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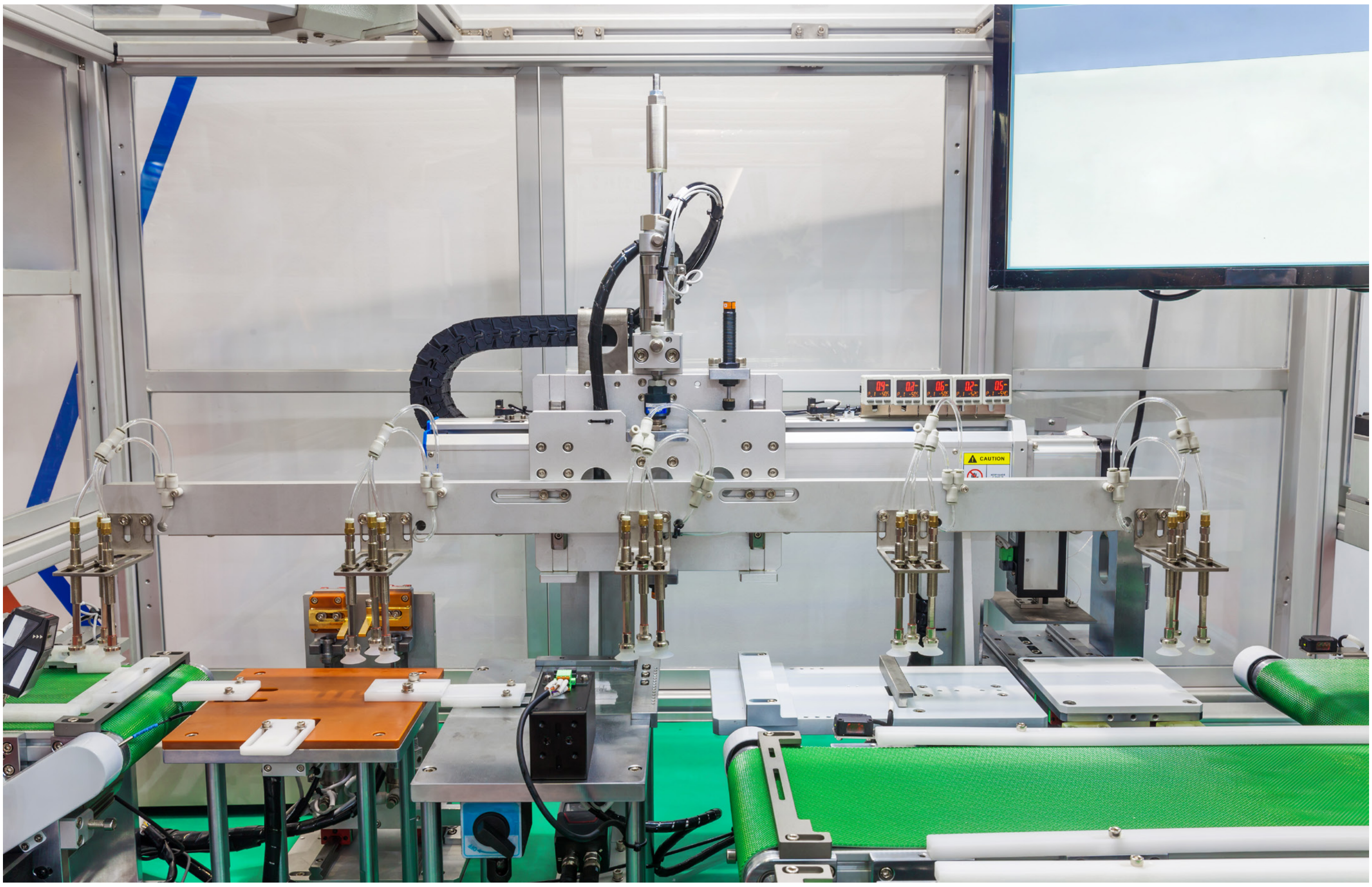

# Addressing Technology Gaps through Collaboration on Advanced Cell Chemistry Batteries

Report

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## Acknowledgment

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## Disclaimer

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October 2023
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# Foreword

# Preface

**Dr Arunabha Ghosh**
CEO, CEEW

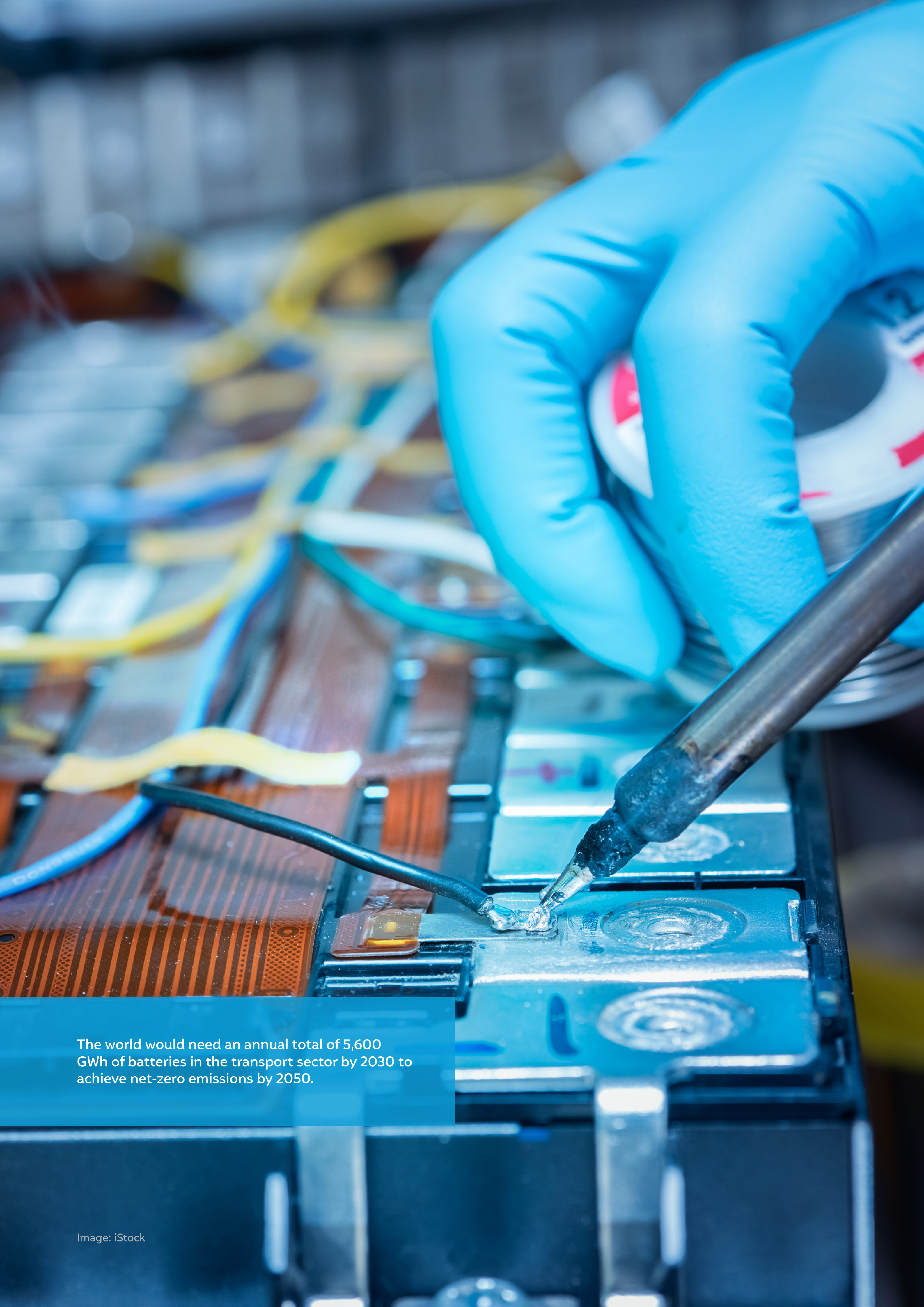
Advanced cell chemistry (ACC) batteries will play a vital role in the global energy transition, by enabling the electric mobility revolution and by storing intermittent renewable energy that will power a pathway to the world's net-zero future. Just a decade ago, ACC batteries were still a niche storage solution. Today, after years of innovations and reductions in the price of these batteries, electric vehicles (EVs) are challenging conventional ones in various market segments. These batteries have also been installed at large scales to support grid balancing of utilities worldwide.

While these successes have been momentous, developments in the past few years have highlighted the limitation of the current global ACC battery industry. In 2022 the price of lithium-ion batteries — the preeminent ACC technology — saw a price increase for the first time, after decades of price reductions. Concurrently, a spate of fire incidents linked to batteries across the world has brought renewed focus on the safety of commercialised ACC battery technologies. Perhaps most significantly, the inextricable link between modern ACC batteries and critical minerals has been tested repeatedly in the last few years. Supply constraints emerging from the global pandemic, regional crises and geopolitical tensions have left battery commodity prices volatile and supplies uncertain.

Innovation will help bridge these gaps in ACC batteries. New battery chemistries and manufacturing processes can bring the cost of technologies down, reduce their dependence on critical minerals, and improve their performance to open new avenues for end uses. Hopefully, ACC batteries could soon see use in niche applications like aircraft or in long-duration electricity storage.

However, to be successful, these innovations must be co-developed. Countries worldwide need to recognise that ACC batteries are a key piece of the climate puzzle. Collaborative development of next-generation batteries will help ensure they are rapidly commercialised and are deployed in underserved markets.

This report, titled "Addressing Technology Gaps through Collaboration on Advanced Cell Chemistry (ACC) Batteries" and prepared for the G20 Energy Transition Working Group, discusses the essential areas in which technology collaboration could be crucial to the development of the next-generation of ACC battery technology. The report proposes a multi-dimensional framework to track ACC innovation and provides recommendations on how collaborative innovation can occur. I thank the Ministry of Power, Government of India, for giving CEEW the opportunity to prepare this study and am grateful for the regular guidance and support from the NTPC Energy Technology Research Alliance team during the research process.



The world would need an annual total of 5,600 GWh of batteries in the transport sector by 2030 to achieve net-zero emissions by 2050.

Image: iStock

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# Acronyms and Abbreviations

| | |
|---|---|
| 2W/3W | 2 or 3 wheelers |
| ACC | advanced cell chemistry |
| AI | artificial intelligence |
| Al2O3 | aluminium oxide |
| BESS | battery energy storage system |
| BEVs | battery electric vehicles |
| BMS | battery management software |
| CAES | compressed air energy storage |
| CAGR | compound annual growth rate |
| CCl4 | carbon tetrachloride |
| CERT | Committee on Energy Research and Technology |
| CES | chemical energy storage |
| CO2 | carbon dioxide |
| CSIR | Council For Scientific And Industrial Research |
| CSIRO | Commonwealth Scientific And Industrial Research Organisation |
| D&D | development and demonstration |
| DNi | direct nickel process |
| DT | digital twin |
| EC | electrochemical |
| EcES | electrochemical energy storage system |
| ECs | electrochemical components |
| EES | electric energy storage system |
| EHS | environment and health safety |
| ES | energy storage |
| ESS | energy storage systems |
| ETIP | European Technology And Innovation Programme |
| ETWG | Energy Transitions Working Group |
| EU | European Union |
| EV | electric vehicles |
| FCAS | frequency control ancillary services |
| FES | flywheel energy storage |
| GES | gravity energy storage |
| GHG | greenhouse gas |
| GW | gigawatt |
| GWh | gigawatt-hour |
| HDV | heavy duty vehicles |
| HTP | human toxicity potential |
| ICE | internal combustion engine |
| IEA | International Energy Agency |
| IP | intellectual property |
| IRENA | international renewable energy agency |
| kT | kilo tonnes |
| kWh | kilowatt-hour |
| LCO | lithium cobalt oxide |
| LCOS | levelised cost of storage |
| LDV | light duty vehicles |
| LFP | lithium iron phosphate |
| Li | lithium metal |
| Li-ion | lithium-ion |
| $Li\text{-}O_2$ | lithium-metal air |
| Li-S | lithium-sulphur |

| | |
|---|---|
| $Li/CF_x$ | lithium/fluorinated carbon |
| $Li_2CO_3$ | lithium carbonate |
| LIB | lithium-ion battery |
| LiOH | lithium hydroxide |
| $LiPF_6$ | lithium hexafluorophosphate |
| LMO | lithium manganese oxide |
| LMO-LTO | lithium manganese oxide-lithium titanium oxide |
| LNG | liquified natural gas |
| LPG | liquified petroleum gas |
| MABs | metal air batteries |
| MDV | medium duty vehicles |
| MES | mechanical energy storage |
| MI | mission innovation |
| MIT | Massachusetts Institute of Technology |
| MRL | manufacturing readiness level |
| MT | metric tonnes |
| MWh | megawatt-hour |
| $NaPF_6$ | sodium hexafluorophosphate |
| NCA | nickel cobalt aluminium |
| Ni-Cd | nickel-cadmium |
| Ni-MH | nickel-metal hydride |
| NMA | nickel manganese aluminium |
| NMC | nickel manganese cobalt |
| NRC | National Research Council |
| NREL | National Renewable Energy Laboratory |
| NTM | nickel titanium manganese |
| ORNL | Oak Ridge National Laboratory |
| OSOWOG | one sun one world one grid |
| PCM | phase change materials |
| PHES | pumped hydro energy storage |
| PLI | production linked incentive |
| PTC | power to curb |
| R&D | research and development |
| RD&D | research development and demonstration |
| RE | renewable energy |
| RFB | redox flow battery |
| ROI | return-on-investment |
| $SiO_2$ | silica |
| sPEEK | sulphonated polyether ether ketone |
| SPHES | seawater-pumped hydro energy storage |
| TES | thermal energy storage |
| TRL | technology readiness level |
| UPHES | underground pumped hydro energy storage |
| US | United States |
| USD | United States dollar |
| USGS | United States Geological Survey |
| V | vanadium |
| VCs | venture capitalists |
| VoD | valley of death |
| VRFB | vanadium redox flow battery |
| VRLA | valve-regulated lead acid |
| ZEBRA | Zeolite Battery Research Africa |

Battery manufacturing is a complex, multi-step process. It involves mineral extraction, refining, active component manufacturing (electrodes and electrolytes), cell manufacturing, and assembly. Cost-effective scaling of these value chains requires significant technical expertise and efficient production processes.

Image: iStock

# Executive summary

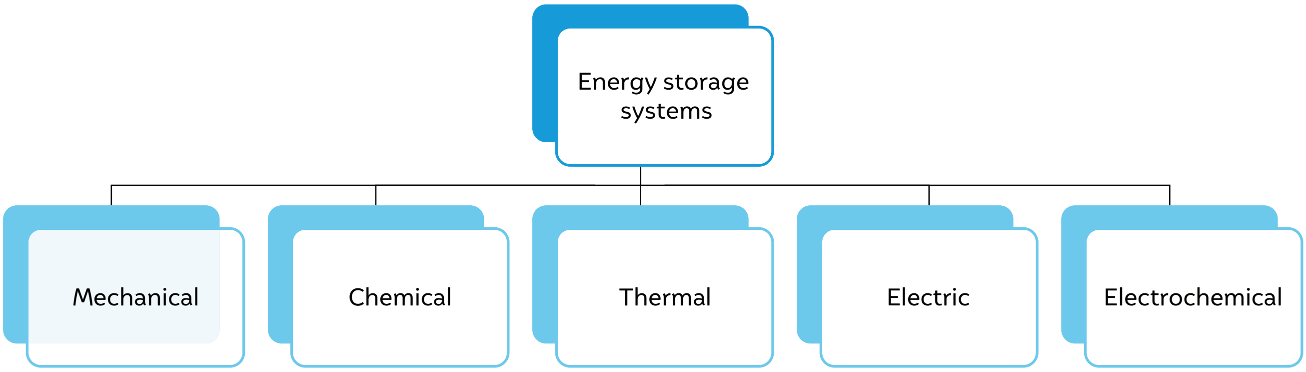
Energy storage technologies will play a critical role in the decarbonisation of the power and transportation sectors. The Group of Twenty (G20) countries have led such climate action, representing a cumulative share of 86 and 89 per cent of global renewable energy (RE) capacity and battery electric vehicle (BEV) stock, respectively, in 2020. Although there are various types of energy storage technologies, like mechanical, chemical, thermal, electric, and electrochemical (Figure ES1), electrochemical technologies (batteries) have attracted particular attention from industry and consumers alike due to their modularity and deployment versatility. Electrochemical batteries are further classified as lead-acid, nickel-cadmium, lithium-ion-based, sodium-ion-based, redox flow, solid-state, and metal-air. Many of these batteries are classified as advanced cell chemistry (ACC) batteries.

The traditional batteries have found use in power and transport sector but **numerous other applications, such as the electrification of aircraft, ships, and spacecrafts, can be unlocked by improving the technological gaps** of the available batteries, including performance and safety. On advancements, even existing applications can potentially witness further scale up. Performance gaps are inextricably linked to the context that batteries are expected to perform in. For example, a high gravimetric energy density may be desirable for batteries used in mobile applications while a high cycle life may be required for energy applications using stationary storage. Safety gaps are linked to the inability of batteries to manage temperature fluctuations or internal heat dissipation, which lead to battery failures and fires. Such accidents also have direct implications for the safety of humans.

Beyond these technological considerations, **the current generation of batteries is also plagued with supply chain and raw material gaps.** Battery manufacturing is a complex, multi-step process involving mineral extraction, refining, active component manufacturing (electrodes and electrolytes), cell manufacturing, and assembly. Cost-effective scaling of these value chains requires significant technical expertise and efficient production processes. Furthermore, there could be significant gestation periods necessary for building new capacity, which can result in supply–demand mismatches. Figure ES2 shows the timelines to bring online different stages of a lithium-ion battery (LIB) production supply chain. Lastly, the current mineral processing and battery production have significant emissions – new ACC battery supply chains must have a low energy footprint and circular processes.

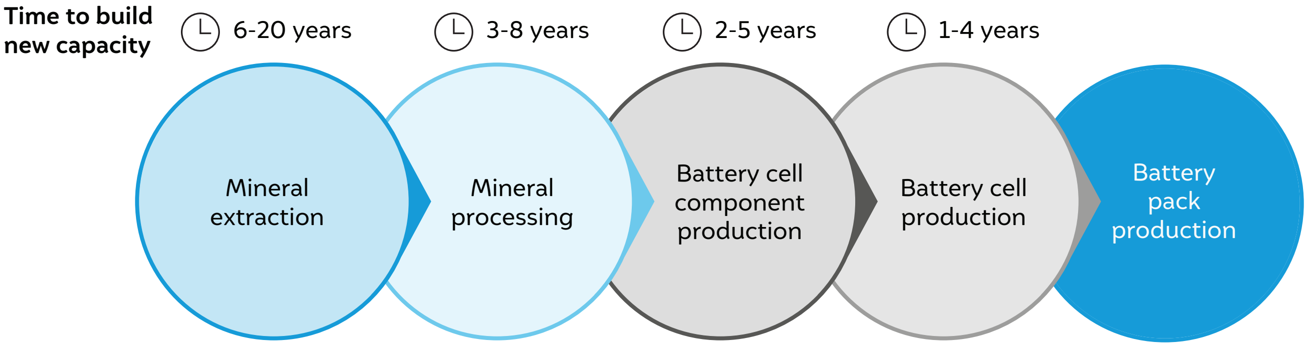
Several of the available batteries use minerals that have limited reserves (for instance, platinum) or are concentrated in a few geographies (such as cobalt). Future ACC batteries should be designed using abundant minerals that can be mined and refined using environmentally sustainable processes.

Figure ES 1 Overview of the different types of energy storage technologies



*Source: Authors' analysis*

**Figure ES 2** Timelines for the different stages of the lithium-ion battery production supply chain



*Source: Authors' recreation from IEA (2022c)*

We have categorised the most significant technological gaps across five indicators and developed associated metrics to assess and track the progress of ACC batteries (Figure ES3):

- **Battery cost**, often perceived as a proxy for viability, could be evaluated based on the upfront or annualised (energy or power) costs. These are further dependent on the price of raw materials and production and maintenance costs. Hence, batteries should be compared using an appropriate cost metric, depending on the application and typical use period.
- **The performance** of a battery determines its suitability for an application. Hence, although there are several indicators to measure the same, only a few matters to identifying an optimum battery for a specific application.
- **The environment, health and safety impacts** of battery technologies can also be tracked. This includes production, usage, and end-of-life stages.
- **The scalability** of a battery refers to the ease of manufacturing. This can be tracked by technology and manufacturing readiness levels (TRL and MRL), the complementarity of the production processes with the existing facilities, the criticality of the raw materials used, and access to intellectual property (IP).
- **Circularity** is an emerging but important indicator for tracking battery progress that focuses on material intensity, design, and ease of reuse and recycling. Batteries that use fewer materials and are easy to disassemble for reuse or recycling could be preferred over others that use complex materials and compounds, which makes subsequent stages energy-or time- intensive.

**Figure ES 3** Indicators for tracking the progress of ACC technologies

| Cost | Performance | Environment, health, safety (EHS) | Scalability | Circularity |
|---|---|---|---|---|
| • Upfront costs (per kWh, per kW)<br>• Annualised costs (per kWh generated, per kW-year) | • Energy density<br>• Cycle life<br>• Calendar life<br>• Charging time<br>• Round-trip efficiency<br>• Optimal operating temperature<br>• Ramp rate<br>• Capacity decay rate | • Manufacturing emissions<br>• Battery waste toxicity<br>• Battery safety | • Technology readiness level (TRL)<br>• Manufacturing readiness Level (MRL)<br>• Current production capacities<br>• Criticality of raw materials<br>• Access to intellectual property (IP) | • Design for disassembly<br>• Reuse<br>• Recyclability |

*Source: Authors' analysis*

**Figure ES 4** Innovations in the battery supply chains for ACC technologies

| Battery chemistry | Mining | Battery cell materials and design | Manufacturing process and deployment | Battery management system |
|---|---|---|---|---|
| • Metal-air<br>• Solid-state<br>• Sodium-ion<br>• Magnesium<br>• Chlorine flow<br>• Room temperature sodium-sulphur | • Direct lithium extraction<br>• Hard rock lithium technology<br>• Direct nickel process | • Cobalt-free batteries<br>• Alternate anodes: Silicon, titatium boride nanosheets<br>• Boundary-free cathode | • Dry coating technique<br>• Space efficiency in battery packs<br>• Two-in-one battery pack<br>• Blade battery packing | • Software improvements<br>• Digital twin |

*Source: Authors' analysis*

Several innovations in processes across the value chain – mineral processing, designing, manufacturing, packing, and deployment – enable the development of new ACC batteries (Figure ES4). Majority of the listed innovations improve performance first, followed by scalability and cost. Circularity is still a novel indicator that only a few innovations are achieving. G20 countries should come together to support these innovations and draw them from the margins to the mainstream.

## Recommendations

Innovative ACC batteries are at various stages of deployment. We have identified two priority areas and action points for the G20 countries to address and scale up ACC batteries:

**Priority 1: Promote innovation and support technological co-development by leveraging the benefits of collective effort**

- Formalise collaborations between global academic institutions to improve performance and reduce the costs of ACC technologies.
- Infuse LiFE principles by developing uniform circularity indicators that will support resource efficiency and waste minimisation.
- Share details on technological breakthroughs in previous generation ACC technologies to reduce the learning time of new innovators.

**Priority 2: Develop markets and unlock new avenues of deployment by sharing best practices and increasing the flow of finance**

- Increase government support to mobilise corporate spending and venture capitalist funding in ACC R, D&D, and the ecosystem.
- Unlock new areas of deployment through dedicated financing via multilateral development banks.
- Jointly develop handbooks and courses to train individuals and institutions on ACC battery applications (EV and grid).

