportunity for establishing local facilities for processing raw materials and manufacturing battery components. However, realizing this potential will require substantial investment in local value-addition activities.

Governments and local authorities can implement targeted policies and incentives to attract domestic and foreign investors to engage in value addition within local supply chains. Measures such as tax breaks, subsidies and grants for businesses that invest in processing and manufacturing operations can incentivize value addition to raw materials before export.

Establishing special economic zones and industrial parks with favourable regulatory environments, infrastructure support, and streamlined administrative processes can significantly attract investments. Such initiatives provide businesses with a conducive environment to operate efficiently and competitively.

Public-private partnerships and collaboration with international organizations are also critical. These partnerships can mobilize resources and expertise, facilitating the development of local industries while ensuring global best practices are adopted.

By implementing these strategies, governments can build a compelling case for investment, resulting in benefits such as job creation, skill development, and increased export revenues. Ultimately, fostering a robust ecosystem for local value addition can lead to more sustainable and inclusive economic development.

### Developing domestic technological capabilities and skills

The success of advanced battery technologies and their chemistries depends heavily on the availability of a skilled and knowledgeable workforce. The development, manufacturing, and implementation of these technologies require specialized expertise in areas such as materials science, electrochemistry, engineering, and related fields. Therefore, investing in education and workforce development is crucial to ensure the industry has access to the talent needed to drive innovation and sustain growth. Encouraging science, technology, engineering, and mathematics education from an early age and supporting vocational training can help cultivate a new generation of researchers, engineers, and technicians.

Partnerships between academic institutions, industry, and government are also essential. Such collaborations can provide hands-on training and real-world experience, bridging the gap between theoretical knowledge and practical application.

For example, joint initiatives could include internships, apprenticeships, and research projects tailored to the needs of the battery technology sector.

By equipping the workforce with the necessary skills and expertise, policymakers can accelerate advancements in battery technology and promote sustainable practices throughout the battery life cycle. A skilled workforce not only ensures the ability to meet the complex demands of advanced battery technologies but also secures a competitive edge in the global market. Without adequate investment in workforce development, the industry risks falling behind, hindering both progress and competitiveness progress in a rapidly evolving energy landscape.

## Promoting Research and Development

The advancement of battery technologies relies heavily on robust R&D efforts. R&D drives innovation by exploring non-traditional materials to meet the growing demands for safer, higher-energy-density batteries while maintaining a competitive edge in the global market. Significant investments are essential to support these initiatives in battery technology and chemistries.

For developing countries, R&D is particularly important, enabling them to leverage their diverse raw material reserves. By building strong R&D ecosystems, these countries can transform resource endowments into technological advantages, fostering economic resilience and industrial growth.

Government funding initiatives play a pivotal role in advancing battery technologies. For example, the Electric Vehicles for American Low-Carbon Living (EVs4ALL) programme in the United States of America provides grants for R&D projects aimed at reducing EV battery costs, improving charging times, increasing cold-weather efficiency, and increasing range and resilience. This programme invites participation from individuals, private industry, national laboratories, and universities, ensuring broad engagement in technological advancements.[104]

In China, government support has enabled significant breakthroughs in battery chemistry. Chinese EV battery start-ups are developing batteries with ranges of up to 2,000 kilometres (1,300 miles).[105] Recent guidelines issued by China's Ministry of Industry and Information Technology emphasize enhancing technology innovation, improving product quality, and reducing production costs.[106]

Collaboration between public institutions and private enterprises is crucial for accelerating R&D. Such partnerships facilitate the exchange of knowledge and best practices, expediting the understanding of diverse battery chemistries, materials, and technologies. International cooperation partnerships play a vital role, as global research initiatives bring together expertise and resources to advance battery technologies more efficiently.

For example, the National Renewable Energy Laboratory (United States of America) and the Faraday Institution (United Kingdom of Great Britain and Northern Ireland) have partnered to improve the sustainability of LIBs.