# 1. Objective

Many countries have accelerated their plans for decarbonisation and are setting their net-zero/carbon neutral goals. Achieving these targets would require countries to reduce their share of emissions from conventional sources of energy and to move towards sustainable and renewable energy (RE) technologies like solar, wind, bioenergy etc. However, countries with greater share of renewables face the concomitant challenge of grid stability due to the intermittent nature of RE generation. Often, energy generation has to be curtailed because the energy cannot be absorbed into the system. Energy storage systems (ESS) can store energy and make it available for later use. Some of these systems are designed to operate only once (non-rechargeable) while others can be used multiple times (rechargeable). Energy storage technologies which can be used multiple times will play a critical role in decarbonising the transport and power sectors, which are the largest contributors to global emissions. These technologies will be able to store and discharge any excess RE when required. Similarly, they can be used to power vehicles, providing alternatives to help them move away from fossil fuels.

Different kinds of energy storage systems have been deployed in the past. They can store energy thermal, mechanical, electrochemical, chemical and electrical forms. Electrochemical energy storage is the most versatile kind; it can be used in various applications due to its scalability, modularity and ease of use. However, much work needs to be done to reduce costs, improve safety, and increase the availability of raw materials used in these technologies. Details on the kinds, functionality and limitations of various energy storage technologies are provided in the Annexure 1 and 2.

Given the versatility of electrochemical energy storage technologies, and the high quantity of emissions from the transport and power sector and the, this report focusses on these technologies only and for their application in these two sectors. Additionally, given the forward-looking nature of the analysis, we limit our discussion to new and advanced electrochemical energy storage systems which will be referred to as advance cell chemistry (ACC) in this report. The definition and contours of ACC are provided in subsequent sections.

Many developed countries such as the United States (US) and Australia have already started deploying ACC storage for various use cases in the power sector. Additionally, countries such as Canada, South Korea, England, have officially announced ambitious targets for the electrification of their transport sectors. However, the infrastructure and the design of the power and transport sectors vary between regions. Hence, the learnings and the technology cannot be directly replicated in any other region. The uniqueness of each application underscores the need for international collaboration. By sharing of learnings from various aspects of technological development and deployment, each country will be able to move forward faster and play an important role in the global decarbonisation effort.

The Group of Twenty (G20) has the potential to become the platform to scale up ACC storage deployment globally. Pandemic induced supply chain disruptions have reinforced the need for diversified supply chain and technology alternatives. Given the magnitude of deployments that is required in the coming decades, there is enough room for each country to participate in and contribute to the development and deployment of ACC storage technologies.

This report will detail the key updates and impending innovations in the ACC storage development, supply chain, manufacturing, and deployment. It not only identifies the technologies of tomorrow but also lists the applications and indicators that need to be tracked for their success. Finally, we make a case for the need for collaboration between G20 member countries on ACC, and how that can accelerate the decarbonisation process in the transport and power sectors.

## 2. Methodology and limitations

Individuals and institutions across the world are working on developing new, and improve on existing, energy storage technologies. This paper focusses on the role of G20 countries to scale up technological gaps in the field of ACC systems.

During our research process, we examined peer-reviewed and published works on energy storage technologies. We reviewed reports and papers by think tanks, academic institutions, multilateral organisations and government agencies were referred as part of the research process. Additionally, we gathered insights via publicly available conference proceedings and presentations. We followed up the discussion with few industry stakeholders to corroborate our findings.

> **G20 has the potential to become the platform to scale up ACC storage deployment globally.**

The sources mentioned were used to gather data on innovations and current trends in electrochemical storage technology. During the process we realised that most of the publicly available information on innovation and trend focusses on lithium-ion batteries (LIBs). While lithium-ion technology is expected to dominate the market, it is also important to increase public discourse on other technologies such as solid-state, metal-air and flow batteries.

We were able to capture key innovations in the current value chain and provide details on new battery technologies. Importantly, the compilation was highly dependent on publicly available information. As such, new technologies/innovations under development, which have not been documented, may not appear in this paper.

Finally, for the recommendations, we relied on learnings from similar sectors where innovations and development of new products were successful. We hope that despite the limitations, the findings and the recommendations of the report will help in the growth of the electrochemical and broader energy storage sector.

# 3. Background

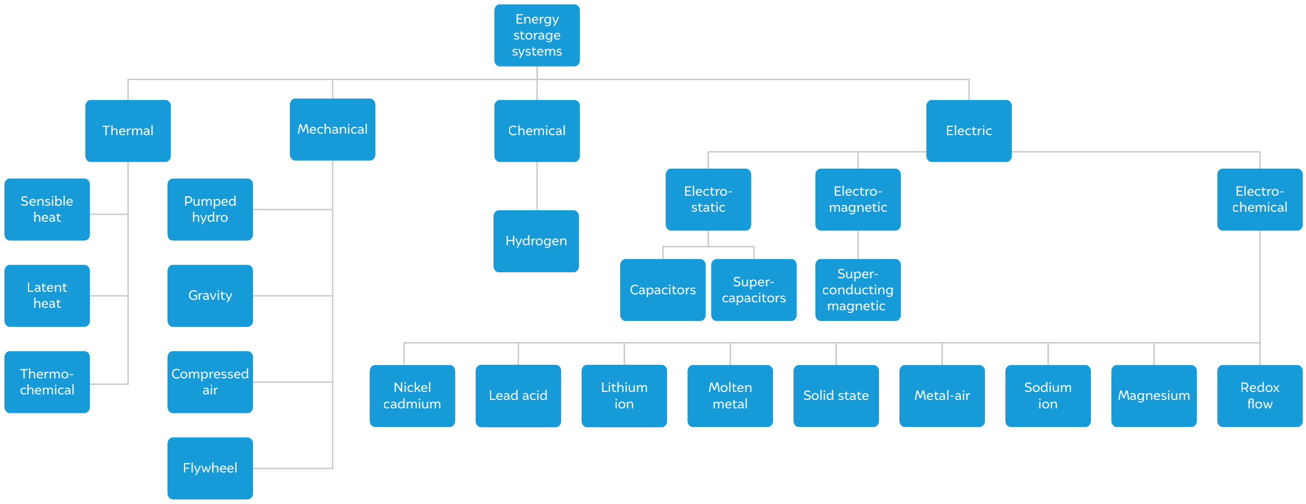
In this section, we introduce the definition of advanced cell chemistry (ACC), and the role they play in the world of energy storage. We also provide context of their historical development and the global scenario of ACC development and deployment.

## 3.1 Advanced cell chemistry batteries – A new era of energy storage

ESS enable harvesting, transformation and storage of energy received from a variety of sources; this energy is then used in multiple applications. ESS technologies can be classified on the basis of the form of energy stored in them: thermal, mechanical, electrical and, chemical energy (Mitali, Dhinkaran, and Mohamad 2022). Figure 1 showcases the broader bifurcation of energy storage technologies; brief descriptions are presented in Annexure 1.

Since the 19th century, an enormous amount of research and development (R&D) in ESS has been done across the world (Gür 2018). Most of the research has focused on rechargeable electrochemical energy storage technologies, also known as batteries, due to their versatility. These technologies primarily operate by ionisation, transport of charged particles and recombination of charges. They are highly versatile and can be used in diverse applications and environmental conditions. Before the 2000s, certain batteries – lead-acid and nickel-based – were the most common rechargeable ones in the market. They were widely adopted due to their cost effectiveness, performance, and constant incremental innovation. Lead acid batteries became popular for use as starter, lighter and ignition batteries in internal combustion engine (ICE) vehicles, while nickel-based batteries (such as nickel-cadmium and nickel-metal hydride batteries), have been used in consumer electronics and power tools.

**Figure 1** Overview of various energy storage technologies



*Source: Authors' analysis*

While lead-acid and nickel-based batteries had mass-market appeal in the previous century, since the 2000s, there has been a surge in the commercialisation of novel battery technologies, which have both complemented and displaced previous generations of batteries. These novel technologies fall under the umbrella of ACC batteries, owing to the advantages these batteries provide over the last generation of battery technologies. The performance enhancements have unlocked new applications in the power and transport sectors.

## 3.2 The evolution of ACC batteries

While ACC batteries have recently grown in popularity, their development has been many years in the making (Figure 2). Research teams across the globe were developing several chemistries for specialised applications as early as the 1960s. This included silver-zinc batteries for use in submarine torpedoes and flow batteries for use in industrial and military settings(Zito and Ardebili 2019). The molten-metal Zeolite Battery Research Africa (ZEBRA) battery was developed by the Council for Scientific and Industrial Research (CSIR) in South Africa in the 1970s and 1980s. This innovation built on work done on sodium-sulphur batteries for the Ford Motor Company's electric vehicle (EV) programme(Thackeray 2021). Many early flow battery technologies, including zinc-bromine flow batteries, were initially developed to enable electric mobility (Zito and Ardebili 2019).

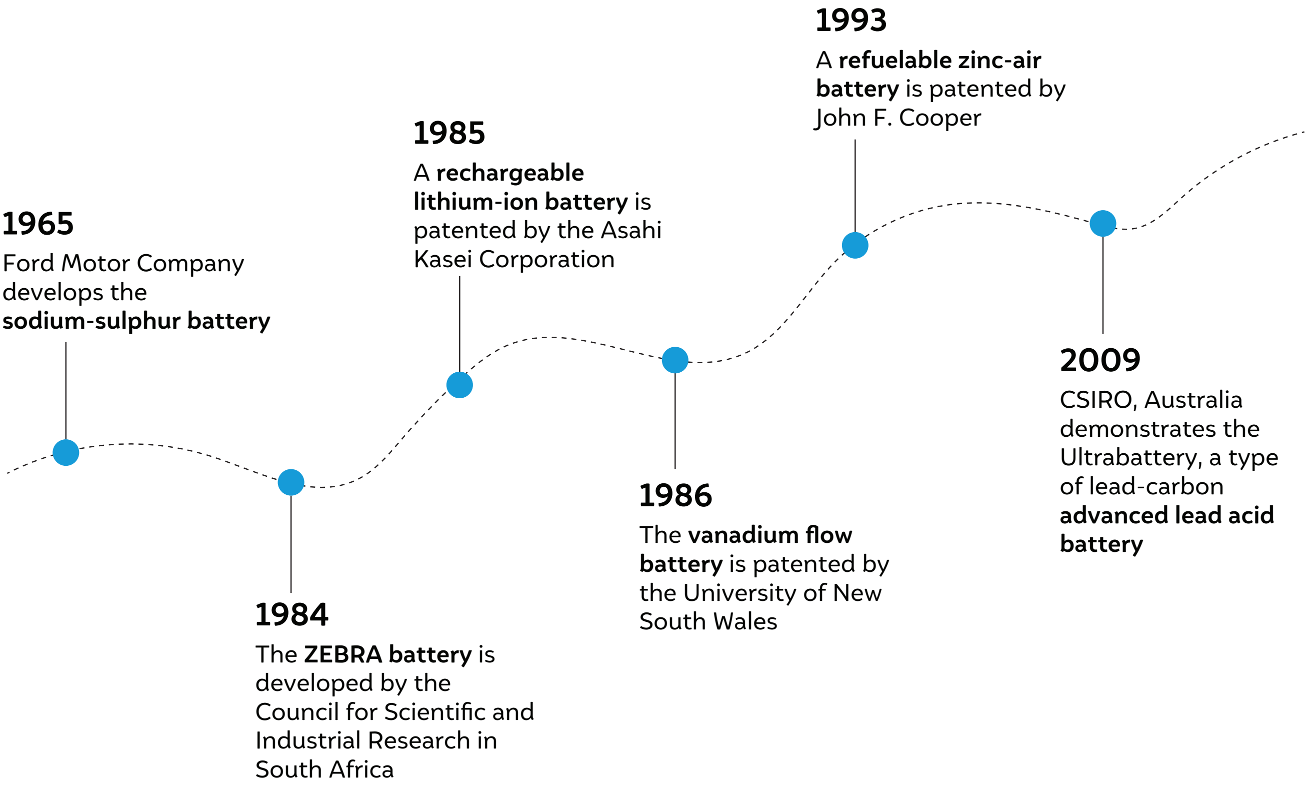
By 1986, the University of New South Wales patented the vanadium redox flow battery (VRFB) (Colthorpe 2021). A decade later, the VRFBs were used in load-levelling stationary storage system implemented by Mitsubishi Electric Industries and Kashima-Kita Electric Power Corporation in Japan, opening up a new avenue for flow batteries (Colthorpe 2021). Since 2010, the use of redox flow batteries (RFB) has significantly increased, particularly in stationary storage applications. More than 700 MWh of RFB storage capacity was installed globally as of 2019 (US Department of Energy 2020).

CSIR's exploration of sodium and lithium redox couples led to a collaboration with John Goodenough at Oxford University in 1981,and the eventual development of the LIB (Thackeray 2021). Indeed, lithium-ion chemistry had been pioneered by Stanley Wittingham during his time at Exxon a decade earlier. But it took until 1991 for Sony to commercialise the technology, using a lithium cobalt oxide (LCO) chemistry. There has been a rapid upsurge in demand for LIBs in recent decades due to astronomical price reductions since the technology first commercialised. For instance, the average price of a LIB was around USD 137/kWh in 2020, this was 98 and 85 per cent lower when compared to 1991 and 2013 levels, respectively (Hannah Ritchie 2021; BNEF 2020). Annual deployment of LIBs grew to 195 GWh in 2019, from a paltry 60 GWh five years prior (US Department of Energy 2020). In 2018, the LIB market size of USD 40 billion was 7 per cent greater than that of lead-acid batteries. LIBs are the most popular technology today. They have replaced nickel-based chemistries in consumer electronics and are being used in several electric mobility and stationary storage applications.

Innovations have led to the development of advanced lead-acid batteries that have higher life spans over their existing counterparts. These batteries have been developed by groups such as Axion Power and Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Patel 2019). Similarly, improvements to sodium-ion batteries have sparked small-scale commercialisation and plans for scaling up the technology. Other technologies, such as metal-air and solid-state batteries, are also being perfected for use in myriad energy storage applications.

> **More than 700 MWh of RFB storage capacity was installed globally as of 2019**

**Figure 2** History of development of ACC batteries



**1965**
Ford Motor Company develops the **sodium-sulphur battery**

**1984**
The **ZEBRA battery** is developed by the Council for Scientific and Industrial Research in South Africa

**1985**
A **rechargeable lithium-ion battery** is patented by the Asahi Kasei Corporation

**1986**
The **vanadium flow battery** is patented by the University of New South Wales

**1993**
A **refuelable zinc-air battery** is patented by John F. Cooper

**2009**
CSIRO, Australia demonstrates the Ultrabattery, a type of lead-carbon **advanced lead acid battery**

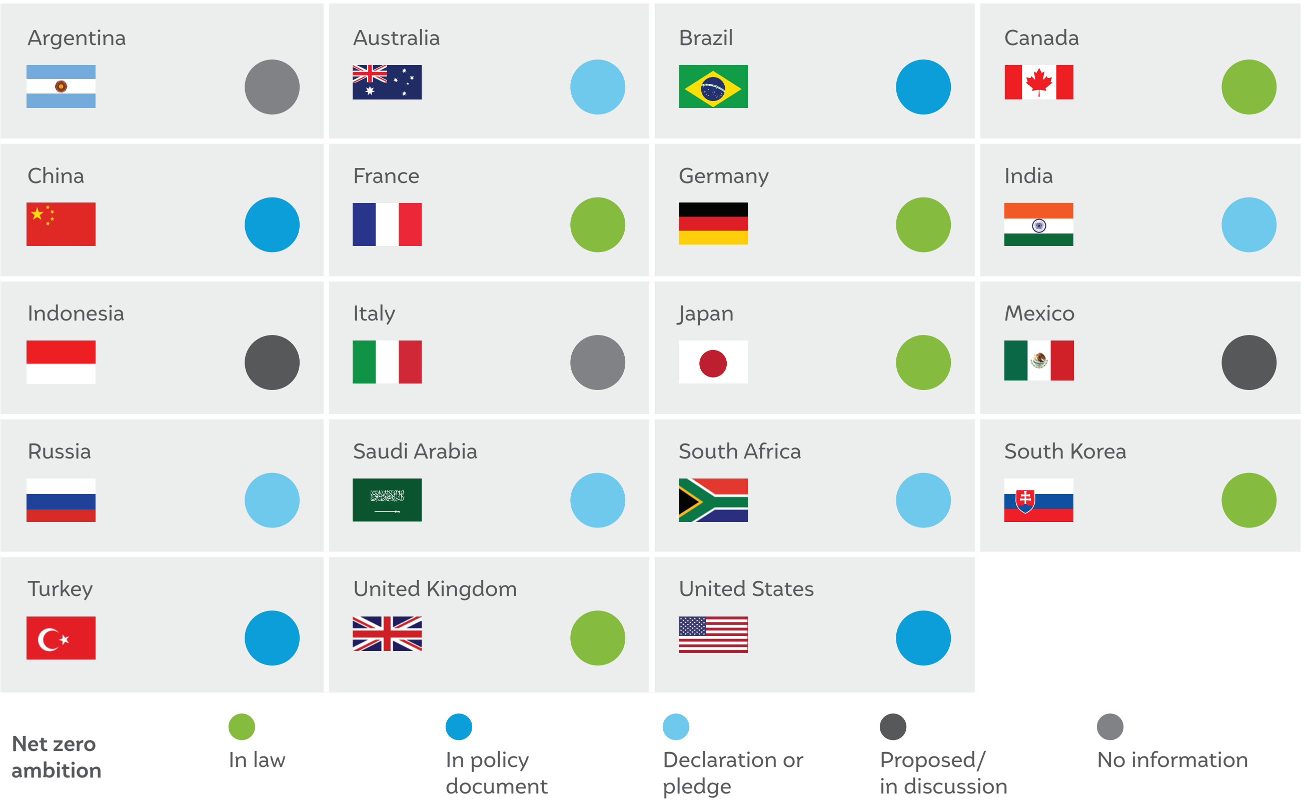
*Source: Authors' adaptation from secondary sources*

## 3.3 batteries and global climate ambitions

Globally, the electricity, heat and mobility sectors are the top contributors of greenhouse gases (GHGs), accounting for nearly three-quarters of overall emissions in 2016 (Ritchie, Roser, and Rosado 2020). The demand for electricity and mobility-related services will only continue to grow in the future, expanding the emissions potential of these sectors. GHG emissions are of particular concern for G20 member countries, which were responsible for nearly 80 per cent of the world's emissions in 2019 (Climate Transparency 2019).

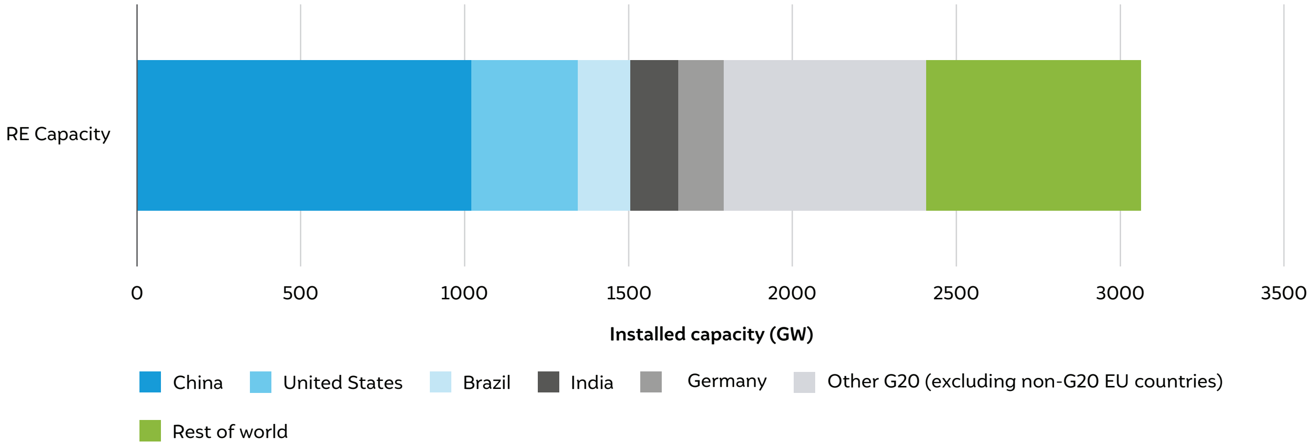
Increased RE generation and the electrification of the transport sector would contribute significantly to meeting international climate change ambitions. Globally, there has been a push to transition to such low-emissions systems. The G20 member nations have led this charge, with many members setting ambitious targets for RE and electric vehicles (EV) deployment (Figure 3).

**Figure 3** **Several G20 countries have shown the intent to decarbonise their power and mobility sectors**



*Source: Authors' compilation from IRENA. 2022a.*

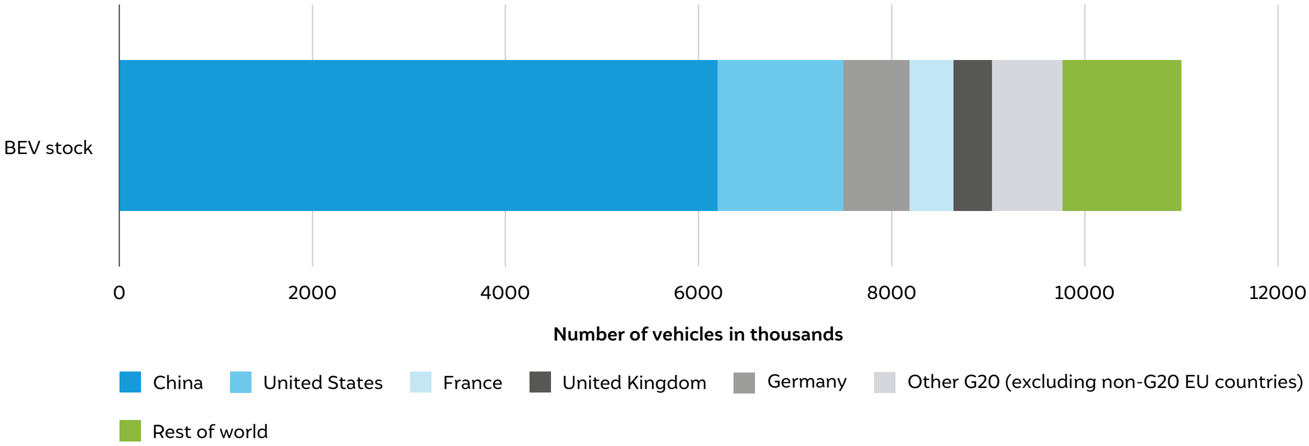
**Figure 4** **~79% of the global RE capacity was installed in G20 countries (excluding non-G20 EU countries) as of 2021**



*Source: IRENA 2022*

Note: The rest of world includes EU countries, which are not G20 members

**Figure 5** Around 89% of the global stock of battery electric vehicles (BEVs) was in G20 countries (excluding non-G20 EU countries) as of 2021



*Source: IEA 2022a*

Note: The rest of world includes EU countries which are not G20 members.

In addition to having these ambitions, G20 countries have led the world towards deploying these technologies. Figures 4 and 5, show the share of deployment of RE and EV technologies in particular G20 countries as well as the rest of the world.

Integrating large quantities of RE in the grid has its inherent challenges due to the intermittent nature of RE generation. ACC battery technologies have proven capable of providing stationary storage services to the grid. Batteries can thus address the intermittency and support the large-scale deployment of RE. The IEA estimates that in 2021, the world had 27 GW of installed battery storage capacity for power-sector related services; this is projected to reach 780 GW by 2030 and net-zero by 2050 (IEA 2022d). Depending on the nature of energy storage required and technology developments in the coming years, a significant fraction of new ESS deployments could be battery energy storage systems (BESS).