104 United States Department of Energy, The Advanced Research Projects Agency-Energy (2022). Electric vehicles for American low-carbon living (Evs4ALL). Available at: https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=f402d267-0a70-4d8e-91d0-ef1fdb30e7bb

105 Ezell S (2024). How Innovative Is China in the Electric Vehicle and Battery Industries? July 2024. Available at https://www2.itif.org/2024-chinese-ev-innovation.pdf

106 Mining.com (2024). China to regulate lithium-ion battery industry amid fast expansion. 19 June. Available at https://www.mining.com/web/china-to-regulate-lithium-ion-battery-industry-amid-fast-expansion/

Their memorandum of understanding supports projects aimed on developing high-capacity batteries and innovative recycling methods.[107]

To further support R&D, it is critical to invest in infrastructure such as well-equipped laboratories, testing facilities, and pilot production lines. These resources provide the foundation for advanced research and prototype development.

Protecting intellectual property is essential to encourage innovation and safeguard investments in new technologies. Governments should implement an adequate intellectual property framework to support patenting processes to ensure a fair and secure environment for technological advancements.

## Establishing enabling environmental regulations

The adoption of newer battery chemistries offers environmental advantages, such as reduced reliance on rare or toxic materials, aligning with global sustainability goals and attracting environmentally conscious investors. To support these advancements, governments should establish clear and supportive regulatory frameworks that allow new battery technologies to thrive.

Key regulatory measures include:

- **Standards for safety and environmental impact:** Setting standards for battery safety, efficiency, and environmental impact ensures that new technologies meet critical benchmarks. Clear guidelines also streamline the approval processes for innovative battery chemistries, encouraging faster market entry.
- **Incentives for sustainable practices:** Governments can incentivize sustainable mining practices, clean manufacturing processes, and efficient recycling methods to reduce the ecological footprint of battery production and use. For example, the extraction of sodium, a more abundant mineral compared with lithium or cobalt, is a less energy-intensive extraction process,[108] resulting in lower carbon emissions and reduced environmental degradation.[109]
- **Promotion of environmentally friendly chemistries:** Encouraging the development and adoption of environmentally friendly battery technologies can reduce the ecological footprint of battery production and use. Providing financial and policy support for alternative chemistries, such as sodium-ion or sulfur-based batteries, can accelerate this transition.
- **International collaboration:** Governments should collaborate with other countries and international organizations to develop and implement global standards for responsible mining and manufacturing practices. This approach can help address cross-border environmental and social issues, ensuring sustainable practices worldwide.

[107] National Renewable Energy Laboratory (2022). International Collaboration Strengthens Sustainable Battery Research. 30 August. Available at https://www.nrel.gov/news/program/2022/international-collaboration-strengthens-sustainable-battery-research.html

[108] Physics (2024). Sodium as a Green Substitute for Lithium in Batteries. 25 April. Physics 17, 73. Available at https://physics.aps.org/articles/v17/73

[109] Nadion Energy (undated). Sodium-ion Batteries are Environment-Friendly in Battery Manufacturing Process. Available at https://nadionenergy.com/sodium-ion-batteries-are-environment-friendly-in-battery-manufacturing-process/

## Setting ambitious targets to drive innovation in energy storage

Setting ambitious targets for energy storage capacity, efficiency, and sustainability can incentivize researchers and companies to develop new battery chemistries that meet these goals. These targets can lead to breakthroughs in materials science and electrochemistry, while creating a pathway for integrating advanced energy storage solutions into the energy grid.

Introducing targets for energy storage deployment sends a clear demand signal to utilities, energy providers, technology developers, and investors. By specifying goals for energy storage integration, policymakers provide a framework that aligns efforts across the energy sector to achieve a defined capacity level. For example, the European Union targets of 200GW of energy storage capacity by 2030, rising to 600 GW in 2050,[110] demonstrate the potential for such mandates to stimulate innovation and market growth, particularly in long-duration storage technologies.

The prospect of a growing market encourages companies to innovate and offer cutting-edge storage technologies to meet the set targets. This fosters healthy competition, driving advancements in efficiency, cost-effectiveness, and environmental sustainability of energy storage solutions. For example, mandates to reduce GHG emissions and promote renewable energy adoption can drive the development of environmentally friendly battery chemistries, such as SIBs or SSBs.

Ambitious targets act also as a catalyst, creating a dynamic environment that encourages the exploration of diverse energy storage solutions. This includes not only battery-based technologies but also alternative storage systems that can complement renewable energy sources.