Similarly, the global demand for lithium-ion batteries in the transport more than doubled between 2020 and 2021, to 340 GWh (IEA 2022d). The world would need 5600 GWh of batteries in the transport sector by 2030, to achieve net-zero by 2050 and confine global temperatures to 1.5 °C above pre-industrial levels (IEA 2022d). McKinsey estimates that, on average the demand for battery cells will grow at a rate of 20 per cent between 2022 and 2030,resulting in a market size of USD 360 to USD 410 billion (Campagnol, Pfeiffer, and Tryggestad 2022).

## 3.4 Battery innovation in G20 countries will enable the energy transition

The G20 has identified clean energy technologies as a key driver of progress towards global climate targets (G20 ETWG 2022). ACC batteries will be important enablers of these clean technologies. Yet a greater focus on development and commercialisation of these battery technologies is imperative for the transition to continue unimpeded.

An international initiative that has set a clear vision for the development of battery technology is Mission Innovation (MI), a leading intergovernmental platform that aims to accelerate clean energy innovation. MI has identified battery innovation targets for the near, medium and long term (Mission Innovation Secretariat 2019). In the short term, the cost, performance (like power density and cycle life), and weight of ACC batteries can be improved. In the longer term, new chemistries might be developed that enable usage in aviation, shipping, and long-duration energy storage. National and supranational entities have begun to provide strategies to battery research sectors within their respective geographies. Many battery technology development programmes have been established in North America as well as European and Asian countries.

Several different areas of innovation exist, and multiple technologies are already at various stages of technology readiness. While some innovators are working on improving LIBs, others are developing and scaling alternative chemistries that can help to overcome the challenges of LIBs in many use cases. These battery technologies include sodium-ion, sodium-sulphur, advanced lead-acid, metal-air, redox flow and lithium-metal batteries (Mandal et al. 2022).

For batteries to keep pace with global ambitions for the energy transition, technological collaboration will need to be a priority. Since the CSIR – Oxford collaboration on lithium-ion technologies, international collaboration has been integral to battery development. Such academic exchanges will have to be scaled up in the coming decades to match the scale of technology deployment. Simultaneously, collaboration will be required between academic institutions, manufacturers, users and financiers to ensure that developed technologies avoid the valleys of death associated with the lab-to-market process (Murphy and Edwards 2003). Public investment often guides or directs private sector investment to areas of the public good – such as clean energy technologies.

# 4. The ACC battery technology landscape

As noted in section 4, an electrochemical storage system is also called a battery. Its key components include positive and negative electrodes, electrolytes, and a porous separator. The electrode at which oxidation occurs is known as anode; the electrode at which reduction occurs is cathode. Batteries are categorised into two types: primary and secondary batteries. Primary batteries are non-rechargeable-the electrochemical reactions in these ones are non-reversible. Chief examples of primary batteries include most alkaline and dry cell batteries. On the contrary, secondary batteries are rechargeable and can be used and reused continuously during their lifetimes. Secondary batteries include lead-acid batteries, LIBs, and nickel cadmium ones. In this report, we discuss secondary (rechargeable) batteries. ACC batteries are secondary electrochemical technologies that provide superior performance to previous generation batteries.

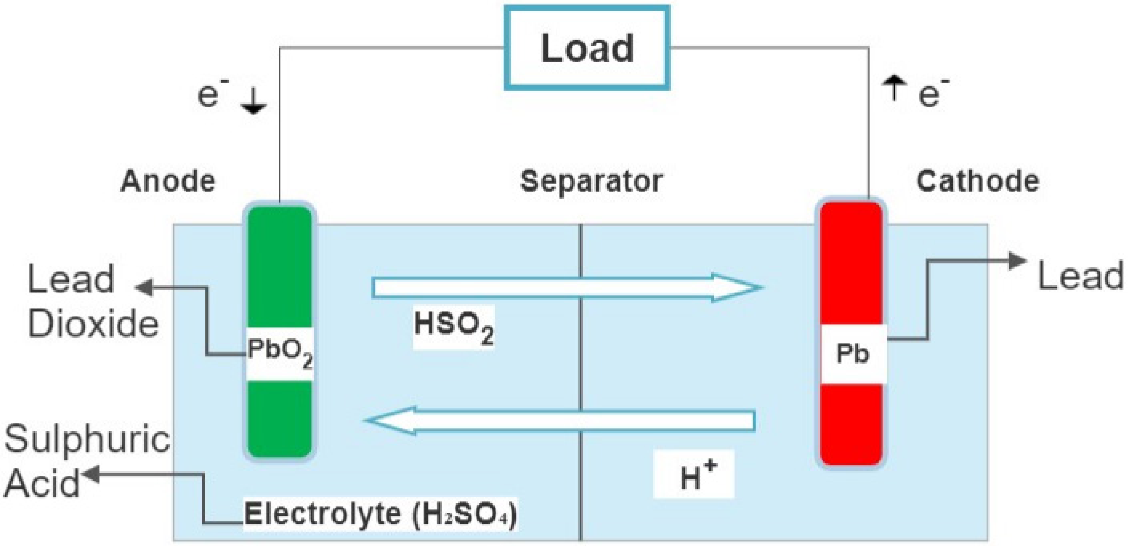
Many different types of battery technologies can be categorised as ACC. The following sections discusses some of the existing ACC technologies in detail; while Table 2 summaries their key performance-related data points.

## 4.1 Advanced lead acid batteries

Lead acid batteries store electrical energy in electrolyte form. They contain lead dioxide for the anode, lead metal for the cathode, and an electrolyte solution consisting of a high concentration of aqueous sulphuric acid (MIT 2022). Figure 6 shows a schematic representation of this battery during charging stage. Several cells are placed in series combination to generate the required voltage. They are tolerant of overcharging. However, if they get completely discharged, the lead sulphate does not get recycled back into the electrolyte- instead, it assumes a stable crystalline form that does not dissolve on recharging. This process is known as sulphation (Mandal et al. 2022). Traditional lead-acid batteries also have the limitations of lower energy and power density. To address these issues and continue reaping the benefits of the traditional lead acid batteries, advanced lead-acid batteries were developed. Lead carbon batteries are examples of advanced lead acid batteries in which carbon is added to both the anode and cathode. This reduces sulphation and internal resistance, resulting in advanced lead-acid batteries with higher energy and power density than traditional lead-acid ones (Prakash, Tiwari, and Maiti 2022).

> **For batteries to keep pace with global ambitions for the energy transition, technological collaboration will need to be a priority.**

**Figure 6** Schematic representation of the charging cycle in a lead acid battery

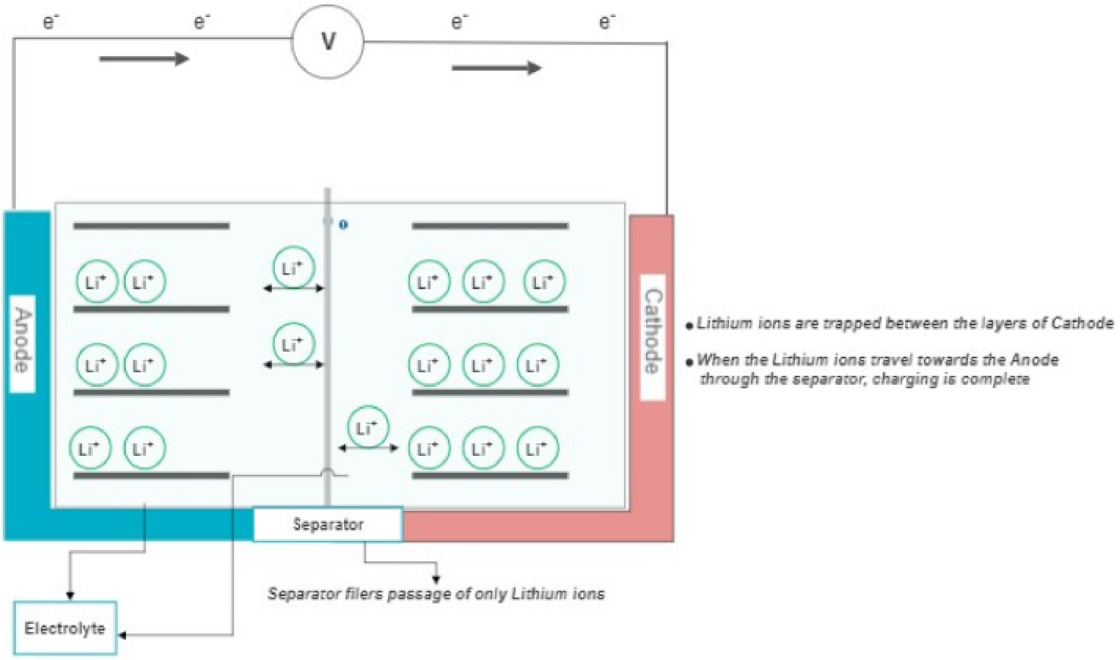


*Source: Authors' adaptation from Mandal et al. 2022*

## 4.2 Lithium-ion batteries

Originally developed for the consumer electronics sector (IEA 2022c), LIBs are rechargeable batteries that use lithium as a current carrier (Figure 7). The electrolyte carries positively charged lithium ions, through the separator, from the anode to the cathode during charging and vice versa during discharging. The movement of lithium ions creates free electrons at anode which move through the outer circuit to reach cathode to reduce the lithium ions. This movement of lithium ions generates electricity. A variety of cathodes are used in LIBs, such as LCO, lithium manganese oxide (LMO) and lithium iron phosphate (LFP). The most commonly used anode is graphite (Andrey et al. 2020). LIBs use lithium hexafluorophosphate ($LiPF_6$) as the electrolyte. Table 1 summarises the various types of LIBs according to their constituents.

**Figure 7** Schematic representation of Li-ion battery during a discharge cycle



*Source: Authors' adaptation from Gür 2018*

**Table 1** Subtypes of lithium-ion batteries

| Lithium-ion battery type | Type of cathode | Type of anode | Performance metrics (energy density [wh/kg] and cycle life ) |
|---|---|---|---|
| LFP | Nanoscale ferro phosphate material | Graphite | 90-120 Wh/Kg; 1,000-2,000 |
| LCO | Layered cobalt oxide (~60% Co and 40% Li) | Graphite | 150-200 Wh/Kg; 500-1,000 |
| NCA (lithium nickel cobalt aluminium) | Lithium NCA (varying percentages) oxide | Graphite | 200-260 Wh/Kg; 500-700 |
| LMO | LMO | Graphite | 100-150 Wh/Kg; 300-700 |
| LMO-LTO (lithium manganese oxide-lithium titanium oxide) | LMO | LTO | 70-80 Wh/Kg; 3,000-7,000 |
| NMC (lithium nickel manganese cobalt) | NMC (varying percentages) oxide | Graphite | 150-220 Wh/Kg; 1,000-2.000 |

*Source: Authors' adaptation from Kebede et al. 2022,Mandal et al. 2022, Phadke et al. 2022,MIT 2022*

## 4.3 Redox flow batteries

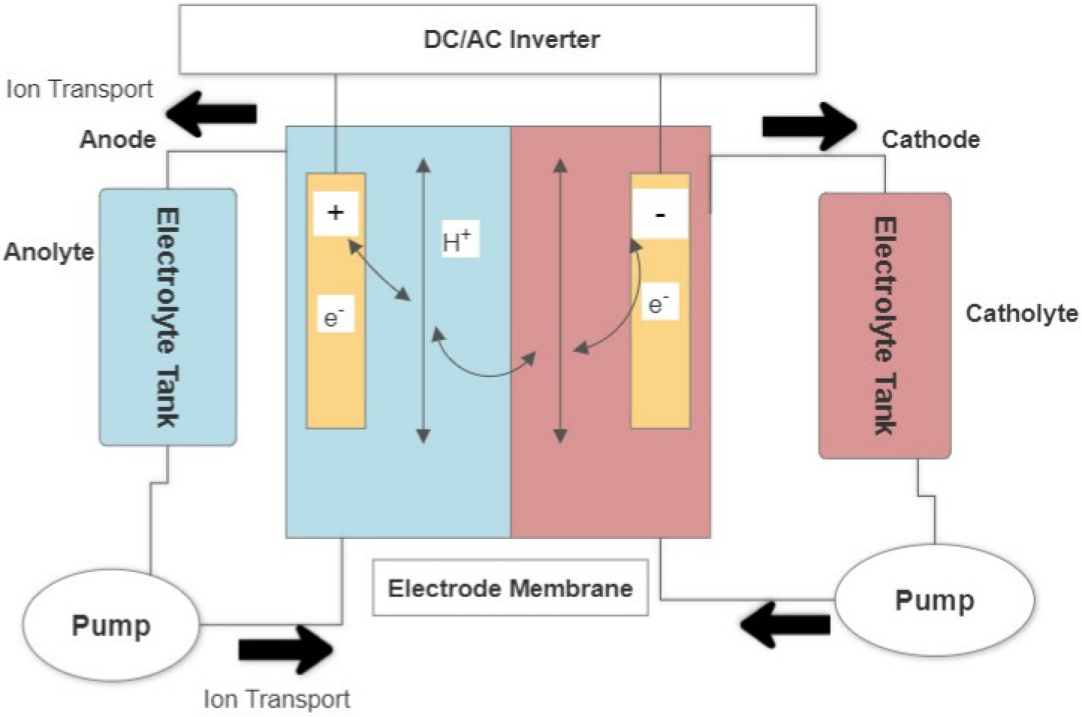
Rechargeable batteries in which electrochemical components (ECs) are dissolved in the electrolyte are known as redox flow batteries. The electrolytes are stored externally in tanks and the ECs are circulated through the centrally located fuel stack during charge and discharge processes (Mitali, Dhinkaran, and Mohamad 2022). When the electrolyte is pumped through the fuel cell stack, ion exchange occurs across the membrane (Figure 8). In this process, a reversible electrochemical reaction takes place; this allows the electrical energy to be stored. The energy storage capacity of these types of batteries is determined by the size of the electrolyte-containing tanks and concentration of ECs in the electrolyte. The power of the flow battery is determined by the chemical composition of ECs, and the configuration, and number of cells. Due to absence of a solid-liquid interface, flow batteries have an operational advantage over other batteries. The following are flow batteries commonly used today:

- **Vanadium redox flow batteries**
  VRFBs make use of the property of vanadium (V) to exist in variable oxidation states to store energy. Vanadium's four oxidation states which are utilised by VRFBs are +2, +3, +4, and +5. Ideally, there is one redox-couple of vanadium in each half-cell. The V(+2)–(+3) and V(+4)–(+5) couples are used as cathode and anodes, respectively. Typically, VRFB's have low energy densities (10-20 Wh/kg) (Mandal et al. 2022; Gür 2018).

- **Iron flow batteries**
  Similar to VRFBs, iron flow batteries make use of variable oxidation states of iron in anode and cathode materials. A cathode is usually made of a salt of iron, which combines the +3 and +2 oxidation states of the metal. Meanwhile, an anode is usually made of a salt of iron in +2 oxidation state. The electrolytes used in such batteries are also iron salts in ionised form. Iron flow batteries have the energy efficiency of almost 80 per cent (Dinesh et al. 2018).

- **Zinc bromine flow batteries**
  Zinc-bromine flow batteries, sometimes known as hybrid flow batteries, have liquid catholyte and a zinc plated anode. They have a higher energy density (65-80 Wh/Kg) as compared to VRFB. An innovation to these batteries is the zinc-bromine gel battery which is light, quick to charge, flexible, and devoid of liquid electrolytes; thus, it is safer than the conventional zinc-bromine battery, which has liquid electrolytes (Gür 2018).

**Figure 8** Schematic representation of flow batteries



*Source: Authors' adaptation from Yao et al. 2021*

## 4.4 Liquid metal batteries

In liquid metal battery, during discharging, positively charged metallic ions travel from one electrode to the other through the electrolyte; electrons do the same via an external circuit. In most batteries, both electrodes are solid; however, in some, they are liquid. The Anode forms the top layer of the battery; it is a low-density liquid metal, such as liquid calcium, sodium-potassium alloy, which can readily donate electrons. The cathode forms the bottom layer and is a high-density liquid metal such as gallium or antimony. The cathode accepts electrons from the anode. The battery's middle layer is formed by the electrolyte- a molten salt that transfers charged particles but does not mix with the materials above or below it. Because of differences in density and the immiscibility, the three materials naturally settle into three distinct layers and remain separate as the battery operates. They have a higher volumetric energy density than state-of-the-art battery technologies (X. Zhou et al. 2022). One of the examples of liquid metal battery is liquid calcium battery (Ambri 2022).

## 4.5 Sodium sulphur batteries

Sodium sulphur batteries have molten sodium as the cathode and molten sulphur as the anode. These two parts are separated by a layer of beta alumina ceramic electrolyte that allows only sodium ions to pass through it. When discharging, sodium and sulphur combine to form sodium polysulphides. During charging, however, the sodium is released back through the electrolyte (Mandal et al. 2022). Unlike the lead-acid, nickel-cadmium, and lithium-ion batteries, sodium sulphur battery does not suffer from self-discharge. Due to their long lifespans, sodium sulphur batteries can potentially be used in grid-related applications in the future. However, their high operational temperature is a disadvantage.

**Table 2** Comparison of existing ACC batteries along some technical parameters

| Battery Type | Gravimetric Energy Density[1] (Wh/Kg) | Lifespan (Cycles) | C-Rate[2] (C) | Energy Efficiency[3] Up To (%) | Operational Temperature Range (°C) |
|---|---|---|---|---|---|
| Lead- acid | 35-60 | 300-800 | 0.2-0.05 | 70 | -20 to 60 |
| State-of-the-art LIBs | 170-275 | 1,000-6,000 | 0.2-4 | 95 | -20 to 60 for discharge, 0 to 45 for charge |
| Redox flow batteries | 10-85 | 10,000-14,000 | 10-12 (N/A) | >75 | -20 to 50 |
| Sodium-sulphur | 150-240 | 1,500-4,500 | 0.16-0.18 | <85 | 300 to 350 |
| Liquid metal | 120-135 | 1000-4000 | 0.2-0.4 | 73 | >300 |
| Metal-air | 350-500 | 300-1,000 (depending on chemistry) | 0.01-0.03 | >90 | -20 to 70 |
| Solid- state | 150-500 | 1,000-10,000 | 0.2-100C | 90 | -73 to 120 |
| Sodium ion | 140-160 | 2,000-5,000 | 0.1-3 | 90 | -20 to 40 |

*Source: Authors' compilation based on Sayahpour et al. 2022,Zhang et al. 2019,Phadke et al. 2022,Mandal et al. 2022, Kurzweil and Garche 2017 and MIT 2022*

## 5. Key metrics to be tracked for the success of ACC batteries

With continuous innovations underway, the landscape of ACC batteries is rapidly evolving. This necessitates a framework that allows interested parties (such as a country or industry) to track innovations and support decision-making to scale, deploy, or test a particular technology. We have identified five crucial battery technology indicators for this purpose: cost; performance; environment, health, and safety (EHS); scalability; and circularity (Figure 9). Any combination of these indicators could be of importance to a country looking to develop, deploy, or manufacture ACC battery technologies. Each broad indicator is defined and accompanied by several metrics. These metrics allow for the indicators to be quantified in a meaningful way. Metrics also allow for nuance in tracking new developments. Many indicators, and associated metrics, acquire importance only in the context of a particular application. Hence, the choice of indicators used to track ACC technology should be made based on future transport and power sector targets, as well as domestic resource availability and manufacturing capability.

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[1] Gravimetric energy density-available energy per unit mass of a battery material

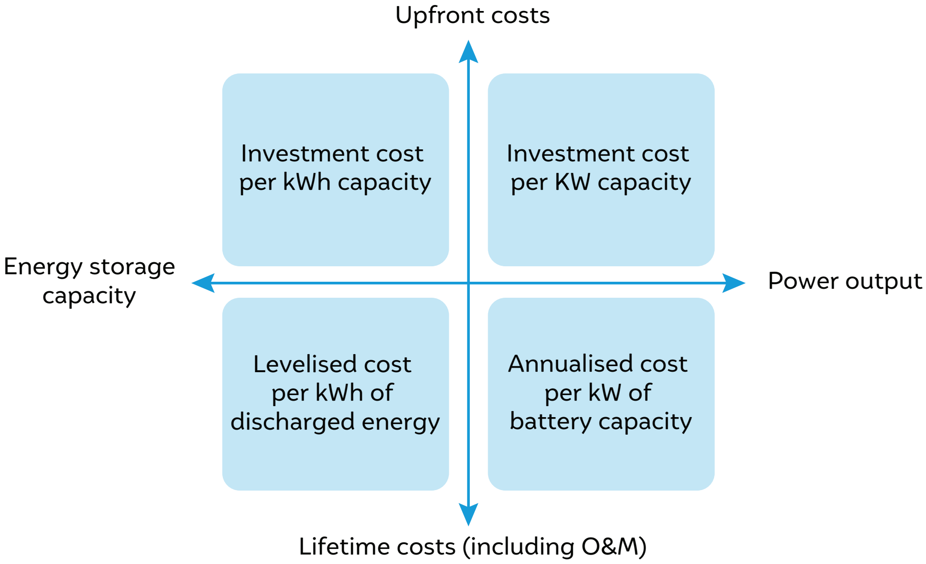
[2] C-rate: unit used to measure the speed in which the battery gets charged or discharged. For example, charging at C-rate of 1C implies that battery is charged from 0-100% in one hour.

[3] Energy efficiency: amount of energy received from a battery relative to the amount of energy that can be put into it

**Figure 9** Key indicators to track ACC innovation

| Cost | Performance | Environment, health, safety (EHS) | Scalability | Circularity |
|---|---|---|---|---|
| Upfront costs (per kWh, per kW)<br>Annualised costs (per kWh generated, per kW-year) | Energy density<br>Cycle life<br>Calendar life<br>Charging time<br>Round-trip efficiency<br>Optimal operating temperature<br>Ramp rate<br>Capacity decay rate | Manufacturing emissions<br>Battery waste toxicity<br>Battery safety | Technology readiness level (TRL)<br>Manufacturing readiness Level (MRL)<br>Current production capacities<br>Criticality of raw materials<br>Access to intellectual property (IP) | Design for disassembly<br>Reuse<br>Recyclability |

**Figure 10** Important cost metrics for battery technologies



*Source: Authors' adaptation from MIT 2022; Lazard 2021; Schmidt et al. 2019*

## 5.1 Cost

Cost is a primary determinant of the viability of a battery technology. As costs reduce, new applications open up and existing applications become more competitive. The upfront cost per kWh of a battery is often the most relevant cost metric, but at least three other useful cost metrics exist depending on the application: Costs can be based on the energy or power capacity of the battery. They can also be based on upfront or lifetime costs, which are either levelised based on the stored energy or annualised based on the rated capacity. A useful visualisation of different cost metrics is provided in Figure 10.

For most applications, tracking the cost per kWh is optimal. This is particularly true for mobility and long-duration storage applications. In certain areas, such as ancillary services, the cost per kW, rather than per kWh, is likely to be more relevant. Combining the upfront cost of battery technologies with other performance metrics – such as efficiency and cycle life, as in the case of levelised cost of storage (LCOS)[4] – could give a more holistic picture of a battery technology's cost. Such an indicator is already being considered by the United States to guide its future long-duration energy storage development (US Department of Energy 2021).

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[4] LCOS has limitations in its applicability, as it is a simplified model of the total lifetime costs.

**Table 3** Important performance metrics for battery technologies

| Performance metric | Definition | Unit |
|---|---|---|
| Energy density (volumetric and gravimetric) | Energy that can be stored per unit mass or volume of the battery | Wh/kg<br>Wh/L |
| Cycle life | Number of charge/discharge cycles that the battery can complete without excessive degradation[5] | cycle |
| Calendar life | Number of years the battery can be used/stored without excessive degradation | Year |
| Charging time | Time taken to fully charge/discharge the battery | Sec |
| Round-trip efficiency | Ratio between discharge energy and charge energy over one cycle | % |
| Optimal operating temperature | The maximum and minimum temperatures within which a battery can operate without long-term degradation | °C |
| Ramp rate | The potential rate of change of power input/output from the battery with respect to the maximum power input/output of the battery | %/sec |
| Capacity decay rate | The total battery capacity lost during each cycle | %/cycle |

*Source: Authors' adaptation from US Department of Energy 2020; Yao et al. 2021; Bills et al. 2020*

When it comes to estimating and forecasting battery costs, both the material prices and the costs of production become relevant (Mauler et al. 2021). Often, these prices are independent of each other, and thus, the battery cost indicators often reflect two very different underlying price regimes (Hsieh et al. 2019).

## 5.2 Performance

The performance of a battery is a broad-brush indicator to reflect how well-suited a battery technology is to perform a specific application. As an indicator, therefore, battery performance is highly dependent on the nature of the application of the battery technology. Even so, certain metrics, such as cycle life or efficiency, are valuable to most battery applications. A selection of important battery performance metrics is provided in Table 3.

For certain applications, such as mobility, where space and weight are constrained, energy density can be the determining factor of a technology's viability. For other applications, such as grid-scale storage, high cycle life and round-trip efficiency are often the pre-dominant performance metrics. In the coming decades, countries will need to track multiple performance indicators depending on their domestic deployment goals. A positive result of such tracking could be the development of application-specific ACC technologies as multiple chemistries find their niche.

## 5.3 Environmental, health, and safety (EHS) indicators

The following EHS metrics are important considerations when tracking ACC innovations:

- **Manufacturing emissions:** Since ACC batteries are generally expected to reduce carbon dioxide emissions when used, the emissions generated during the production of an ACC battery might be an important metric to track. Often, such emissions are tracked as overall emissions created during production (mining, beneficiation, and manufacturing) per kWh of battery capacity produced (Hall and Lutsey 2018).
- **Battery waste toxicity:** The leaching of metals contained in waste batteries into the environment can lead to toxicity in humans and other biotic systems. Various metrics can be used in conjunction to evaluate the potential toxicity of different ACC batteries once discarded. These include the percentage content of environmentally sensitive material, human toxicity potential (HTP), and abiotic resource depletion potential (Kang, Chen, and Ogunseitan 2013; US Department of Energy 2020).

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[5] Excessive degradation is usually defined as reduction in the battery capacity to less than 80 per cent of the original capacity (US DOE 2020)

- **Battery safety:** ACC batteries are energetic systems, so there is a potential for fires to start and propagate. The fire risk differs based on the battery chemistry. Therefore, it is useful to categorise the risk potential for different battery technologies. Battery fire safety metrics include the limited oxygen index – the minimum concentration of oxygen required to sustain combustion – as well as flame propagation and self-extinguishing time of the battery electrolyte (US Department of Energy 2020; Swiderska-Mocek et al. 2020). Battery safety issues pose a direct threat to the people who use these batteries in various contexts.

## 5.4 Scalability

The following scalability metrics facilitate the categorisation of battery technologies based on how easily the technology can be manufactured at scale.

- **Technological readiness level and manufacturing readiness level:** Technological readiness level (TRL) is the measure of the readiness of a particular technology for commercialisation. The TRL scale consists of nine steps, ranging from starting from research, then development, and finally deployment and mass commercialisation. A similar but distinct metric, manufacturing readiness level (MRL), measures the maturity of a manufacturing process (Héder 2017; OSD Manufacturing Technology Program 2007).
- **Existing production capacity:** While many new technologies require the creation of completely novel value chains, many incremental developments only require the implementation of minor process changes. Often, new chemistries can also be considered 'drop-in' – they can, in most cases, be manufactured on the pre-existing line with small tweaks. In these cases, it is necessary to understand the existing battery manufacturing capacity of a country. Another valuable metric is the capacity of the domestic supply chain that caters to the manufacture of a particular ACC battery technology.
- **Criticality of raw materials:** Given their chemical nature, ACC batteries often require the mining and beneficiation of large quantities of raw materials (IEA 2021). Depending on a battery's chemistry, raw materials for battery production could become critical to a country if they are not available domestically, are concentrated only in specific geographies, or are globally limited in supply. Certain useful metrics exist to determine this criticality: the share of domestic reserves of a mineral to total demand of ACC battery production, the geographic concentration of input minerals, and the recyclability and substitutability of a mineral in a particular battery technology.
- **Access to intellectual property:** Access to intellectual property (IP) can be a major barrier to scaling a battery technology (Gifford 2022). Understanding the number of patent-protected technologies and processes required to manufacture a particular ACC battery at scale can shed considerable light on its scalability.

## 5.5 Circularity

A circular approach is necessary for three reasons: to secure resource adequacy, to minimise environmental impact of the products, and maximise the social benefits from the product use. Circularity can be achieved at three stages of a battery's life:

- **Design:** Efficient production and consumption by reducing material consumption in manufacturing, targeting multifunctional products, or justifying the need for a product.
- **Use:** Extended use of products and/or components by reusing a discarded product; repairing a defective one; restoring an old one via refurbishing; remanufacturing a new product with a discarded product or its parts for the same application, or repurposing a defective product or its parts for other applications.
- **End of life:** Useful application of materials by recycling the waste to obtain materials of the same or lower grade and energy recovery via incineration of waste materials.

Currently, majority of industries and policymakers focus on the end-of-life stage (recycling and recovery), followed by product use. The European Union (EU) (EC 2020), India (MoEFCC 2022), and the United States (CFR 2022) have directives for the responsible management of battery waste. However, design innovations relevant to circularity are very few. The EU's Battery Directive is the sole regulation that considers the entire lifecycle of a battery, including eco-design requirements and ethical and safe material sourcing (EC 2020).

> **Access to intellectual property can be a major barrier to scaling a battery technology.**

# 6. Application landscape of ACC batteries

This section outlines the key applications of ACC batteries in the transport and power sectors, summarises the associated challenges in these use cases, and highlights some case studies across geographies. Many of the applications are already technically and economically feasible for the existing generation of ACC batteries. However, there are several new applications that can be unlocked with the innovations that are underway.

## 6.1 Existing applications

ACC batteries have multiple use cases in the transport and power sectors. In addition to reducing reliance on traditional fuels, electric vehicles (EVs) can provide grid support services (this is the vehicle-to-grid concept). However, the applications of ACC batteries are more diverse in the power sector than in the transport sector. These deployments are broadly classified into two categories: grid connected and off-grid. Grid-connected batteries are used to support grid functions while off-grid systems primarily offer electricity access to connected users. The following sections provide the details.

### 6.1.1 Transport sector

As mentioned in earlier sections the annual global demand for LIBs in the transport sector was 340 GWh in 2021 (IEA 2022d). With a 120 per cent increase in registrations between 2020 and 2021, passenger cars contributed the most to this demand; meanwhile, other transportation modes like medium and heavy trucks lagged. It is now estimated that the world would need an annual total of 5,600 GWh of batteries in the transport sector by 2030 to achieve net-zero emissions by 2050 and keep the global temperatures at 1.5 °C above pre-industrial levels. Electric cars will continue to drive this demand, representing 75 per cent (255 GWh annually) by 2030.

Although there are several types of EVs like battery electric vehicles (BEV), hybrid EV and plug-in hybrid EV, this report focuses on BEV. The battery specifications related to energy density vary with the vehicle mode: two-or three- wheelers (2W/3W), light duty vehicles (LDV),medium duty vehicles (MDV) and heavy-duty vehicles (HDV).[6] The battery capacities of two- or three-wheelers and light duty BEVs are between 1.2 to 48 kWh (Gode, Bieker, and Bandivadekar 2021). The battery capacities for medium-duty BEVs ranged between 48 to 200 kWh while that for heavy duty BEV between 120 to 1,000 kWh (ORNL and NREL 2019).

- **Two and three-wheeler BEVs**
  Two-and three-wheeler (2W/3W) BEVs typically require batteries with small capacities in the range of 0.3- 8 kWh. The lower end of this range suitable for two-wheelers like bikes and scooters and higher end for three-wheelers like autos. In many developing countries, three-wheelers are often used as the last-mile connectivity transportation mode. Electric bikes are becoming an affordable alternative to cars for urban commuters and in cities with poor public transport systems. In some markets like the US, electric bikes have outdone the annual sales of electric cars (Toll 2021).

  As these vehicles are mainly used to travel short distances (usually intrastate), 'range anxiety'[7] is not a major issue for consumers. However, as these vehicles are often sold in a price sensitive consumer segment, less expensive batteries are preferred to make these vehicles cost competitive with ICE vehicles. Studies suggest that due to the short operating range (km), reduction in pack cost that accompanies improvements in the specific energy (Wh/kg) is negligible for this vehicle segment (Sripad et al. 2019) So, the focus for this segment can be to bring down battery pack costs.

  Another peculiarity of this vehicle segment is the high susceptibility of batteries due to driving conditions and habits. Poor road infrastructure leading to shocks and sudden stops, and erratic charging behaviour can have a detrimental impact on battery life (Inverted 2022). Low-cost batteries with improved lifecycles and safety, and which can endure non-standard operation and maintenance, could be quickly adopted in this vehicle segment.

> **Many of the applications are already technically and economically feasible for the existing generation of ACC batteries.**

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[6] The US Federal Highway Administration categorises vehicles into Light Duty (Class 1-2), Medium Duty (Class 3-6), and Heavy Duty (Class 7-8)

[7] Range anxiety refers to anxiety of an EV driver on whether the battery charge would last for trip(s) between two charging instances.

- **Light-duty electric vehicles**
  LDVs, like passenger cars and light commercial vehicles, require batteries with high specific energy. These vehicles also have greater range than two- or three-wheelers, typically around 300 to 600 km, and maintain a low power to curb ratio (PTC) (Sripad and Viswanathan 2017). The currently available models (with a specific energy of 200 Wh/kg at the battery pack level or 400 Wh/kg at battery cell level) offer a range of 300 to 400 km. Hence, lithium-ion chemistries like NCA and NMC are preferred over lower energy variants like LFP and LMO (IEA 2021a).

  The further extension of range while remaining cost competitive with ICE vehicles remain a challenge. As battery weight varies inversely with specific energy, the PTC of a vehicle is high for batteries with low specific energy. Therefore, vehicles with high PTC would need more energy to transfer the same load as those with low PTC. Technologies like solid-state batteries having lithium metal anode, lithium-sulphur (Li-S), sodium-ion and lithium-air could find applications in this vehicle segment owing to their high energy densities.

- **Medium and heavy-duty vehicles**
  Battery requirements of reliability, durability, lifetime, and tolerance of demanding duty cycles are more important to MDVs and HDVs than LDVs. Space availability in these segments allows for the use of batteries with low specific energy compared to other segments. However, large batteries would also need greater power for fast charging than LDVs; this can put additional load on the grid (ORNL and NREL 2019). Payload capacity is another important consideration for this vehicle segment. It varies inversely with the battery weight implying that the vehicles can transport less load per trip while also spending considerable energy on moving the battery rather than the payload (Sripad and Viswanathan 2017).

  Currently, LFP batteries dominate this vehicle segment (IEA 2021). However, because of the cost, fast charging, and payload capacity requirements, fuel cell vehicles and ultracapacitors are being considered as potential alternatives to batteries (Sagaria et al. 2021).

> **World would need about 780 GW of battery capacity by 2030 to reach net-zero by 2050**

### 6.1.2 Power sector

In 2021, the world had 27 GW of installed battery storage capacity for power sector-related services. This figure is projected to reach 780 GW in 2030 to achieve net-zero by 2050 (IEA 2022d). Increased deployment of RE sources (solar and wind) to meet the flexibility requirements drives battery demand in power sector. Furthermore, in a net-zero scenario, flexible sources based on coal and gas would be phased out, thus also increasing the demand for batteries. In the power sector, batteries can be classified according to their application in energy or power. Energy applications use batteries over long periods of time (hours, months, seasons) and hence require that they have high energy ratings[8]. For example, these batteries provide backup power in case of grid outage. Power applications use batteries for short durations (typically less than one hour) with frequent charge and discharge cycles, and thereby require high power ratings[9]. For example, these batteries provide ramping or frequency regulation services to the grid.

- **Grid-connected systems**
  Grid-connected applications can be classified into behind-the-meter and front-of-the-meter.
  **Behind-the-meter systems**, connected to the distribution network, are deployed at the consumer end, and primarily used for power backup, load shifting or peak shaving (Table 4). Batteries with long discharge times are suitable for these applications. Such applications also help in phase out of fuel-based backup generators running on diesel or natural gas in areas with irregular power supply (Ericson and Olis 2019). The commercial and industrial segments are the main users of this technology. However, batteries, coupled with a distributed RE source like rooftop solar, offer a clean, reliable and, in some cases, economical alternative (Ericson and Olis 2019).

  Behind-the-meter installations can also be aggregated by a third party or by distribution companies to expand their services and create a smart grid (Tyagi, Kuldeep, and Dave 2020). Such systems have the potential to provide energy and peaking capacities to meet the local demand surges, reduce procurement expenses through energy arbitrage, defer distribution network upgradation, and provide ancillary services like demand response and participation in power markets. However, unlocking such applications requires enablers such as advanced infrastructure,

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[8] Energy rating (represented in kWh) refers to the amount of energy a battery can deliver or absorb in one hour (McLaren Joyce 2016)

[9] Power rating (represented in kW) refers to the amount of power can flow in and out of a battery at any instant (McLaren Joyce 2016)

enhanced institutional capacity and regulatory changes in metering arrangements and market reforms (Bowen and Gokhale-Welch 2021).

**Front-of-the meter** installations can be connected to any part of the power network (distribution, transmission, or generation) and are used to support grid functioning. They include capacity firming and ramping, as well as ancillary services like frequency regulation, voltage regulation and reserves. As the share of RE increases, many of these applications may become even more relevant. Table 5 provides details about the application, including the likely service off-takers, and nature of the application.

**Table 4** Potential behind-the-meter applications of ACC batteries

| Application | Description | Nature of application (energy or power) |
|---|---|---|
| Power back-up | Storing excess energy (grid/distributed renewables) to provide power during local grid outages | Energy |
| Load shifting | Changing electricity consumption patterns to minimise electricity bills | Energy |

*Source: Authors' analysis*

**Table 5** Potential front-of-the meter applications of ACC batteries

| Application | Description | Service off-taker | Nature of application (energy or power) |
|---|---|---|---|
| Ramping support (up/down) | Increasing or decreasing output from a generator in response to the demand | Generator | Power |
| Black start | Powering generators after a grid outage | Generator | Power |
| Capacity firming | Maintaining a reliable generation capacity to meet the requirements during peak periods | Generator, distribution company | Energy |
| Reserves[10] | Maintaining a reserve capacity to meet the frequency imbalance or shutdown of a generation source. | Generator | Both |
| Frequency regulation | Maintaining grid frequency within the specified range. | Generator and transmission company | Power |
| Voltage regulation | Maintaining the same voltage at input and receiving end | Transmission and distribution company | Energy |
| Energy arbitrage (energy time-shift) | Optimising the energy consumption to match demand in peak and lean periods | Distribution companies and generators | Energy |

*Source: Authors' analysis*

- **Off-grid systems**
  Batteries, combined with distributed RE sources, are primarily used to provide energy access in remote areas. They also improve the electricity reliability and quality for essential services like healthcare centres and cold chain. Recent studies also indicate huge potential to use off-grid systems for livelihood services in rural areas; these include micro solar pumps, solar refrigerators, silk reeling machines, solar charkha and solar looms (Tyagi, Kuldeep, and Dave 2020). These applications require batteries with long discharge time, low cost, and affordable operation and maintenance. Lead acid, lithium-ion and redox flow batteries are some potential candidates for this category (Kebede et al. 2022).

## 6.2 Emerging applications

The following sections outline some of the emerging applications of batteries such as aviation, aeronautics and shipping, and outlines the battery performance requirements for these applications.

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[10] Spinning, non-spinning, supplemental

### 6.2.1 Aircraft

In 2019, the aviation sector contributed 2.1 per cent of the global human-induced $CO_2$ emissions (ATAG 2020). Hence, the electrification of aircrafts is critical to combatting the rising emissions that are contributing to climate change. Recognising this, the aviation sector has pledged to make global civil aviation operations net zero by 2050 (ATAG 2021).

Commercial aircraft are broadly classified into two categories based on passenger load-carrying capacity: narrow body and wide body. The pack-level specific energy requirement of batteries in these categories lies between 600 to 1,300 Wh/kg (Bills et al. 2020). However, even at these thresholds, these aircraft cover less than 25 per cent of the current average aircraft ranges and passenger miles. Currently available batteries – including various lithium-ion and lithium sulphur batteries – cannot support these requirements. Lithium metal-air (Li-O2) batteries, which can provide 900 Wh/kg at a power-to-energy ratio of 150, are a potential candidate (Bills et al. 2020). Lithium/fluorinated carbon (Li/CFx) batteries, providing 850 Wh/kg, are also considered, but their use is limited due to their primary nature (Ban et al. 2021).

### 6.2.2 Aeronautics and space exploration

This sector covers suborbital and deep space exploration. There are multiple applications in this category that can be powered by batteries: high-altitude airships, solar aircrafts, spacecrafts, satellites, advanced instrumentation, drones, and rovers.

These applications require lightweight batteries with high energy density, long calendar life, safety, and tolerance for fluctuations in temperature, radiation, and gravitational force. Some conventional aerospace batteries include nickel-cadmium, nickel-hydrogen, and silver-zinc; however, these are not suitable for planetary explorations (Ratnakumar et al. 2003) such as Ni-Cd, Ni-H2 and Ag-Zn, are inadequate to meet these demands. Lithium ion rechargeable batteries were therefore chosen as the baseline for these missions. The 2003 Mars Exploration Rover (MER. Recently, Li-S, LIBs with alternate anodes (like silicon), and lithium solid-state inorganic electrolyte batteries have been used for these applications (Hepp et al. 2022). These batteries are advanced versions of prevalent batteries, with improvements in specific energy, energy density, calendar life, and performance at low and high temperatures.

> **Emerging applications of ACC batteries include aviation, aeronautics and shipping, which are significant anthropogenic emission sources.**

### 6.2.3 Shipping

Emissions from shipping[11] represented about 3 per cent of the global anthropogenic greenhouse gas emissions[12] in 2018; this is projected to increase by 90 to 130 per cent of the 2008 levels by 2050 (IMO 2021). Hence, there is a significant opportunity for the shipping industry to transition to cleaner energy alternatives like batteries.

There can be two types of configurations of batteries in ships: hybrid and pure. In hybrid systems, batteries support the combustion engine in the vehicle, besides providing peak shaving and spinning reserve; this results in fuel savings (Craig 2020). These systems are preferred for long journeys. Battery-electric ferries are suitable for short journeys as they require frequent charging and a high-power source onshore. There are some such vehicles already in operation across the globe, such as the passenger E-ferry Ellen (Danfoss 2020), the solar-powered passenger electric ferry Aditya (Navalt Solar & Electric Boats 2022), and the electric container vessel Yara Bikerland (Yara International 2022).

The currently available LIBs, like NMC and LFP, have technical and operational limitations on their safety and energy density. Solid-state batteries with lithium anode, lithium-air batteries, and other metal-air battery variants, are some promising battery alternatives for this segment. However, non-electrochemical ESS like supercapacitors are also being considered for hybridisation with batteries. Despite these advancements, the maximum range is expected to be around 1,000 km (Craig 2020), indicating that a hybrid solution might work best for long journeys.

## 6.3 Case studies

This section provides some examples of ACC batteries used in the power sector for commercial purposes. These are not exhaustive but rather indicative of the different applications mentioned in the previous section.

### 6.3.1 Australia's big battery at Hornsdale

Commissioned in 2017, the Hornsdale Power Reserve has a 100 MW/129 MWh lithium-ion BESS (Hornsdale power reserve 2019). It is grid-connected at the same

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[11] Covers international, domestic, and fishing shipping

[12] Includes carbon dioxide, methane and nitrous oxide expressed in $CO_2$ equivalent

voltage as the nearby wind plant. About 70 MW of the discharge capacity is contracted by South Australian Government for system security services; the remaining 30 MW capacity and 119 MWh storage is allocated for the market participation. The reserve was expanded in September 2020 to add 50 MW/64.5 MWh battery capacity; that raises the cumulative capacity to 150 MW. The project successfully provides frequency regulation, peaking, and inertial services to the grid, supporting greater integration of variable RE sources into the grid (Hornsdale power reserve 2022). In 2019, the project reduced the cost of frequency control ancillary services (FCAS) by AUD $116 million, and led to a 91 per cent drop in system level FCAS costs for South Australian generators (ibid).

### 6.3.2 Virtual power plants in the Netherlands

A power producer operating in the Netherlands has introduced a virtual power plant called CrowdNett which provides financial benefits to the consumers (Middelkoop 2017). It gains from participating in the national electricity market for grid-balancing services. It focuses selling home battery systems at a discounted price to customers with an installed solar energy system. When consumers enhance their self-consumption of solar, they receive additional financial compensation for allocating part of the battery capacity to the company for grid balancing services. The Netherlands has a reliable grid, with net-metering services for solarised consumers. Hence, it is the additional monetary incentive that persuades consumers to opt for these home storage systems.

### 6.3.3 Vehicle-to-grid services in California, US

Vehicle-to-grid is a concept that allows EVs to interact with the grid and provide grid services. Favourable regulatory changes allowing this interaction and incentivise owners to charge and discharge during off-peak and peak hours result in dual wins for the owners and grid operators. EV owners can benefit from the additional financial incentives that improve the affordability of EVs, and grid operators may benefit from investing further in the deployment of grid-scale batteries. In 2021, California piloted a vehicle-to-grid service at the Los Angeles Air Force Base (E. G. Brown 2021). They replaced the existing gasoline- and diesel-fuelled fleet vehicles with plug-in EVs and plug-in hybrid EVs. The pilot demonstrated the feasibility of the concept, infrastructure development, and financial incentive structure. The study also found that battery life reduces in such applications- it is almost 19 per cent less than that of a battery tested in a controlled environment. However, the batteries retained 80 per cent of their original capacity, indicating the potential for second life use.

### 6.3.4 Indian ACC PLI

The union cabinet of the Government of India approved a production-linked incentive scheme, *National Programme on Advanced Chemistry Cell (ACC) Battery Storage*, in the fiscal budget of 2021 (Ministry of Heavy Industry and Public Enterprises 2021). It aims to achieve greater domestic value addition in local battery-cell manufacturing while ensuring a globally competitive levelised cost of batteries. The scheme has an outlay of about USD 2.3 billion[13] for 50 GWh of annual manufacturing capacity. It promotes a technology-agnostic approach, encouraging bidders to manufacture any battery technology that meets the desired performance levels. The minimum manufacturing capacity is 5 GWh, while the maximum has been capped at 20 GWh. The winners should ensure at least 25 per cent domestic value addition and a mandatory investment of about USD 28 million/GWh within two years of operation. The incentives shall be disbursed over five years. There is also a proposal to create a single-window mechanism for potential investors that covers providing land, trunk infrastructure, and power at reasonable rates to these manufacturing facilities.