Policymakers can also use targets to bridge the gap between industry capabilities and policy objectives, ensuring that technological advancements are aligned with broader energy and climate goals. Clear, ambitious targets create certainty for investors, encouraging them to fund R&D and support scaling up production of energy storage technologies.

## Addressing social impacts of large-scale mining for battery materials

Large-scale mining of materials like lithium and cobalt often leads to significant social issues in mining communities. These include child labour, unsafe working conditions, and the undermining of land and water rights. Governments can take several actions to address these social impacts. For example, establishing and enforcing strict regulations to ensure safe working conditions, fair wages, and the protection of workers' rights can significantly reduce worker exploitation. Rigorous monitoring and auditing of mining operations should be undertaken to prevent child labour and exploitation.[111] Governments should also encourage companies to adopt responsible sourcing practices by requiring transparency in supply chains and supporting certifications that verify ethical mining practices. This can help ensure that materials are sourced in a way that respects human rights.

## Promote recycling

The growing demand scale for battery materials requires alternative sources of minerals to reduce dependence on primary resources.

[110] European Association for Storage of Energy (2022). Energy Storage Targets 2030 and 2050. Available at https://ease-storage.eu/publication/energy-storage-targets-2030-and-2050/

[111] Franken, G., Schütte, P (2022). Current trends in addressing environmental and social risks in mining and mineral supply chains by regulatory and voluntary approaches. Miner Econ 35, 653–671 (2022). Available at https://doi.org/10.1007/s13563-022-00309-3

This can be achieved through government incentives for recycling companies and regulations that require manufacturers to take responsibility for the end-of-life management of their products. Educational campaigns that raise public awareness about the importance of recycling and sustainable practices in battery production and disposal can help increase recycling rates. These initiatives can also mitigate the negative impacts of mining, provide long-term benefits to local communities, and promote overall sustainability.

### Regional cooperation

Regional cooperation can significantly enhance the development of battery chemistries, offering various benefits. By pooling resources, sharing knowledge, and leveraging each other's strengths, collaboration can accelerate R&D, fostering innovation hubs where companies, research institutions, and government agencies drive technological advancements. Such cooperation can diversify supply chains, reduce costs, and improve the resilience of the battery industry. Addressing common challenges like environmental sustainability and ethical sourcing, and harmonizing regulations and standards, ensures more efficient development of new battery chemistries, with economic and environmental benefits.

Governments should promote collaboration through regional agreements and frameworks that encourage joint funding programs, the establishment of common standards, and shared innovation goals. Organizing conferences, workshops, and symposiums facilitates knowledge exchange and best practices among experts and stakeholders. Establishing regional innovation hubs where academia, industry, and government can collaborate on battery R&D will strengthen regional capacity and drive advancements in battery technologies, leading to breakthroughs in efficiency, cost reduction, and sustainability, ultimately contributing to the global transition to cleaner energy solutions.

## Conclusion

Advancing battery technologies and their chemistries requires a comprehensive and multifaceted approach. Investing in research to discover and develop alternative, non-toxic mineral sources is crucial for reducing the environmental impact of extensive mining as the demand for battery minerals continues to rise due to the energy transition. These advancements will improve battery chemistries, enhancing the performance characteristics and enabling the development of high-density battery storage systems. This is particularly important in developing countries where energy access is limited.

Addressing these challenges involves investing in education and training programmes to build a skilled workforce capable of supporting technological advancements. Additionally, sharing best practices and technologies through international collaboration is crucial for addressing common challenges and ensuring sustainable development in the battery industry.

Recognizing the need for a closer examination of social, economic and environmental issues around critical energy transition minerals, in 2024, the United Nations Secretary-General established a Panel of experts to develop a set of global and common voluntary principles for their responsible management. The Panel on Critical Energy Transition Minerals has developed Principles to apply to the entire value chain and life cycle of critical energy transition minerals, guiding the exploitation of these minerals towards equity and justice by spurring sustainable development, respecting human rights, protecting the environment, and powering prosperity in resource-rich developing countries.

This integrated approach ensures that the growth of the battery industry aligns with global sustainability and development goals, fostering a cleaner and more equitable energy future.

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