Besides boosting domestic battery production, the scheme shall have several co-benefits (PIB 2021):

- It shall support the development of a local battery supply chain to strengthen India's energy security and reduce import dependence. This scheme expects to bring annual import substitution of around USD 2.5 billion.
- It shall facilitate domestic demand creation for batteries, accelerating EV adoption and grid integration of renewables. Greater EV adoption shall further translate into net savings of USD 25 billion–32 billion due to the oil import bills accrued during this scheme's period.
- The PLI scheme will boost foreign direct investment in the country. Overall, USD 5.7 billion in direct investments are expected in battery manufacturing.

> **Solid state batteries are promising options for several emerging applications of ACC batteries.**

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[13] 2022 average annual USD to INR rate (78.6).

- The new industry shall also create several employment opportunities, with about 0.2 million direct opportunities expected (PIB 2023).

The industry received the scheme well, submitting bids for 128 GWh capacity against the 50 GWh allotments. Three companies signed the programme agreement in July 2022 for setting up 95 GWh-capacity infrastructures (PIB Delhi 2022).

## 7. Identifying existing gaps in ACC technologies

The previous section discussed the plethora of ACC technologies in use today. There are several shortcomings in these current technologies; these limitations are driving global innovation. Often, the battery innovation needed to bridge an existing gap is not easily evident. In some cases, new chemistries need to be developed. In others, the incremental developments of various battery components or production processes might be sufficient. To better understand the ACC battery innovation landscape, member countries will need to identify innovation gaps to quantify progress through new developments. Importantly, in countries with vibrant battery research, development, and demonstration RD&D ecosystems, goal-setting based on identified gaps streamlines the process of securing research funding and the piloting technologies.

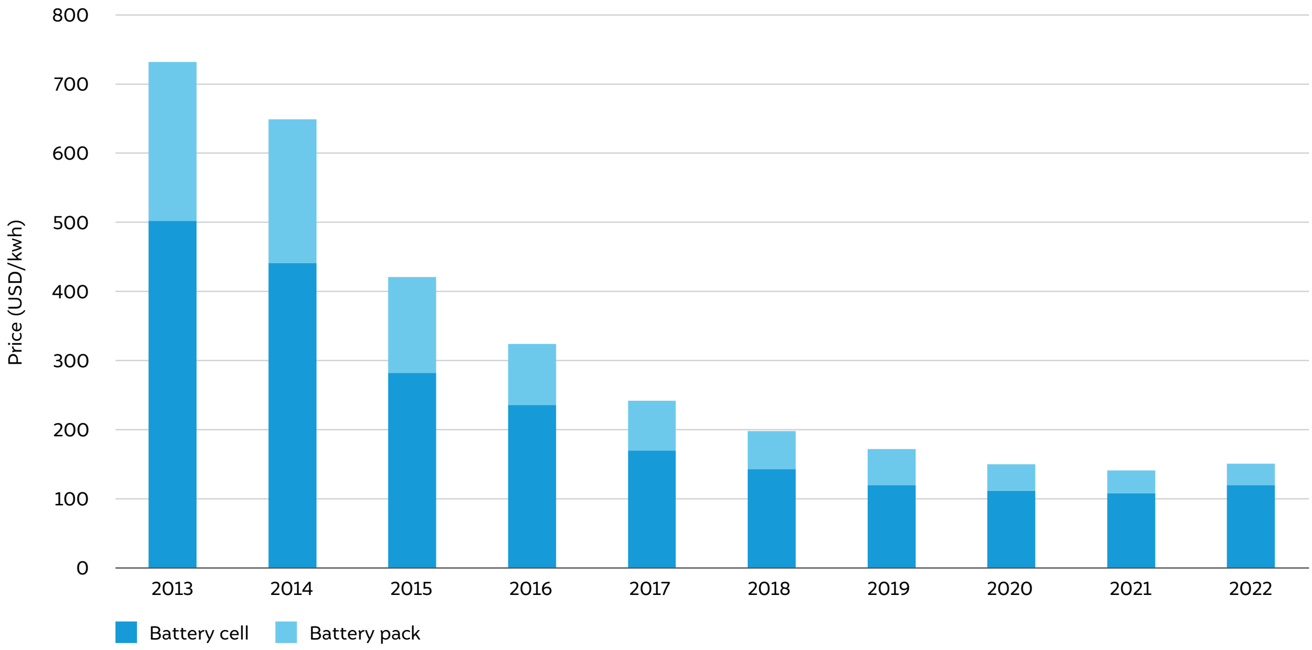
The following sections highlight certain globally recognised gaps in current ACC technologies. Some of the identified gaps have already been used to develop technology programmes in China, Japan, the US, and the EU (Hao et al. 2017; Marinaro et al. 2020). Innovation gaps in this section have been discussed as either a cost or a performance gap, as defined in Table 6. These gaps will be benchmarked against existing batteries in commercial use, particularly LIBs.

**Table 6** Categorisation of ACC battery gaps

| | Gap category | Definition |
|---|---|---|
| 1 | Cost | The cost of the technology prohibits it from providing economical application |
| 2 | Technical | Limitations in the capability of current battery technologies to perform anticipated future applications and meet anticipated quality criteria |

*Source: Authors' analysis*

**Figure 11** Lithium-ion battery prices have largely stagnated after years of dramatic falls



*Source: BNEF 2022*

## 7.1 Cost gaps

Given the global experience with lithium-ion batteries, we know that innovations in chemistry and material sciences have driven majority of the cost reduction in the sector (Ziegler, Song, and Trancik 2021). Between 1990 and 2018, the price of lithium-ion cells dropped by nearly 97 per cent (Ziegler, Song, and Trancik 2021). LIB prices continued to fall between 2013 and 2020, but from 2020 to 2022, this trend has largely slowed, and even reversed, as seen in Figure 11 (BNEF 2022).

A major reason for this change in price trends is that battery prices consist of two intrinsic factors. Some portion of the price can be attributed to the cost of production of the battery, including manufacturing, transportation, and assembly. Material costs are responsible for the remaining portion of the price, ignoring profits and warranties. Analysis has shown that while the production costs of LIBs have gone down significantly, the materials costs have only declined marginally (Hsieh et al. 2019). This was true before 2020 as well, but the COVID-19 pandemic has further exacerbated commodity price issues and driven material costs for batteries up. Some analysis suggests that battery prices, particularly of common NMC-type lithium batteries, will hover between the USD 100/kWh and USD 150/kWh marks even in 2030, which contradicts other existing price projections (~USD 70/kWh in 2030) that do not take into account the price floor posed by material costs (Hsieh et al. 2019).

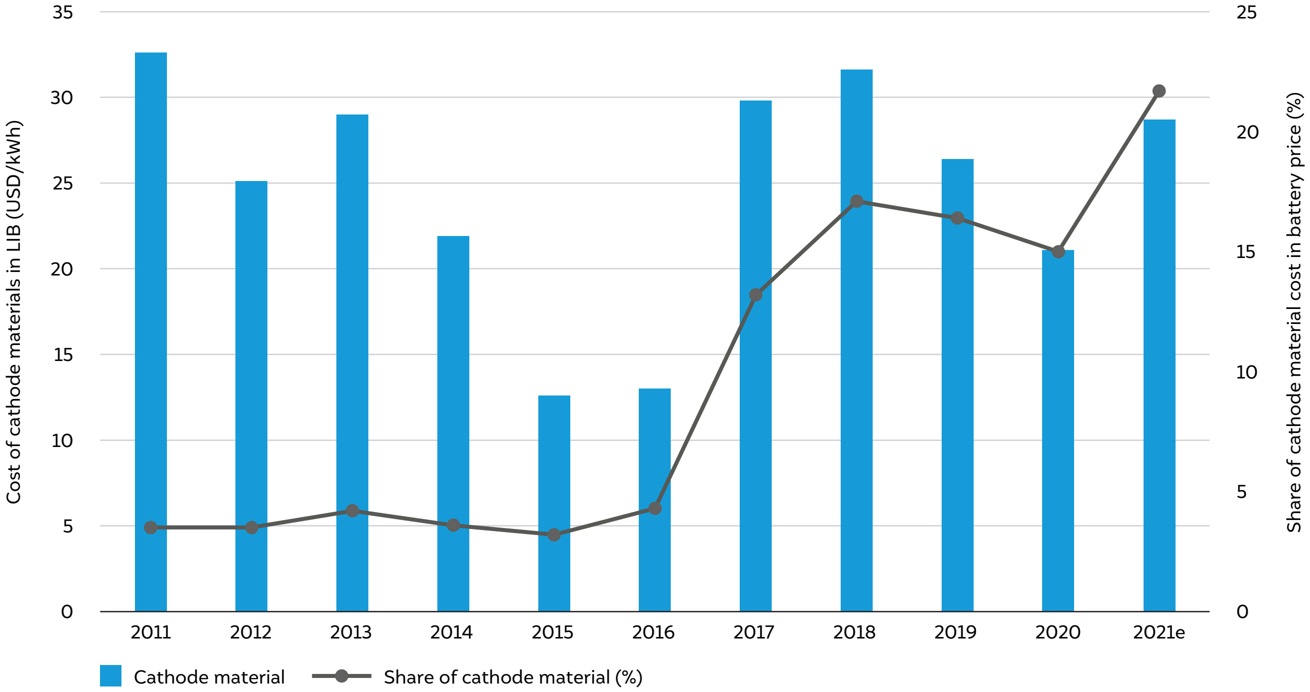
Figure 12 showcases how cathode material costs have stayed almost stagnant, even as the price of batteries has fallen. Figure 13 highlights how this trend is likely to continue as the cost of production falls further.

Why does this matter? The costs of the incumbent battery technologies today are still prohibitive for many applications. Some analysts have identified thresholds to unlock mass adoption:

- One such threshold is a USD 100/kWh–battery for EVs to reach price parity with internal combustion engine (ICE) vehicles, particularly in the United States (McKinsey & Co 2017).
- The European Union has also estimated that the cost of batteries may need to be halved to make them viable for stationary storage applications that do not provide fast-response services (Batteries Europe ETIP 2022).

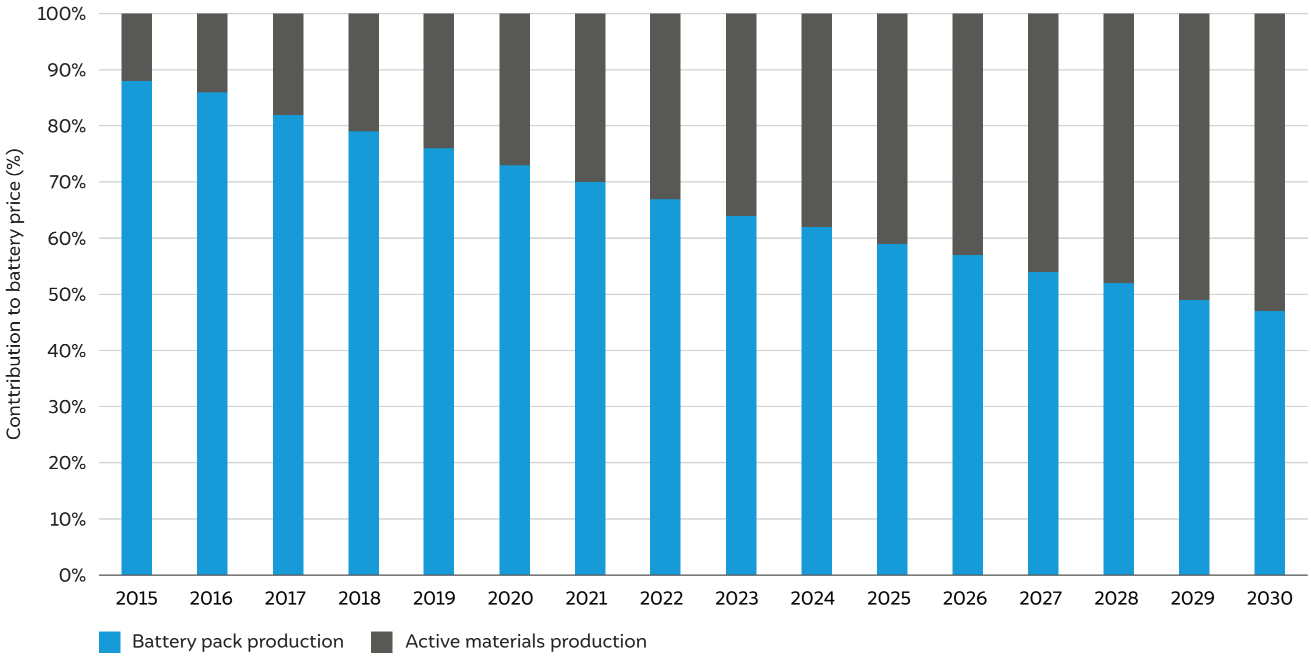
Table 7 highlights different ways in which innovation can bring down the cost of batteries in the coming years. None of these innovations will change costs in isolation; rather, they will have cascading effects on other technology indicators, such as performance and scalability.

**Figure 12** Cathode material costs have increased even as the price of LIBs has plummeted



*Source: IEA 2022a*

**Figure 13** The share of active materials in the cost of the battery pack will increase significantly by 2030



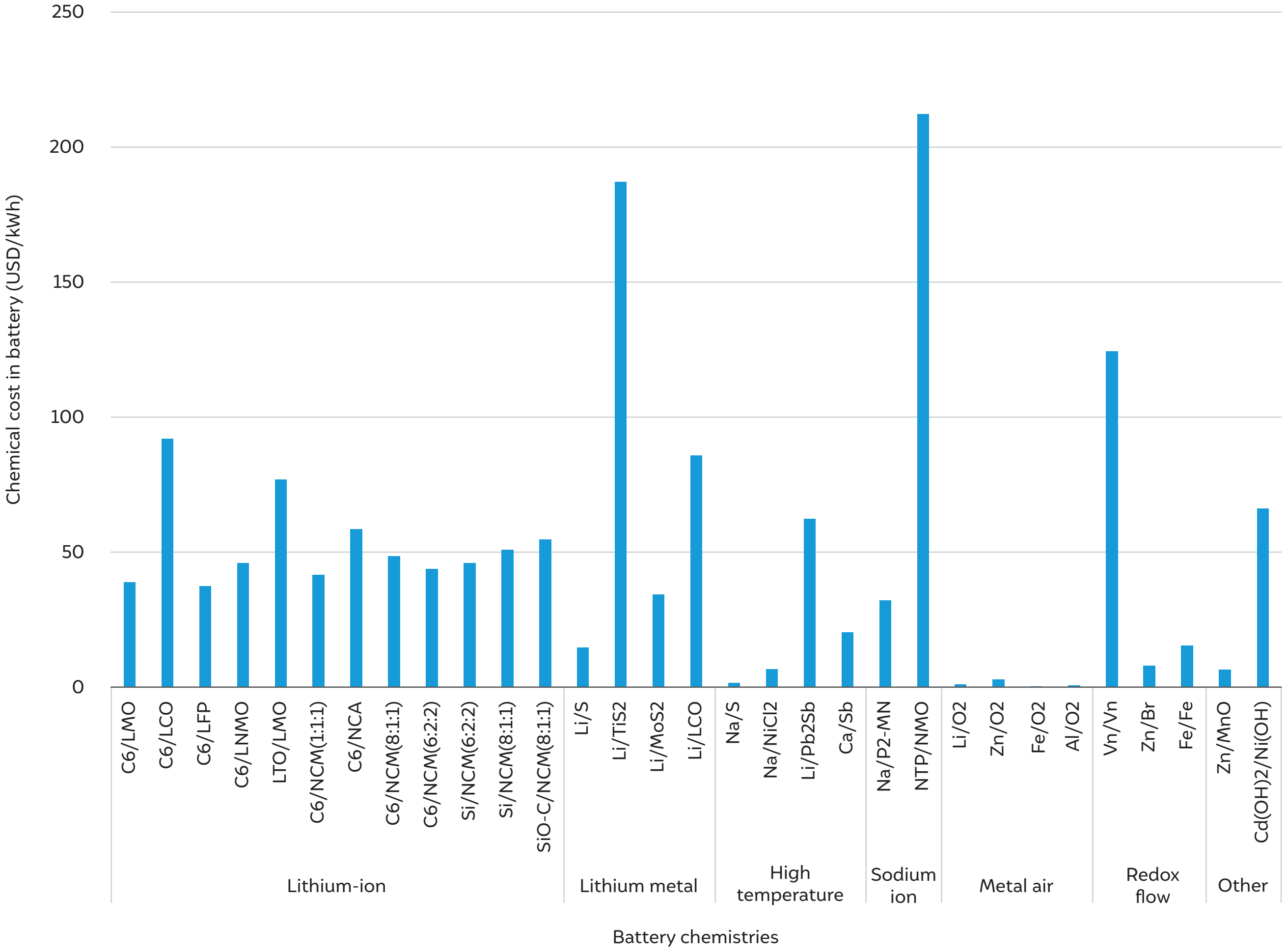
*Source: Hsieh et al. 2019*

**Table 7** Pathways to reduce battery costs through innovation

| Lowering raw material costs | Lowering production costs |
|---|---|
| Reducing the quantity of scarce raw materials used in current chemistries and maintaining the same performance characteristics | Developing less capital-intensive processes for beneficiation and cell/battery manufacturing |
| Developing new chemistries that use cheaper raw materials or substituting cheaper raw materials with existing chemistries | Developing new chemistries that entail lower processing and production costs |
| Developing more efficient and cost-effective mining processes | Increasing the efficiency/reducing the wastage caused by existing production methods |

*Source: Authors' analysis*

**Figure 14** Some ACC chemistries have very low chemical costs, but their viability will depend on many other factors



*Source: MIT 2022*

A useful reference point to identify which technologies may most likely achieve significant price reduction is to consider the cost of the chemicals used in different battery chemistries, as shown in Figure 14. Chemical costs are only one of the several benchmarks that will influence the final cost of storage, including TRL and MRL levels, the scale of production, and the efficiency and cycle life of a particular technology.

**Table 8** Performance improvements expected from battery technologies by 2030

| | Gravimetric energy density | Volumetric energy density | Cycle life | C-rate (1/charging time) | Operating temperatures |
|---|---|---|---|---|---|
| Electric mobility | ⬆⬆ | ⬆ | | ⬆ | ⬆ |
| Electricity sector (energy application) | | ⬆ | ⬆⬆ | | ⬆ |
| Electricity sector (power application) | | ⬆ | ⬆ | ⬆ | ⬆ |

⬆⬆ Major improvement targeted

⬆ Minor improvement targeted

*Source: Authors' adaptation from Batteries Europe ETIP 2021*

## 7.2 Technical Gaps

When it comes to energy storage applications, low cost is not always sufficient to ensure the viability of ACC tech. Technical considerations discussed subsequently, such as the performance, safety and manufacturing emissions may also be important for customers. In some applications, such as ancillary or black start services, the performance of the technology may be the key parameter of evaluation.

### 7.2.1 Performance

Performance gaps are inextricably linked to the use cases that batteries are expected to perform. Depending on the application, one or several performance metrics might need to be improved upon. Table 6 provides a high-level expectation of performance improvements from battery applications in the mobility and electricity (power and energy) sectors by 2030.

China and the US have targeted an energy density of 500 Wh/kg at the cell level for traction batteries by 2030, compared to 300 Wh/kg or lower in 2021 (Hao et al. 2017; US Department of Energy 2021). The European Commission, meanwhile has targeted a cycle life of 12,000 cycles, charging times of 12 minutes, and round-trip efficiency of 97 per cent for batteries in stationary storage applications by 2030 (compared to 5,000 cycles, 22 minutes to charge, and 95 per cent in 2020) (Batteries Europe ETIP 2022). These targets indicate the performance gaps that current technologies need to overcome. Beyond these broad targets, technologies that can enable novel use cases will also need to be developed. Aviation is an application for which pack energy densities between 500–1,500 Wh/kg will be required; this is much higher than the requirement from batteries used in mobility or stationary storage applications.

Performance metrics set by the industry need to be translated effectively into cell-level technical performance metrics for use by academics developing new technologies. For example, the specific capacity, voltage window, and mass loading of a combination of cathodes and anodes are important in determining the final energy density of a battery. Similarly, the coulombic efficiency and structural stability of a cell will decide its cycle life (Lin et al. 2018). Various technology gaps can be closed with the conversion of industrial performance expectations to lab-level metrics. However, new technologies should not compromise on certain performance parameters in order to improve others unless such trade-offs are appropriate. This is a particular risk for technologies being developed in labs, where trade-offs may not be properly assessed during the validation of performance improvements (Lin et al. 2018).

**Table 9** Safety vulnerability of different battery chemistries

| Battery type | Comments on safety |
|---|---|
| Lithium ion | Thermal runaway is a potential vulnerability |
| Metal air | Toxicity and corrosion issues that can compromise safety |
| Solid state | Solid, non-flammable electrolytes, but unstable cyclic stability resulting from interfacial resistance is a safety vulnerability |
| Sodium ion | The reactive nature of sodium and dendrite formations makes it prone to safety issues |
| Lithium sulphur | High thermal tolerance |

*Source: Durmus et al. 2020*

### 7.2.2 Battery safety

Primary issues associated with batteries across technologies include temperature tolerance and excessive internal heat generation within the battery cell (Bisschop et al. 2019). The latter can trigger thermal runaway, which can further spread through the pack, and lead to battery failures and fire. The creation of thermal runaway is a recurring problem LIBs and metal-air batteries (MAB). Along with overheating, short circuits are connected to impending thermal runaway (Chen, Gao, and Sun 2021). Battery separators are active safety measures that work against thermal runaway and internal short-circuits-a melting separator absorbs the heat and shuts down the electrochemical reaction of the battery. Structural damage to the battery can also lead to safety issues such as venting, leakages, pack malfunctions, permanent damage, and fires (Chen, Gao, and Sun 2021).

Manufacturing defects can cause the improper sealing of cells. This can lead air or moisture to react with electrodes and electrolytes, resulting in cell failure and compromising the safety of the battery over time. Just as other battery types, flammability is an issue for LIBs. (Table 9).

Thus, innovation needs to happen at multiple levels of the value chain. Smart temperature limiting and regulation is an important safety functions provided by battery and thermal management systems. High-quality design and manufacturing of cells ensure that operation at the cell and pack levels is safe in normal use cases and ambient environmental conditions. New materials with higher thermal stability and minimal reactivity could also lower the chance of thermal runaway occurring. Finally, the physical design of the battery pack can reduce the spread of fire between cells, and minimise the chance of fires propagating at the pack level.

### 7.2.3 Manufacturing emissions

In 2018, the battery value chain created 24 million tonnes of $CO_2$ equivalent (MT $CO_2$e) emissions for the global demand of 369 GWh. This figure is projected to increase to 182 MT $CO_2$e by 2030 (for a cumulative global demand of 1,724 GWh), if current manufacturing trends continue (World Economic Forum 2019). Most of the emissions are produced during the active material production and cell manufacturing stages of the battery value chain. Many countries are looking to promote greener and more sustainable battery value chains. Thus, reducing manufacturing and processing emissions will be a key focus of future ACC innovation. A large chunk of emissions can be mitigated through the use of RE during production. But, avenues for innovation exist here as well. Technologies that enable the electrification of mining, beneficiation, and manufacturing processes will allow for increased use of RE during production. Further, new materials can be developed, to reduces the need for energy-intensive processing at all stages of the value chain.

> **Reducing manufacturing and processing emissions will be a key focus of future ACC innovation.**

## Box 1 Supply risks of minerals and energy security: an important consideration

The battery technologies discussed in this report contain various materials such as lithium, sodium, vanadium, and graphite, as shown in Table 10. The list will continue to evolve with innovations in battery chemistries. The natural abundance, exploration, and geographical concentration of these materials vary drastically. Some materials, such as rare earth metals, might have limited reserves, while others, like cobalt, are heavily concentrated in a single country (DR Congo in the case of cobalt). In some cases, like lithium, it is not easy to extract the material in an environmentally sustainable manner. All these factors, and many more, influence the supply of raw materials for battery technology.

**Table 10 Snapshot of elements used in battery technologies**

| | | | | |
|---|---|---|---|---|
| Aluminium | Cobalt | Copper | Graphite | Iron |
| Lithium | Magnesium | Manganese | Nickel | Phosphorous |
| Silicon | Sodium | Titanium | Vanadium | Zinc |

*Source: Authors' analysis*

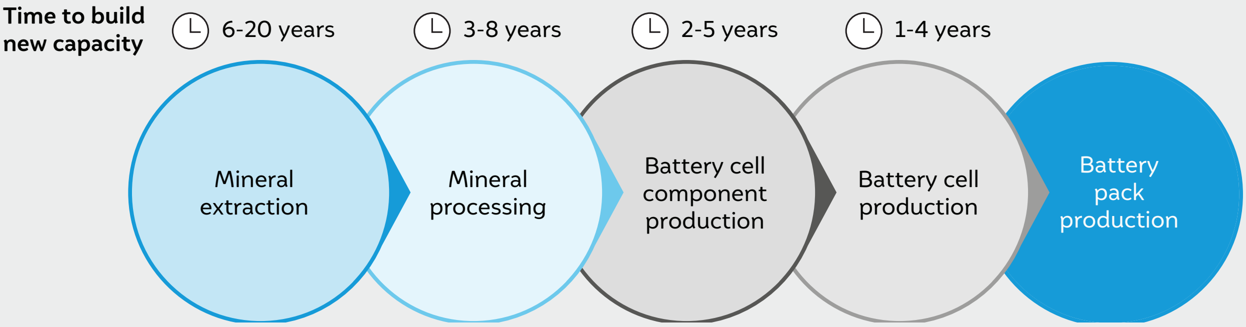
### Raw material criticality

The availability of raw materials is an essential consideration for the scalability of battery technology. Manufacturers prefer technologies with a reliable supply of raw materials that allows them to scale and sustain battery production. Indeed, a reliable supply of raw materials is also crucial from a national energy security perspective. As batteries support the decarbonisation of the power and transport sectors, disruptions to the material supply chains make it difficult for countries to transition away from fossil fuels. Availability of raw materials will be a major roadblock to the scaling of new battery technologies. However, it can also catalyse the development of technologies with low "critical" mineral use.

The criticality of a material indicates its economic importance and supply risk. Several countries have developed frameworks to assess the criticality of materials. A US framework developed in 2008 uses the impact of supply restrictions to capture the use of a material and supply risks to capture the potential supply restrictions (NRC 2008). The European Commission framework, first developed in 2010 and updated every three years, uses the economic importance and supply risks (based on historical data) to assess the criticality of a material (EC 2020). In essence, economic importance includes the end-use share of raw materials in an industry and the value added by that industry. The substitution index of the raw material, indicated by its technical performance and cost in the identified sector, can also be used to estimate the economic importance of the material (EC 2017). The supply risk focuses on raw material extraction unless its processing is proven to be the bottleneck in the supply chain. Supply risks are calculated based on the concentration of a raw material in a country, the country's governance, import reliance, recyclability, and the substitution index.

Many minerals used in modern batteries, particularly LIBs, are critical in several countries. While the availability such resources might be a concern, more so is the issue of the economic viability of these minerals. Further, while many resources might already exist, the exploration and exploitation of a resource/reserve can take up to 20 years. Thus, even existing reserves cannot be assumed to be exploitable in the short term, and innovation must be planned with these constraints in mind.

**Figure 15** The different stages of the LIB development value chain



*Source: Authors' adaptation from (IEA 2022c)*

It is important to note that the sourcing of the mineral does not end at the mining stage. Depending on the grade of the mineral being used, many different types of refining processes might have to be employed to ensure they meet the quality criteria for batteries (IEA 2021). The refining processes can play a major role in affecting the economic viability of certain mineral resources and thus pose a potential gap when scaling battery production.

Several innovation pathways can be explored to address raw material gaps that have been identified here. For one, novel chemistries can be developed to reduce the dependence on minerals that are critical to certain geographies and/or finding suitable substitutes. Concurrently, R&D can also target increasing the viability of global resources through new extraction and refining processes.

# 8. Innovations in ACC

Significant progress has been made in the realm of ACC which has continually transformed the landscape of energy storage. Plethora of discoveries in materials and design have led to high-performance batteries that have improved energy density, extended lifespans, and quicker charging speeds. The advancements in ACC research, development and deployment carries tremendous promise in propelling transport and power sectors forging a path towards a sustainable and electrified future.

## 8.1 Future battery technologies

This section focuses on the future technologies in ACC which will include discussions on technologies currently under research and development or early deployment stage.

### 8.1.1 Metal-air batteries

In MABs, air functions as the cathode (oxygen is the cathode active material). They have a higher energy density than present state-of-the- art LIBs. Moreover, since they use air to operate, they are less prone to thermal runway than other batteries. The absence of a metal-based cathode also promises a lower cost per kWh for MABs than LIBs (CNBC 2021).

Current research on the development of MABs focuses on increasing the longevity of the battery by investing effort in enhancing its cycle life. The superior performance of MABs makes them good candidates for use in EVs (Mandal et al. 2022). They can provide more mileage (up to 500 Km on single charge) than their currently available counterparts. However, there are certain challenges associated with their development; for instance, metal deposition during the charging cycle due to complex reactions occurring in the chemical and electrochemical reactions inside the cell (this is also known as dendrite formation). This decreases the cycle life of the batteries, and hampers their rechargeability.

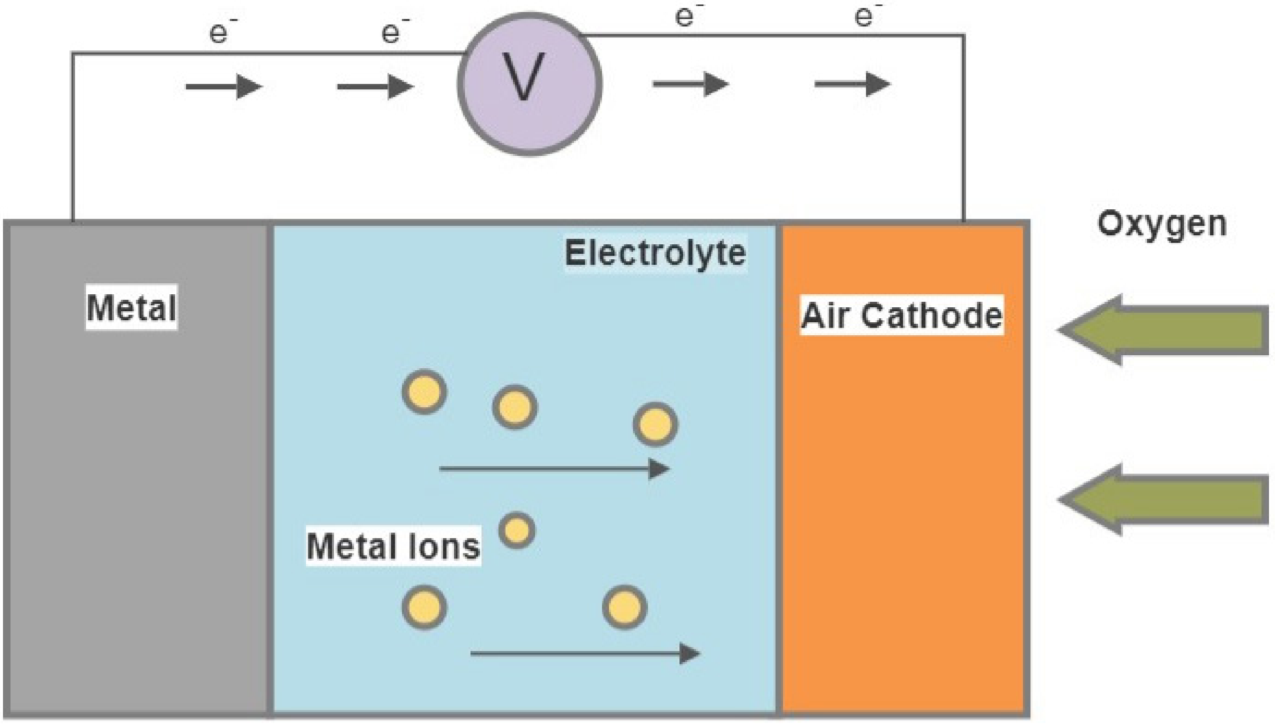
The working of MABs is illustrated in Figure 19. The air cathode is tri-layered:  it has a gas diffusion layer, catalyst layer and current collector layer. The porosity of the cathode allows for an easy continuous oxygen supply from surrounding air. The catalyst layer is made up of inert metals such as platinum, palladium, silver, and gold. Electrolytes used in MABs can be aqueous or non- aqueous. The anode is composed of different combinations of metals such as zinc, lithium, aluminium, manganese, sodium andiron. While discharging, oxygen (from air) reacts with positively charged metal ions (such as lithium ions, zinc ions and aluminium ions) to form oxides thereby generating electric energy. Depending on the nature of the anode employed, one can make a choice between using aqueous or a non-aqueous electrolyte (Kebede et al. 2022).

### 8.1.2 Low cost, rechargeable zinc-air batteries

Zinc-air batteries contain zinc metal as anode. They require ambient air, which is neither too dry nor too moist, to operate. During the discharge process, the hydroxide ions from the aqueous electrolyte combine with zinc anode to form zinc hydroxide. This reaction is irreversible, which is why the battery cannot be charged again. The batteries can be made rechargeable with the addition of catalysts made of metals such as gold, platinum, silver and palladium. However, this would add to the overall cost of production (C. Zhou et al. 2022).

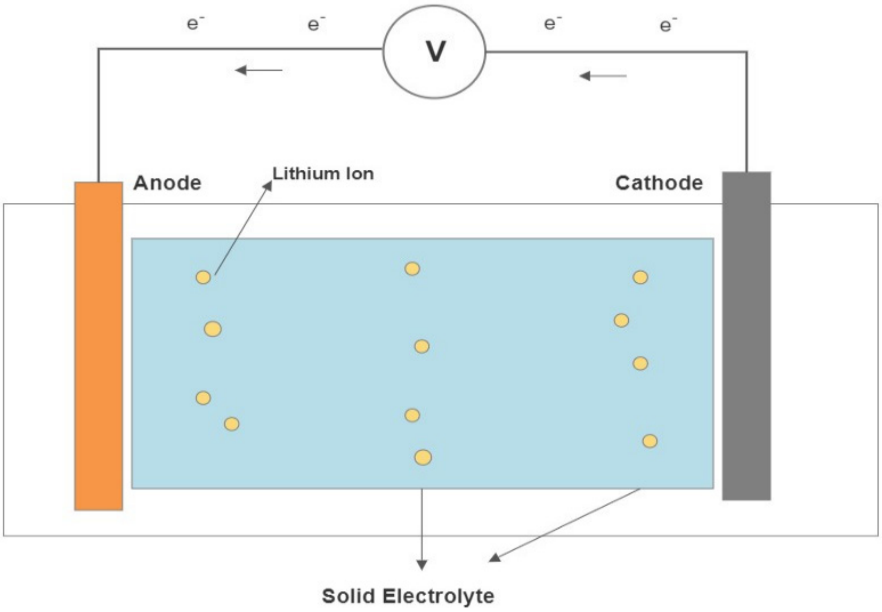
To overcome the cost hurdle, a low-cost bifunctional catalyst is made by carbonising a polymer known as sulphonated polyEther ether ketone (sPEEK). Zinc ions are anchored into this sulphur-containing carbon framework using a process known as ion-exchange. This process allows loading of zinc even at low concentration of the catalyst. Other advantages of ion-exchange deposition process include the homogeneous dispersion of particles, and control over the particle size and composition. This cost-effective process yields a highly active and stable cathode. This catalyst serves the dual function of oxygen reduction (discharging) and evolution (charging) (C. Zhou et al. 2022). This technology is currently in the lab testing stage and future innovations entail scaling up of production of such low-cost bifunctional catalysts for zinc air batteries.

**Figure 16** Schematic representation of the discharging cycle of a metal air battery



*Source: Authors' adaptation from Zhang et al. 2019*

**Figure 17** Schematic representation of the charging cycle of solid-state battery



*Source: Authors' adaptation from Mandal et al. 2022*

## 8.1.3 Solid-state batteries

Solid state batteries employ solid electrolytes; this makes them safer to use than those with liquid or gel electrolytes. Other advantages of solid-state batteries include high energy density (>1,000 Wh/Kg) and low self-discharge. However, the conductivity of solid-state electrolytes is low at room temperature and below. Solid electrolytes also do not allow dendrite formation on electrodes during the charge/discharge cycles. Moreover, the contact of solid electrolytes with solid electrodes is poor when compared to the contact of liquid electrolytes with solid electrodes in LIBs (MIT 2022). Future innovation would focus on overcoming these limitations by using materials such as manganese garnets and manganese oxide nanomaterial-based cathode materials (MIT 2022).

As illustrated in Figure 17, the working of solid-state batteries is similar to batteries that employ liquid. They use carbon, titanates, lithium alloys and metallic lithium as anode materials, while lithium-based oxides (LCO, NCA), and phosphates (LFP), vanadium oxides are common cathode materials (Kurzweil and Garche 2017). Electrolytes are polymeric films such as nitrogen-based or silver-doped germanium thin films.

## 8.1.4 Ionic liquid-based cathode materials for safer solid-state batteries

Ionic liquids are non-volatile, fire-resistant, and more conductive than polymeric films. They have a minimal effect on the manufacturing process of cells as they leave the cathode slurry (from which cathode is formed) virtually untouched. They also improve the contact between solid-state electrolytes and the cathode, and reduce the dendrite formation on electrodes (Cheng et al. 2022). These advancements enhance the cycle life of the battery.

Researchers have recently demonstrated a prototype battery made with 11 weight per cent ionic liquid infused into the cathode. This kind of cathode in a solid-state battery is known as a quasi-solid-state cathode. This prototype also consists of solid electrolyte with a structure similar to garnets. This prototype shows good rechargeability, and 80 per cent capacity retention after 100 charge/discharge cycles at an elevated temperature of 60°C (Cheng et al. 2022).

## 8.1.5 Sodium-ion batteries

Sodium-ion batteries have sodium-containing materials as the cathode. As sodium is a naturally abundant metal, these batteries are a more attractive technology than LIBs. Moreover, they have wider range of operating temperature than currently commercialised battery technologies; which makes them safer to use. However, drawbacks include low energy density and their high weight. Future R&D would focus on improving the performance of sodium-ion batteries, exploring ways to scale them up (Peng et al. 2022).

The working principle of sodium-ion batteries is same as that of LIBs. Similar to the shuffling of lithium ions between the cathode and anode during charging and discharging in LIBs, sodium ions are exchanged between cathode and anode in sodium-ion batteries (Figure 18). The anode is made of hard carbon, and the cathode can be composed of a variety of materials such as Prussian blue analogues, layered oxides, and polyanions (made of sodium and combinations of metals such as aluminium, iron, potassium, magnesium, titanium, zinc and copper). A commonly used electrolyte in these batteries is sodium hexafluorophosphate ($NaPF_6$) (Peng et al. 2022).

### 8.1.6 Magnesium batteries

Magnesium batteries are an up-and-coming alternative to current battery technologies due to its reliance on a naturally abundant metal magnesium, high energy density and resistance to thermal runway. Using magnesium metal as an anode yields a superior theoretical volumetric energy density of 3,833 Ah/L versus 2,062 Ah/L for lithium. The cathode materials currently being tested include zirconium disulphide, manganese dioxide, tungsten di selenide, and vanadium pentoxide (S. A. Brown et al. 2022).

However, these batteries are in the laboratory stage of development. Moreover, they require the development of suitable electrolytes to overcome existing limitations like electrode corrosion, a short electrochemical window, low ion mobility and coulombic efficiency.

### 8.1.7 Chlorine flow battery

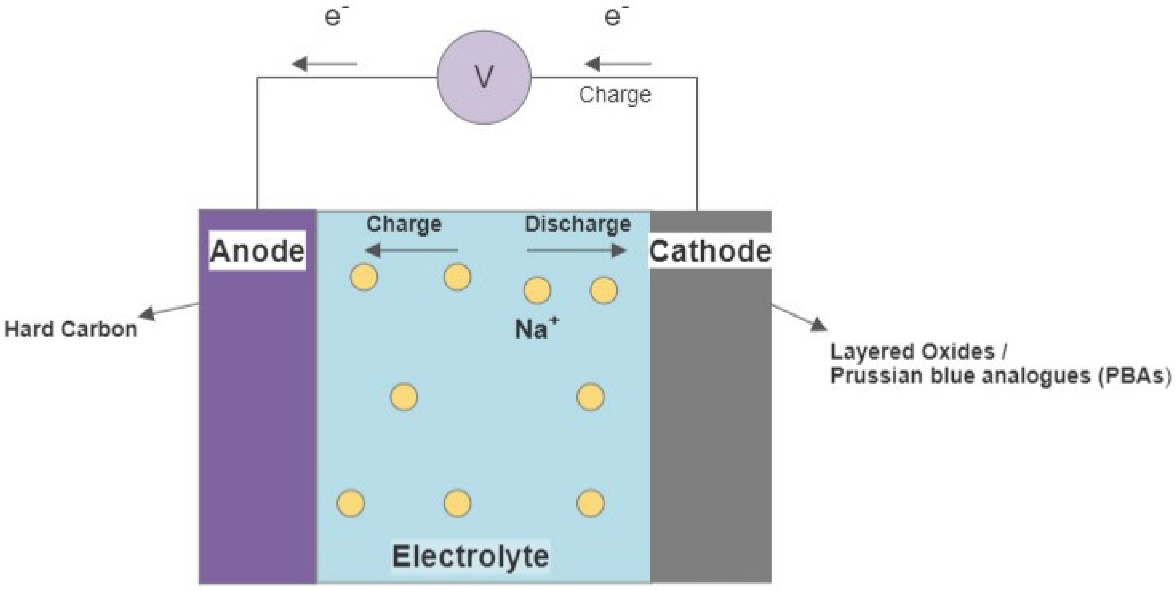
Chlorine flow batteries work on the same principle as RFBs described in section 5. A sodium titanium phosphate coated anode in a solution of the carbon tetrachloride ($CCl_4$) is used as the anolyte and an aqueous sodium chloride solution serves as the catholyte (Hou et al. 2022).

Chlorine flow batteries possess much higher energy density (125.7 Wh/L) than transition metal-based (such as vanadium and zinc) RFBs. They also show high energy efficiency of about 65 per cent, even at C-rate of 315 C, and cycle life of 1,000 cycles. However, the leakage of chlorine gas is a potential drawback. The current research focus is on making them safer, to reduce risk at the time of scaling up.

### 8.1.8 Redox mediated nickel-metal hydride flow battery

The nickel-metal hydride flow battery utilises and combines the advantages of metal hydride and flow batteries. Metal hydride batteries have high energy density and are safe to use. Meanwhile, flow batteries allow for easy replacement of their materials. These two features make redox-mediated nickel-metal hydride flow batteries, a superior technology over to the existing RFBs Metal hydride in a mixture of alkaline potassium ferrocyanide and 2,6- dihydroxyanthraquinone serves as the catholyte, while nickel hydroxide in a mixture of alkaline potassium ferrocyanide and 7,8 dihydroxyphenazine-2-sulfonic acid as acts as the anolyte (Páez et al. 2022).

**Figure 18** **Schematic representation of the charging cycle of a sodium-ion battery**



*Source: Authors' adaptation from Peng et al. 2022*

This battery type has an energy density that is approximately twice that of the currently available vanadium and bromine RFBs. This new technology is in the prototype testing stage for domestic energy storage and heavy-duty vehicle transportation (Páez et al. 2022). Future research further increases in energy density.

### 8.1.9 Room temperature sodium sulphur batteries

Traditional high temperature sodium sulphur batteries, which operate within temperature range of 300-350 °C have been used commercially in large-scale energy storage applications. However, their usage in EVs is not feasible owing to their high operating temperature. R&D has focused on making sodium-sulphur batteries that can operate at room temperature. In a recent study, sodium-sulphur batteries were made operable at room temperature; they had high energy density of 1,274 Wh/Kg (Park et al. 2006). However, this system suffered with rechargeability issues due to polysulphide corrosion that resulted from repeated cycling.

Recently, a new electrolyte, which can decrease negative effects on battery performance by suppressing polysulphide corrosion, has been incorporated in room-temperature sodium-sulphur batteries (Xu et al. 2018). The carbonate-based electrolyte consists of propylene carbonate and fluoroethylene carbonate co-solvents, highly concentrated bis (trifluoromethane) sulphonimide sodium salt, and an indium triiodide additive. The electrolyte tweak performed in the batteries enhanced energy density to 1,477 Wh/Kg at 0.1 C-rate and an extended cycle life (Xu et al. 2018). The experiments have been carried out in laboratories, and further research is ongoing to scale up the batteries.

## 8.2 Innovations in lithium-ion battery development value chain

LIBs are consistently being developed for applications in power and transportation sectors. The current and future focus of research is on improving performance, cycle life and thermal stability of these batteries. Moreover, manufacturers are trying to decrease the overall carbon footprint of the production of these batteries. Currently, key innovations are taking place at each step of the value chain. The innovations listed as follows, have been picked from plethora of research papers available. The innovations have been picked based on the advancement of research and market readiness.

### 8.2.1 Mining stage

**Lithium is one of the key minerals used in LIBs. It is estimated that the demand of lithium for batteries may increase to 152 kilo tonnes (kt) by 2030 from 20 kt in 2021 (IEA 2021).**

- **Alternate pathways to lithium mining**
  Given the significant increase in the demand for mineral, many new methods of extraction are being developed either for current mines or new locations. Conventionally, lithium has been mined in two major ways:

1. Ore mining – Lithium is found in small quantities in igneous rocks. These rocks are processed to extract lithium and other minerals.
2. Salt deserts – Lithium is found in underwater salt deserts (salars). The underground brine water is pumped into shallow ponds and left for the water to evaporate. This leaves behind lithium salts, which are processed to recover lithium.

   Several innovations and improvements to the lithium extraction process are underway. They aim not only to make the existing processes more sustainable but also to commercialise new ways to extract the metal. Several procedures are detailed as follows:

   - **Hard rock lithium technology** – This process is an improvement on the conventional ore mining method of obtaining lithium. In this method, a low boiling solvent is added to a mineral of lithium known as spodumene (lithium aluminium silicon oxide). The solvent dissolves the lithium present (in forms of lithium carbonate ($Li_2CO_3$), lithium hydroxide (LiOH) or lithium (Li)) in the grains of minerals. These different lithium species diffuse out of the granular matrix, and are collected for further processing. Some value-added commodity by-products, including aluminium oxide ($Al_2O_3$) and high-quality silica ($SiO_2$), are also obtained in the process (Tadesse et al. 2019).

  - **Direct lithium extraction** – This method improves on the process of obtaining lithium from salars as well as geothermal brines. It uses a highly selective absorbent to extract lithium from brine. The brine from salars is subjected to filtration, during which its constituent flora and fauna are removed. Next, the brine is then subjected to heat using liquified natural gas. This heated brine is then sent to extraction chamber, where lithium chloride containing water is extracted and further sent to a concentration/water recovery chamber. The concentration chamber separates the water and lithium chloride. Pure battery grade lithium chloride is thus obtained(Stringfellow and Dobson 2021; IBAT 2022).

- **Alternative pathways for nickel processing**
  Nickel laterites are one of the most important ores used for mining nickel. They are of two kinds: nickel limonites and nickel saprolites. Conventionally, the differences in the nature of ores necessitate varying kinds ofextraction processes: hydrometallurgy, pyrometallurgy, and the caron process (a blend of pyro/hydrometallurgy) (Khoo et al. 2017).

  **Direct nickel process** (DNi) is a new method for extracting nickel from various ores. It has the advantage of versatility over the before-mentioned nickel processing techniques, which are ore-selective and use sulphuric acid. DNi can treat all kinds of nickel ores, and uses nitric acid, which is recyclable. It follows an atmospheric hydrometallurgical processing route on a single flow sheet. DNi involves steps such as ore preparation, leaching with acid, liquid-solid preparation, iron hydrolysis, aluminium precipitation, mixed nickel-cobalt hydroxide precipitation, evaporation, thermal decomposition, nitric acid recovery and, finally the extraction of nickel. DNi utilises the leaching property of nitric acid. It also employs recovery recycles, and returns more than 95 per cent of the nitric acid for reuse (Khoo et al. 2017). During leaching half of the ore gets dissolved in nitric acid, leaving behind acid-insoluble minerals, which undergo prescribed industrial treatments involving distillation, slurry formation, and precipitation to produce mixed hydroxide nickel cakes. These cakes can be used as raw material for battery manufacturing (He et al. 2022).

> **Improvements in battery cell materials can lead to further performance enhancements and cost reductions.**

### 8.2.2 Battery cell material inclusion stage

The current generation of LIBs uses cathode materials such as LCO, NCA, and LFP, graphite anodes, and liquid electrolytes. There is still scope of improvement to the cell materials, which can lead to further performance enhancements and cost reductions. Some key innovations to the cell materials are as follows:

- **Less cobalt in NMC batteries**
  **Globally,** cobalt has limited resources; thus its production is constrained (USGS 2022). Due to this, there are developments focusing on reducing the cobalt content in battery electrode materials like NMC cathodes (IEA 2021). This is done by increasing the content of nickel and manganese, which are more freely available than cobalt. LIBs have changed from containing 60 per cent cobalt in NMC(622) battery type (60 per cent nickel, 20 per cent cobalt, and 20 per cent manganese in weight percentages) to having 10 per cent cobalt in NMC(811) battery type (80 per cent nickel, 10 per cent cobalt, and 10 per cent manganese in weight percentages) (Yuan et al. 2017). Future innovations in NMC batteries may target the issue of a short battery life due to reactions of nickel atoms \ on the surface of the cathode with the cell's electrolyte, in cases where nickel content increases beyond 80 per cent in the cathode material (MIT 2022).

- **Cobalt-free batteries**
  Apart from efforts to reduce the cobalt content, innovations to develop cobalt-free batteries are underway. Some examples of such batteries are nickel titanium magnesium oxide (NTM) batteries and nickel manganese aluminium (NMA) batteries. These batteries have higher upper voltage limits than conventional batteries with a higher cobalt content. However, most of these batteries are in the lab-testing stages, with rigorous research and development happening to create better prototypes (MIT 2022).

- **Silicon-based anodes**
  Replacing graphite with silicon increases the specific capacity[14] of the anode 10-fold (from 372 to 4,212 mAH/g). However, the high specific capacity of silicon is accompanied by large volume changes (over 300 per cent more than the conventional battery volume) (MIT 2022). Such large volume changes can cause severe cracking and disintegration in the electrode and lead to significant capacity loss (Mitali, Dhinkaran, and Mohamad 2022). Future research in this sector would

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[14] Specific capacity is the amount of electric charge the electrode material can deliver per gram of material (mAh/g).

entail efforts to circumvent the above-described degradation of silicon-based anode materials during cycling (Ranninger and Haufe 2022).

- **Titanium boride nanosheets as anodes:**
  To improve the performance of LIBs, different kinds of nanosheets have been tested as anode materials. One of them is a titanium boride nanosheet-based anode that has a discharge capacity[15] of 380 mAh/g for a current density of 0.025 A/g (Varma et al. 2022). Some researchers have reported discharge capacities of 174 mAh/g for a high current density of 1 A/g, with a 10-minute charge time and capacity retention of 89.7 per cent after 1,000 cycles. Further R&D promises anodes that can sustain higher current rates, of the order of 15–20 A/g, enabling ultrafast charging in approximately 9-14 seconds.
- **Boundary free-cathode design for NMC batteries:**
  Present-day NMC cathodes develop cracks during charge/discharge cycling at high voltages. This is due to presence of microscale spherical particles, each constituting several small particles. These spherical particles have boundaries between themselves which cause cracking during battery cycling (MIT 2022). R&D in this area, has focused on finding ways to eliminate these cracks and maintain the battery's performance. One solution involves putting a protective polymer coating around these particles (Liu et al. 2022). However, this does not solve the problem completely, as there are still boundaries hiding inside the particles.

  Another approach uses single crystals to produce boundary-free cathode particles so that each particle behaves like a cathode (ibid). This material had 25 per cent more energy density than the currently available NMCs, with almost no loss of performance after100 cycles of testing even at high voltages. Researchers conclude that these boundaries are vulnerable to losing oxygen atoms while the battery charges; this leads to degradation. Eliminating boundaries prevents oxygen release, thereby improving cathode safety and stability while cycling (Liu et al. 2022).

### 8.2.3 Battery manufacturing processes

The manufacturing process of batteries involves a series of steps to create these high-performance ES devices. It begins with the preparation of cathode and anode materials, followed by the preparation of electrodes, electrode stacking, cell assembly, formation and aging, battery testing, module and pack assembly, battery management system (BMS) integration and then final testing and quality control.

- **Dry coating technique**
  Currently, electrodes are made using wet processes that involve coating a slurry of active electrode materials with a conductive material and binding agent onto copper or aluminium current collectors. One of the limitations of this process is that it uses hazardous solvents, which require significant energy to dry. The dry coating process, on the contrary, uses an electrostatic spraying technique and rolling to coat the slurry onto the current collector (Ludwig et al. 2016). As a result, this technique uses less energy than the wet process and eliminates the requirement of a solvent recovery unit, thereby reducing the process costs. Electric vehicle battery manufacturers are trying to switch from the wet to dry process while making cells.

### 8.2.4 Battery deployment stage

Battery deployment is the strategic installation and implementation of BESS in various applications. In deployment stage, the battery technologies are integrated into EVs and grid.

- **Space efficiency in battery packs**
  A battery pack's design is an important consideration, with performance improving with packing efficiency. Many automotive and battery manufacturing companies are working towards optimising packing efficiency and have managed to achieve72 per cent volume utilisation in their cell-to-pack designs. However, these types of battery designs come with the downside of reduced serviceability. This may limit their use in commercial vehicles (Yang, Liu, and Wang 2021).
- **Two-in-one battery pack**
  Current R&D is attempting to integrate sodium-ion and lithium-ion batteries into one battery pack (also known as an AB battery solution). Depending on the application, this combination will have the advantages of the low-temperature performance of sodium-ion batteries and the high energy density of LIBs. When used in the mobility sector, this combination can improve the performance of EVs at low temperatures (CATL 2021).

> A battery pack's design is an important consideration where performance can improve through packing efficiency.

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[15] Discharge capacity is battery capacity (in Ah) divided by the number of hours it takes to charge or discharge a battery.

- **Blade battery pack design for mass-market EVs**
  In a conventional battery, cells are used to build a module, and then modules are assembled into a pack. A blade battery pack, on the contrary, builds on wide and short cells and assembles them directly into a pack, thereby ensuring much higher mass and volume integration efficiencies than the conventional packs (Jiang et al. 2022).
- **Improvements in battery management software**
  Battery management software (BMS) helps to improve multiple aspects of battery performance without even dealing with the challenges associated with materials which make battery electrodes. For example, the analytics of a recently innovated BMS software can simultaneously improve the safety, cycle life, charge time, and useable capacity of a battery. This is done using a combination of battery use data and cell impedance measurements taken from physical models of lithium-ion cells, which are used to optimise operation and charging protocols (QNOVO 2022). The future of batteries will surely involve trade-offs between the key performance characteristics of energy density, cycle life, fast charging, and safety in the cell development stage. Therefore, an improvised BMS could feasibly offer improvements to all of these aspects.
- **Application of a digital twin in smart BMS**
  A digital twin (DT) is based on the idea of accurately establishing a real-time connect between the physical and the virtual worlds. At present, a full life cycle management framework is required for batteries, as the conventional BMS cannot store or process large amounts of data during the operation of a vehicle, due to poor real-time capability and an inadequate data utilisation rate. To improve BMS efficiency, it is necessary to study various mechanisms, such as battery ageing and thermal runaway, in-depth. The integration of advanced technologies like big data and artificial intelligence (AI) into the BMS is a promising future innovation in the field, to realise battery lifecycle data management.

  Researchers have created a DT which, using sensors, collects voltage, current and temperature data from a real battery. The corresponding battery models- geometric, ageing, and thermal- are digitally established in the cloud (Wang et al. 2021). Real-time data monitoring is achieved with AI, cloud computing, big data, blockchain, and other technologies, which estimate the state, thermal management, and feedback control of the real battery while updating the virtual model. The cloud BMS and on-board BMS work together in a DT model. Such visualisation of battery information makes the battery more transparent to scientists and engineers who work towards improving the BMS installed in vehicles (Wang et al. 2021).

In summary, the ACC value chain is continuously evolving. It is almost impossible to comprehensively include the enormous amount of ongoing R&D in this report. The key innovations mentioned have created initial pathways for further research in this field. While some developments offer only incremental benefits, their combination will usher in enhanced performance of the ACC batteries.

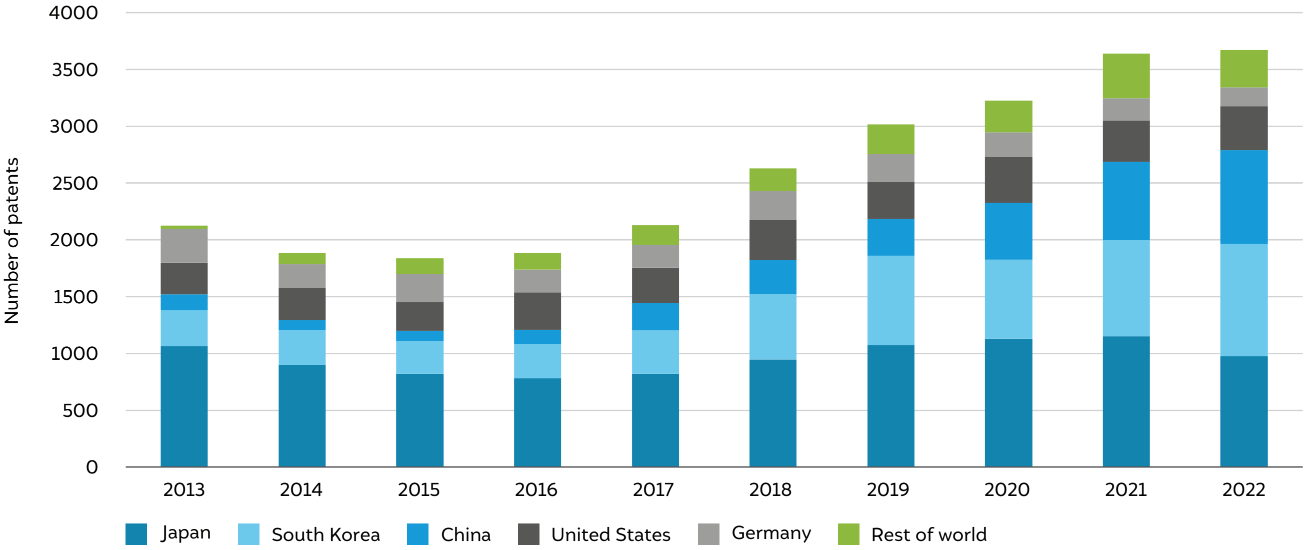
# 9. Avenues for national and international support to scale-up ACC batteries

## 9.1 Fostering investment in ACC innovation

The G20 has identified clean energy technologies as key drivers of progress towards global climate targets (G20 ETWG 2022). ACC batteries will be important enablers of these clean technologies. As we have seen, ACC batteries will support the clean energy transition in power and mobility sectors. Still, a greater focus on development and commercialisation of battery technologies will be imperative for the transition to continue unimpeded.

> **An improvised battery management system can improve key performance parameters of the battery.**

**Figure 19** The number of international secondary cell patents filed nearly doubled between 2013 and 2021; more than 98% of inventors are citizens of G20 countries



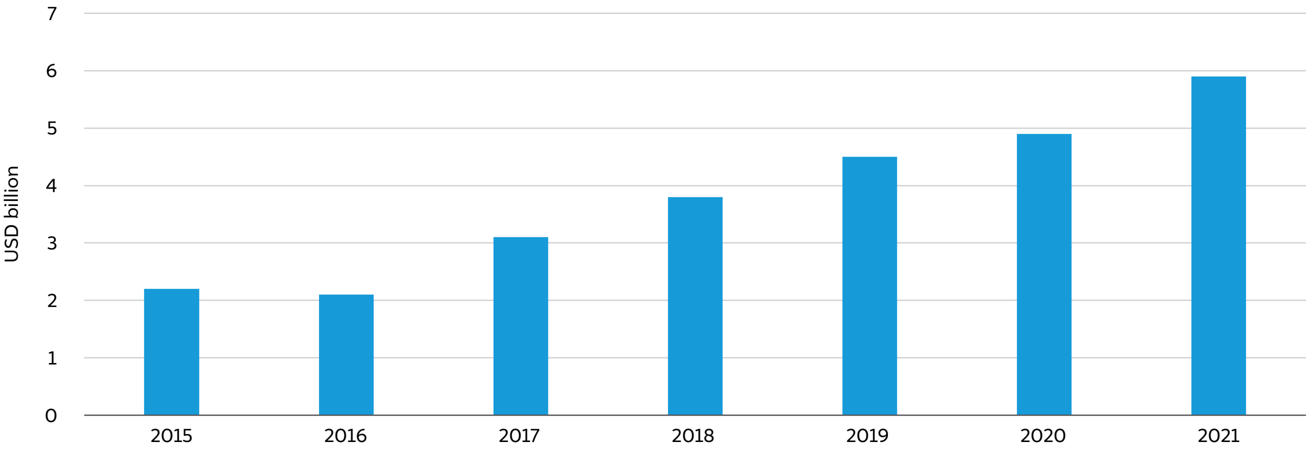
*Source: Authors' compilation from World Intellectual Property Organisation (WIPO) – Patentscope*

*Note: Search using field combination search tool, fields used: 1. International Patent Classification (IPC) - H01M10/00 ("Secondary cells, Manufacture thereof"), 2. Applicant Nationality*

There has been a global push towards innovation in the battery sector, led by G20 member countries, (Figure 19). Since 2013, the number of international patents[16] filed annually that relate to rechargeable battery cells (secondary cells) have increased from around 2,000 to over 3,500. The constant R&D has driven improvements in battery performance and manufacturing processes. As such, battery prices continued to fall. The ongoing LIB technology development is primarily responsible for the commercial success of the battery.

Government spending on energy R&D increased to USD 38 billion in 2021 from USD 29 billion in 2015 (IEA 2022e). Meanwhile, corporate spending on energy R&D grew much more – it crossed USD 117 billion in 2021 compared to nearly USD 90 billion in 2015 (ibid). Moreover, corporate spending on battery R&D increased to USD 5.9 billion in 2021 from USD 2.2 billion in 2020 witnessing a CAGR of nearly 18 per cent (Figure 20).

**Figure 20** Corporate R&D in batteries by listed companies over the years



*Source: Authors' compilation from IEA 2022d*

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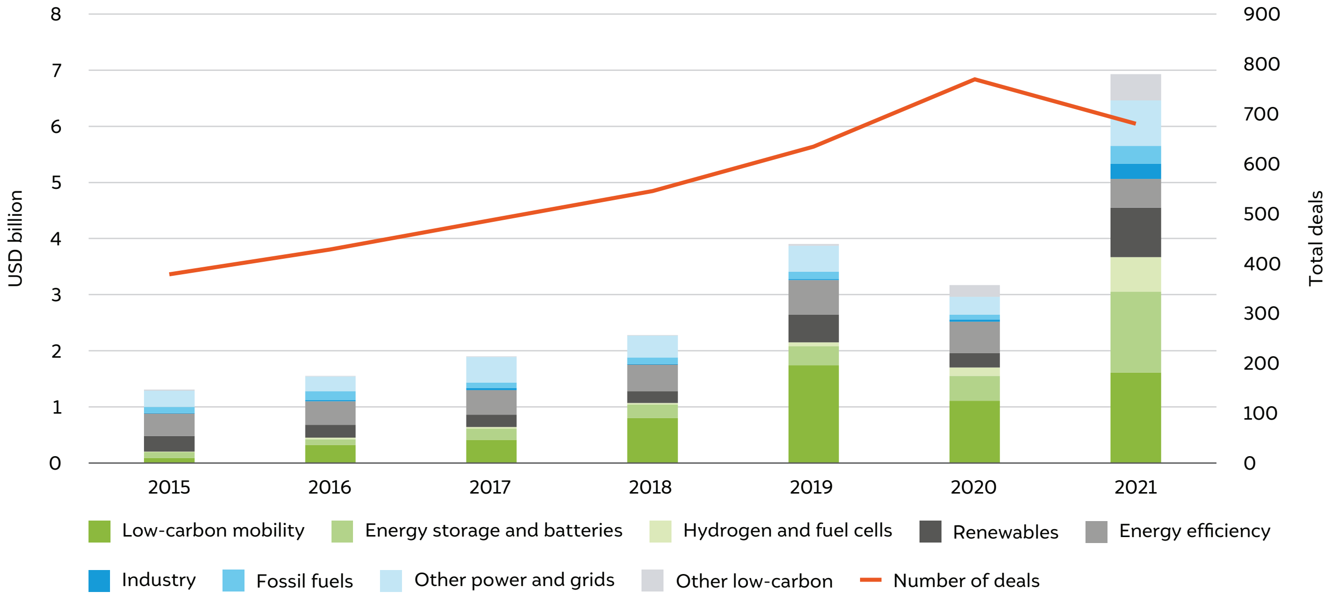
[16] Patents filed under the Patent Cooperation Treaty (PCT)

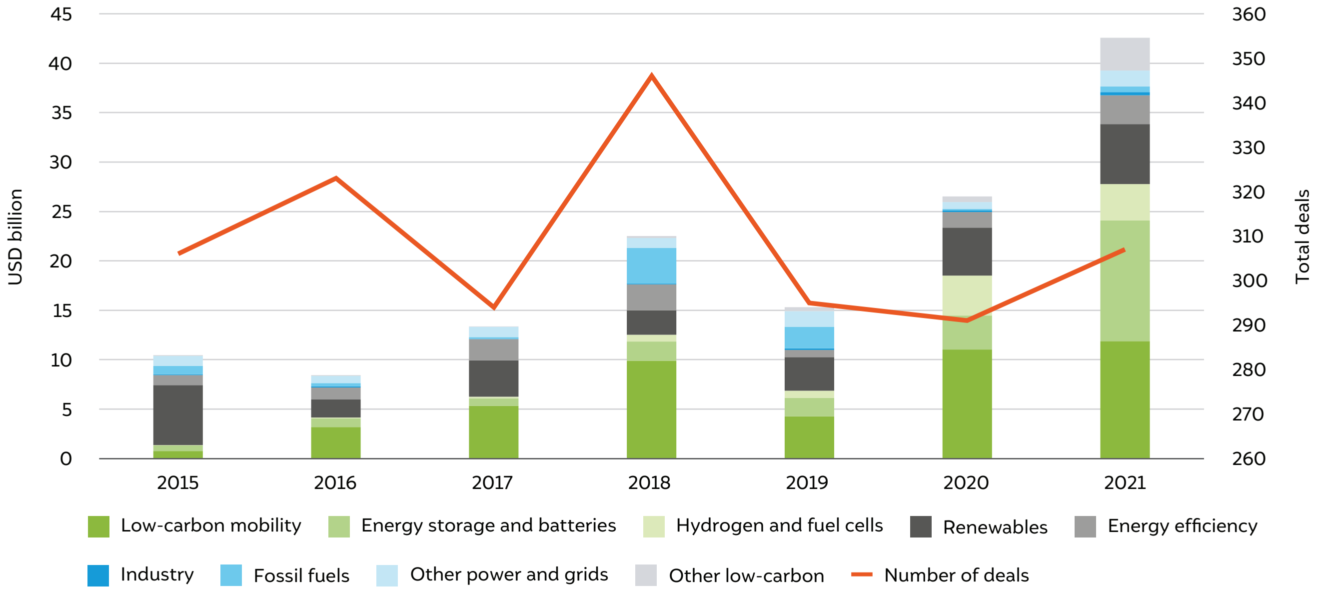
There has also been a significant increase in investments by venture capitalists (VCs) in both early- stage and late-stage clean energy start-ups. Cumulatively startups invested approximately USD 50 billion in the energy sector in 2021 (Figure 17 and 18) (IEA 2022e). The energy storage sector witnessed over 50 per cent CAGR in investments by VCs in both early-and late-stage startups between 2020 and 2021 (Figure 21 and 22).

**Figure 21** Early-stage capital investment in energy sector by venture capitalists



*Source: Authors' adaptation from (IEA 2022e)*

**Figure 22** Late-stage investment by venture capitalists across sectors



*Source: Authors' adaptation from (IEA 2022e)*

**Table 11** Causes of the valley of death

| | | | | | | |
|---|---|---|---|---|---|---|
| Limited Funding | High Initial Costs | Lack of Cashflows | Institutional Pressure | Insufficient time | Unclear Return on Investment (ROI) process | Lack of relevant skills/ competences |
| Low entrepreneurial acumen | Lack of government support | Inactive actors | Poor Innovation systems | High risks | Poor understanding of business environment | Poor Technology development |
| Sales and Marketing Challenge | Bureaucratic delays | Complex Customer Base | Lack of successful demonstration | Less attention on sustainable IP problem | Asymmetry of information | Need for Safety and efficacy of new technology |
| Poor Application of Technology | Conflicting interests | Lack of Quality assurance | Economic Crisis | Communication Problem | Use of wrong metrices | Concentration on a specific industry |

*Source: : Authors' adaptation from Gbadegeshin et al. 2022*

**Table 12** Potential solutions for overcoming the valley of death

| | | |
|---|---|---|
| Appropriate funding | Early Commercialisation | Engaging relevant stakeholders |
| Collaborations | Competent and Qualified Team | Applying different management strategies |
| Market knowledge | Conductive government policies | Inter-organizational Relations |

*Source: Authors' adaptation from Gbadegeshin et al. 2022*

Despite such promising trends, many innovations often don't get scaled up or receive any support from government, corporate or VCs. The Valley of Death (VoD) can be regarded as a condition wherein the development of innovative products is hindered (Gbadegeshin et al. 2022). There can be numerous reasons for this disruption, including the funding gap, inability to break even or failed commercialisation (Table 11). VoD analysis is applied to high-technology innovations to ascertain what stifles the growth of an early-stage startup. High technology in this context refers to innovative technology that adds value or disrupts an existing ecosystem. The business industry views VoD as a financial gap between the initial and later availability of funds (Gbadegeshin et al. 2022). The term 'valley' signifies the dip in funding; such lack of funding results in the failure of high-technology startups to scale and commercialise. Additionally, the no net-profit time for an early-stage startup, during which the company cash flow is negative, is also a time for VoD uncertainty. When a technology company is not able to transition its lab innovation to market, the separation between the product and its commercialisation can also be regarded as VoD. There is risk and uncertainty associated with VoD. VoD challenges the business development of high technology companies. Alternatively, authors propose that a VoD exists at the interface between the tail-end of scientific discovery, and genesis of a credible commercial opportunity (Ellwood, Williams, and Egan 2022). The description of VoD in these terms doesn't include business development process of a start-up than the academic journey of an innovation. Table 12 provides some means for companies to overcome the VoD

## 9.2 Role of international collaboration in scaling up ACCs: lessons from space, atomic energy, and artificial intelligence

Multilateral groups and consortiums have the potential to drive innovations. A lot of progress across various technologically complex sectors – including space, AI, and atomic energy – is a result of active collaboration. Such groups have demonstrated the power of cooperation in advancing technology development and achieving common goals. The learnings from these sectors can guide international collaboration in scaling up ACC technologies, which are essential for driving the development and growth of the energy storage sector.

International cooperation in the space sector has led to significant advancements in space exploration, satellite technology, and international space cooperation, as exemplified by the International Space Station project involving the United States, Russia, Europe, Japan, and Canada (NASA 2023). This project underscores the importance of sharing resources and expertise to achieve common goals.

Similarly, the AI sector has seen the emergence of various consortiums and multilateral organisations that have played a crucial role in driving AI innovation and promoting ethical and responsible AI development. Developing common standards and protocols for AI systems has been essential for ensuring the compatibility and interoperability of AI systems across different platforms and applications. Partnership on AI is a consortium of major technology companies and non-profit organisations, including Amazon, Google, Facebook, and Microsoft, which aims to promote the responsible development and use of AI (Partnership on AI 2023). Similarly, the European AI Alliance, an initiative by the European Commission, has been set up to foster collaboration and dialogue on AI development and adoption among stakeholders across Europe (European AI Alliance 2023).

The atomic energy sector has also seen the emergence of various multilateral organisations and consortiums that develop atomic energy technologies and promote nuclear safety and security. For example, the International Atomic Energy Agency (IAEA) is a global organisation that promotes the peaceful use of atomic energy and helps ensure atomic technology's safety and security through international cooperation and regulatory frameworks (IAEA 2023).

The importance of international cooperation and the sharing of resources and expertise demonstrated in the space sector has set a precedent for the kind of international collaboration needed to increase the development and deployment of ACCs. Furthermore, the regulatory frameworks and global cooperation models developed in the atomic energy sector can provide valuable lessons for the kind of international cooperation required for the safe and responsible deployment of ACCs and to promote the adoption of energy storage systems across different geographies.

International collaboration can help address several key challenges faced by advanced cell chemistries, including:

- **Material supply chain**: A variety of materials used in advanced cell chemistries, such as lithium, cobalt, and nickel, are sourced from a limited number of countries. Global collaboration can ensure a stable and sustainable supply chain for these materials by diversifying sources and promoting responsible mining practices.
- **Research and development:** The development of new and improved cell chemistries requires significant research and development efforts. Resources, expertise, and funding can be pooled easily through international collaboration to accelerate progress. This would further ensure that the benefits of these advancements are shared globally.
- **Standardisation:** The lack of standardised testing and evaluation procedures can make comparing and optimising advanced cell chemistries difficult. Global cooperation and collaboration can help establish standard testing and evaluation protocols that enable meaningful comparisons and promote rapid innovation.

> **International collaboration can help align policies and regulations to create a more level playing field for manufacturers and promote the adoption of ACC batteries worldwide.**

- **Policy and regulation:** Policies and regulations regarding developing and using advanced cell chemistries differ across various countries. International collaboration can help align policies and regulations to create a more level playing field for manufacturers and promote the adoption of advanced cell chemistries worldwide.
- **Intellectual property:** Intellectual property rights can be a significant barrier to global collaboration in developing advanced cell chemistries. However, collaborative efforts such as patent pools or licensing agreements can help facilitate technology transfer and promote innovation while protecting the interests of all parties involved.
- Following are some examples of international collaborations working globally towards scaling up innovation in the energy storage sector:
- **Energy Storage Partnership (ESP):** A collaborative effort of 29 organisations, including the World Bank Group, that are working towards the development of energy storage solutions customised to meet the specific requirements of developing nations (World Bank 2019).
- **Battery 2030+ Initiative**: A European Union–funded research project launched in 2019 to develop next-generation batteries for sustainable energy storage (Battery 2030 2023).
- **Global Battery Alliance:** An initiative launched by the World Economic Forum (WEF) to promote the sustainable and responsible production, use, and disposal of batteries (Global battery alliance 2023).
- **National Alliance for Advanced Technology Batteries** (NAATBatt): A consortium of companies, universities, and government organisations that collaborate on research and development of advanced battery technologies (NAATBatt 2023).

> The evolution of national and sub-national policies also plays an important role in determining the scalability of a battery technology.

## 9.3 Role of markets and policy in scaling ACC

The emergence and scalability of an ACC technology depends considerably on the markets and national policies. If a market recognises the need for a certain application, then they strive to find the most suitable technological solution. For example, in the mobility, the markets have recognised the opportunity in two- or three-wheelers and passenger cars this has led to advancements in LIB technologies. Similar rigour is missing from other sectors like aviation and shipping, resulting in delays in technological evolution for such applications. This is a collective opportunity for G20 countries to identify such innovative applications that can create the demand for new technologies.

The evolution of national and sub-national policies also plays an important role in determining the scalability of a battery technology. For example, in the mobility sector, several countries are signatories to the EV30@30 campaign (Clean Energy Ministerial 2022). This has led to the establishment of several national targets to electrify the vehicle fleet, in-turn increasing the demand for EVs (Figure 3). A similar mandate for other sectors, like shipping and aviation, can push technological innovations and help scale them up.

Another example of a policy directive is prioritising shared mobility over the use of private vehicles. As mentioned before, the battery requirements for EVs differ across the mobility sector. If a country strengthens its public transport infrastructure and promotes public transport and shared mobility options, then it can shift to technologies with low critical mineral requirements and energy density.

### 9.3.1 Challenges and limitations

There are several challenges associated with the uptake of ACC batteries. These are classified into policy and non-policy categories.

Some non-policy challenges are as follows:

- **Lack of standards in maintenance and adherence to quality and safety:** Uniform standards in battery maintenance and quality will enhance battery safety during the use, repair, and disposal phases.
- **Availability of funding**: This is by far one of the biggest challenges for ACC batteries. As the majority of these technologies are at a nascent stage, they can be a risky proposition for investors. To support the scalability and deployment of these technologies, the sector requires market stimulation measures such as emission taxes, incentives for technologies, and public procurement strategies to create a market for new technologies.
- **A lack of skilled manpower**: ACC batteries have advanced chemistries and need a highly skilled workforce to research, design, manufacture, and deploy these technologies. Industries need to map these new skill sets, support the creation of training programmes, and provide on-the-job-training to the existing workforce and offer vocational training to create a talent pool.

Some applications of the ACC batteries require policy support. This is particularly true for grid-connected applications. Following are the policy challenges impeding the scaling of grid-interactive ACC battery applications:

- **Restrictions on residential EV battery charging**: Several electricity regulators do not allow residential consumers to set up EV charging facilities. These constraints the uptake of EVs in this consumer segment.
- **A lack of grid price signals for all consumers:** Currently, differential time-of-day tariffs and other price signals are not available to all consumers, because of which behind-the-meter batteries are not prioritised for grid applications.

> Collaborations across relevant institutions will help avoid duplication of efforts in innovations to improve performance of ACC batteries.

**Restrictions on batteries in electricity markets**: Several electricity markets prohibit the use of behind-the-meter batteries in the power and ancillary services markets. Such restrictions reduce the economic viability of batteries for owners, as many of the new revenue streams are inaccessible.

- **Limited operating models for batteries**: Several electricity markets do not recognise the new operating models for batteries, where ownership of the system extends to different players in the power sector (generators, transmission companies, and distribution utilities). Such restrictions limit the participation of power sector players, thereby impeding the uptake of the batteries.

# 10. Recommendations

G20 countries account for 80 per cent of global greenhouse gas emissions, with the largest share (80 per cent) attributed to the $CO_2$ emissions from their energy sectors (OECD 2021). Hence, G20 countries can help ensure that a long-term strategy shapes ACC battery innovation. As we saw in previous chapters, significant development has taken place in the technological innovation of ACC battery storage systems. Nonetheless, research on improvements that can increase the commercial viability and scalability of such battery systems is also underway. Following the mission of *One Earth, One Family, and One Future* as a part of India's G20 presidency, this chapter highlights some of the priority areas and action points therein for G20 in short to medium term.

## Priority 1: Promote innovation and support technological co-development by leveraging the benefits of collective effort

Co-ordinated innovations and technological co-development can have multiplier effect as the world aims to transition to a low carbon pathway. Collaboration between countries and institutions will be essential to improve existing and develop new battery technologies.

**Action 1: Formalise collaborations between global academic institutions to improve performance and reduce costs of ACC technologies:** Collaboration can reduce the lead times for problem identification, solution design, and implementation. The innovations in ACC technology are increasing by the day, and the chances of overlap are very high. It is hence important that countries, institutions, and individuals work together to develop solutions with higher impact. The existing initiatives like *Mission Innovation*, IEA's Committee on Energy Research and Technology (CERT) and *Technology Collaboration Programme*, *Breakthrough Agenda*, and *Green Grids Initiatives* can be leveraged to support such innovations. Additionally, many government and private labs across the world are working to develop new technologies. G20 countries can agree on a mechanism for information sharing on the latest technological developments in these labs. Wherever possible, labs can also collaborate on topics of mutual interest.

**Action 2: Infuse LiFE principles by developing uniform circularity indicators that will support resource efficiency and waste minimisation:** As the demand for batteries grows, the demand for various materials and minerals used in manufacturing will also increase. If designed well, most of the materials and minerals can be recovered after the end-of-life of a battery. It is hence important that 'Lifestyle For Environmental'

principles (LiFE) are considered during the design and manufacturing phases. Such actions will not only promote circularity but also ensure that the prices of new minerals do not increase abruptly. Collaboration exercises on developing circularity indicators will ensure that we use our resources efficiently and create localised jobs in the recovery phase.

**Action 3: Share details on technological breakthroughs for previous generation ACC technologies to reduce the learning time of new innovators:** R&D activities and numbers of patents filed are rapidly increasing for batteries. As discussed earlier, the battery cost has two components: material costs and other costs. The material cost is expected to remain volatile and even increase in the coming years. However, based on previous experience, the balance of material costs has declined significantly. The governments and industry, through appropriate mechanisms, should agree to share previous generation technology details, which had led to the reduction in costs during the manufacturing or packing processes. With fast-moving R&D in the ACC battery space, it is likely that many patents will not go into production but can be used by others to build upon. A common portal can be created to share these IPs. As seen earlier, sharing of ideas and collaborations can have a multiplier effect on technological development, and such steps can ensure that ACC technologies become affordable.

## Priority 2: Develop markets and unlock new avenues of deployment by sharing best practices and increasing the flow of finance

Commercialisation and deployment of new technologies requires multifaceted strategies. Countries often adopt different interventions based on the application of the technologies and competing options. It is hence essential that countries collaborate to share the best practices, learning and failure to develop for the markets for new ACC batteries.

**Action 1: Increase government support to mobilise corporate spending and venture capitalist funding in ACC R, D&D and the ecosystem:** Innovators require financial support during various stages of product development. From procuring raw materials to setting up pilots – there is a constant requirement for financial support. There has been a significant increase in R&D spending by corporates. Many venture capitalists are now supporting start-ups in the field of energy storage. Going forward, it will be important to continue supporting innovators through domestic/regional mechanisms and ease the process of raising financial support through international markets. Governments can share learnings from successes and failures on policies that have increased R, D&D in the battery ecosystem. Existing platforms like Clean Energy Ministerial and *Mission Innovation* may be leveraged in this regard. The governments can start by focusing on technologies with lower material costs and aim to reduce the balance of material costs of a battery system.

**Action 2: Unlock new areas of deployment through dedicated financing via multilateral development banks:** ACC technology is vital for decarbonisation. However, most of these technologies are in the early stages of deployment and are expensive to deploy. Without financial support, deploying ACC technologies in the grid or for EVs can become expensive. In this aspect, multilateral development banks can act as anchor investors by providing low-cost, long-term finance for both the manufacture and deployment of ACC technologies. Such steps will not only reduce the cost of the final project but also provide much-needed momentum to the energy storage ecosystem. MDBs such as World Bank, Asian Development Bank, European Investment Bank, Asia Infrastructure Investment Bank, etc., can play a pivotal role in deploying ACC technologies across geographies.

**Action 3: Jointly develop handbooks and courses to train individuals and institutions on ACC battery applications (EV and grid):** To achieve the large-scale impact of technology, innovation must diffuse globally through active and passive interventions. Skilled manpower will be critical to manufacture, deploy, and service ACC systems. With a rapidly changing technology, the skills of the workforce will need to be upgraded regularly. In this aspect, handbooks and technical courses must be developed to train key stakeholders in the ecosystem. A greater focus on training the trainers can ensure that knowledge is shared locally within a country. Organisations like the International Labour Organization can work with member countries, industries, and academic institutions to develop training material (online and offline) on ACC technology.

# 11. Conclusion

ACC battery technologies are a vital asset in solving the climate change crisis. These technologies have the potential to enhance clean energy ambitions by supporting the electrification of new sectors, such as aviation and shipping, and improving the utilisation of renewable energy through grid-interactive applications.

Although several existing ACC batteries are used in the mobility and power sectors, there are several areas for improvement around cost, performance, safety, and scalability. Hence, future ACC technologies must bridge these gaps while ensuring accessibility for larger communities. However, taking these innovations from the margins to the mainstream will require financing, collaboration, and demonstration support. G20 countries can play an essential role at each stage. They should demonstrate leadership in fostering innovation, promoting technology transfer, and setting a vision for deployment.

An active supporter of multilateral cooperation, India has spearheaded various global initiatives – such as the development and distribution of a COVID-19 vaccine as well as the establishment of the International Solar Alliance for scaling solar energy – which have been impactful. In its G20 presidency, India has an opportunity to create a global movement for scaling essential climate change mitigation solutions like ACC batteries.

# Annexure

## Annexure 1: Types of energy storage technologies

Energy storage technologies of various kinds exist. The scalability of a technology depends on its maturity, use case, and the cost of deployment. While the report has focused on electrochemical storage, this section provides an overview of other types of technologies. Energy can also be stored in a hybrid form which is the blend of any two systems.

- **Thermal energy storage**
  Thermal energy is naturally available in the form of solar and geothermal energy or artificially produced through various processes in power plants or industries. Thermal energy storage (TES) systems are deployed to capture the energy which may otherwise get dissipated in the environment. The heat generated by large sources such as thermal and nuclear power plants is stored in a specific storage medium to be utilised later for heating or electricity generation purposes (Mitali, Dhinkaran, and Mohamad 2022). Residential and Industrial facilities use this stored heat energy in various applications such as space heating/cooling, hot water production, or electricity generation. The heat is also used in industrial cooling, heating and storage systems and operates in a temperature range of -18 to 175° C.

  The technologies utilised for the implementation of TES can be classified into three broad groups based on the principles of its operation.

  - **Sensible heat storage**
    Sensible heat storage is the most commonly used and advanced form of TES that stores energy by heating/cooling the medium of storage but without its phase change. Sensible heat storage offers storage capacity ranging from 10 kWh to 50 kWh per tonne depending on the specific heat of the storage medium. The storage medium used can be solid state or molten salts, depending on the requisite characteristics (Prakash, Tiwari, and Maiti 2022). Applications of sensible heat storage materials include the power sector, industry, and infrastructure heating and cooling; e.g., buildings, pipelines, etc.

  - **Latent heat storage**
    This storage technology uses latent heat principles and depends on the phase-change properties of the medium. Low-temperature, high-temperature, and sub-zero-temperature phase change materials are utilised for heat storage.

  - **Thermochemical energy storage systems**
    This type of ESS makes use of enthalpy of a reaction i.e. heat released or absorbed during the association or dissociation of molecules (MIT 2022). In open and closed thermochemical energy systems, heat is directly released into the environment directly and via heat exchanger surface, respectively.

- **Mechanical energy storage**
  Mechanical energy storage (MES) systems store energy through the transformation between mechanical and electrical energy forms(Mandal et al. 2022). MES systems are further differentiated as follows: pumped hydro energy storage (PHES), gravity energy Storage (GES), compressed air energy storage (CAES), and flywheel energy storage (FES) (Mitali, Dhinkaran, and Mohamad 2022). Potential energy is stored in PHES, GES, and CAES systems whereas kinetic energy is stored in FES systems. MES are capable of quickly converting and releasing stored mechanical energy. The various types are discussed in detail as follows:

  - **Pumped hydro energy storage**
    One of the most widely deployed MES is PHES (Arteconi and Bruninx 2018). A typical PHES system has three main components: two large reservoirs (with a large elevation difference), water pumping unit from lower to the higher reservoir, and a turbine to generate electricity as water flows from upper to lower reservoir.

    During the charging process the electrical energy from the power source gets converted into mechanical energy through the pumping and storing the water from lower to higher reservoir. Once pumped, the energy is stored in the form of potential energy. During the discharging process, the water stored in the upper reservoir is released, rotating the turbines and thereby creating electricity through generators. In this process, water flows back to the lower reservoir. (Cooper

2004). The amount of energy stored is determined by the difference in elevation between reservoirs and volume of water stored in them.

Some examples of novel PHES systems are underground PHES (UPHES) and seawater PHES (SPHES), differentiated based on the nature of lower reservoir used. In UPHES, abandoned quarries or mines are the lower reservoirs whereas in SPHES, the sea is used as the lower reservoir. Out of these two, the SPHES is considered superior as it saves on construction costs and time. PHES systems are primarily applied in the context of frequency control (secondary and tertiary reserves), voltage control, bulk power storage, seasonal storage, transmission-congestion relief in the grid, and upgrade deferral (Arteconi and Bruninx 2018).

- **Gravity energy storage**
  The GES technology utilises gravitational energy or potential energy for storage; this energy is generated by changing the height of an object. In the currently operational GES units, heavy concrete blocks are stacked by a multi-headed crane into a tower and thus acquire potential energy during the elevation gain. When electricity has to be supplied, the crane lowers these blocks to the ground, with the motors functioning as generators, thereby creating electricity (Glover et al. 2022).

- **Compressed air energy storage**
  As the name suggests, a CAES system utilises compression of air to store energy. The amount of energy stored depends on the volume of the storage container, pressure and the temperature at which the air is stored (Mitali, Dhinkaran, and Mohamad 2022). A typical CAES system has five major components: a multi-stage compressor that compresses the air, a motor to drive the compressor, a container or cavity for storing the compressed air (underground caverns/porous reservoirs), a turbine train (including both high and low-pressure turbines), and a generator which produces electrical energy.

  During the charging process the electrical energy drives the motor leading to a multi-stage compression process leading that increases the air pressure. The compressed air is then stored in locations like underground caverns. During discharging, the compressed cavern air is used to drive the pressure turbines which convert compressed air energy into mechanical energy. This mechanical energy drives the generator and generates electricity.

- **Flywheel energy storage**
  FES systems store kinetic energy. In other words, the rotational energy of a massive cylinder is utilised. There are five essential components of a FES: a flywheel, magnetic bearings, electrical motor/generator, power conditioning unit, and a vacuum chamber. During charging, the integrated reversible electrical machine acts as a motor. It rotates the flywheel system at high speeds and stores kinetic energy (Cooper 2004). During discharging, the rotor decelerates, the reversible machine operates as a generator and the kinetic energy stored in the flywheel is converted to electrical energy. Electricity is thus used to accelerate/decelerate the flywheel in the FES (Arteconi and Bruninx 2018). An integrated motor/generator transfers the stored kinetic energy to/from the flywheel.

- **Chemical energy storage**
  In chemical energy storage (CES) systems, the chemical bonds formed between the atoms and molecules of a material store energy. This stored chemical energy is released during chemical reactions and changes the composition of materials. This is due to the breakage of chemical bonds of reactants and formation of new bonds in the produced materials. Globally, the predominant usage of chemical fuels is in the electricity and mobility sectors (Andrey et al. 2020). Coal, gasoline, diesel fuel, natural gas, liquefied petroleum gas, propane, butane, ethanol and hydrogen are some common chemical fuels. The chemical energy of these materials is first converted into mechanical energy and subsequently into electrical energy. CES systems primarily include hydrogen, solar fuel and synthetic natural gas energy storage systems as discussed below.

  - **Hydrogen**
    Hydrogen can be produced by splitting water using thermal, thermochemical, electrical,

photoelectrical or solar energy, or biologically by biomass conversion, or photobiological processes. Although hydrogen can be produced in many ways, its conversion into electrical energy happens via fuel cells. In these cells, during charging, an electrolyser splits water to produce hydrogen which is then stored in tank (Schmidt et al. 2019). During discharging, electricity is generated through the burning of hydrogen using fuel cells.

  - **Solar fuels**
    Solar energy storage harvests the energy of the sun, converts it to usable forms and stores it in the chemical bonds of fuel (Andrey et al. 2020).

- **Electric energy storage**
  In an electric energy storage (EES) system, electrical energy is stored after being generated with the help of an electrostatic field made of two closely spaced metal plates separated by a dielectric layer of a non-conducting material (MIT 2022). During the process, as a voltage source is applied across the metal plates, one plate gets positively charged while negative charge is induced in the other plate.

  There are two types of EES systems: electrostatic energy storage systems and magnetic energy storage systems. Capacitors and supercapacitors are used in electrostatic energy storage systems whereas superconducting magnet is used in a magnetic energy storage system.

- **Electrochemical energy storage**
  An Electrochemical energy storage system (EcES) operates primarily by ionisation, transport of charged particles, and the recombination of charges. Extensive R&D are underway to enhance electrochemical storage capabilities and cater to evolving use cases across sectors.

## Annexure 2: The history of conventional batteries

The story of rechargeable electrochemical storage – secondary batteries - began around 1860, when Gaston Plante invented the lead acid battery. This was the first battery that could be recharged after use (Zito and Ardebili 2019). The lead-acid battery, while revolutionary, was far ahead of its time, since the most common application for batteries in those days was to power telegraph lines, for which non-rechargeable primary batteries sufficed. The secondary battery truly came into its own with the advent of the electric starter for ICE vehicles (Zito and Ardebili 2019). A lead-acid battery was economical, and had sufficient power density to start the engines in automobiles. Since that pivotal development in 1912, lead-acid batteries have been inseparable from the automobile.

In 1899, the nickel-cadmium (NiCd) battery was invented by Swedish scientist Ernst Waldemar Jungner (Kurzweil 2009).The durability, energy density, and cost-effectiveness of this new battery chemistry precipitated its widespread use in subsequent years. It was first commercialised in Sweden in 1910, and was used in many portable devices – two-way radios, power tools and medical devices (Patel 2019). The popularity of the NiCd battery began to wane in the 1990s, after decades of technological improvements, with the commercialisation of the nickel metal hydride (NiMH) battery. Developed by Battelle-Geneva Research Centre, NiMH batteries were less toxic than NiCd and had nearly twice the energy density of lead acid batteries (Economist 2008; Patel 2019).

At the turn of the millennium, these batteries – lead-acid and nickel-based – were the most common rechargeable batteries on the market. Their popularity could be explained by their cost effectiveness and beneficial characteristics, but also by their constant, incremental innovation. Even though these chemistries originated in the 1800s, research continued throughout the 20th century (Kurzweil 2009). For lead-acid batteries, significant developments were made to the lead alloys used. This led to a reduction in the maintenance requirements of these batteries. Another major step was the development of sealed valve-regulated lead acid (VRLA) batteries which enable controlled water loss (Kurzweil 2009). NiCd batteries underwent similar improvements decades after their invention, making them more gas-tight and maintenance-free (Kurzweil 2009).

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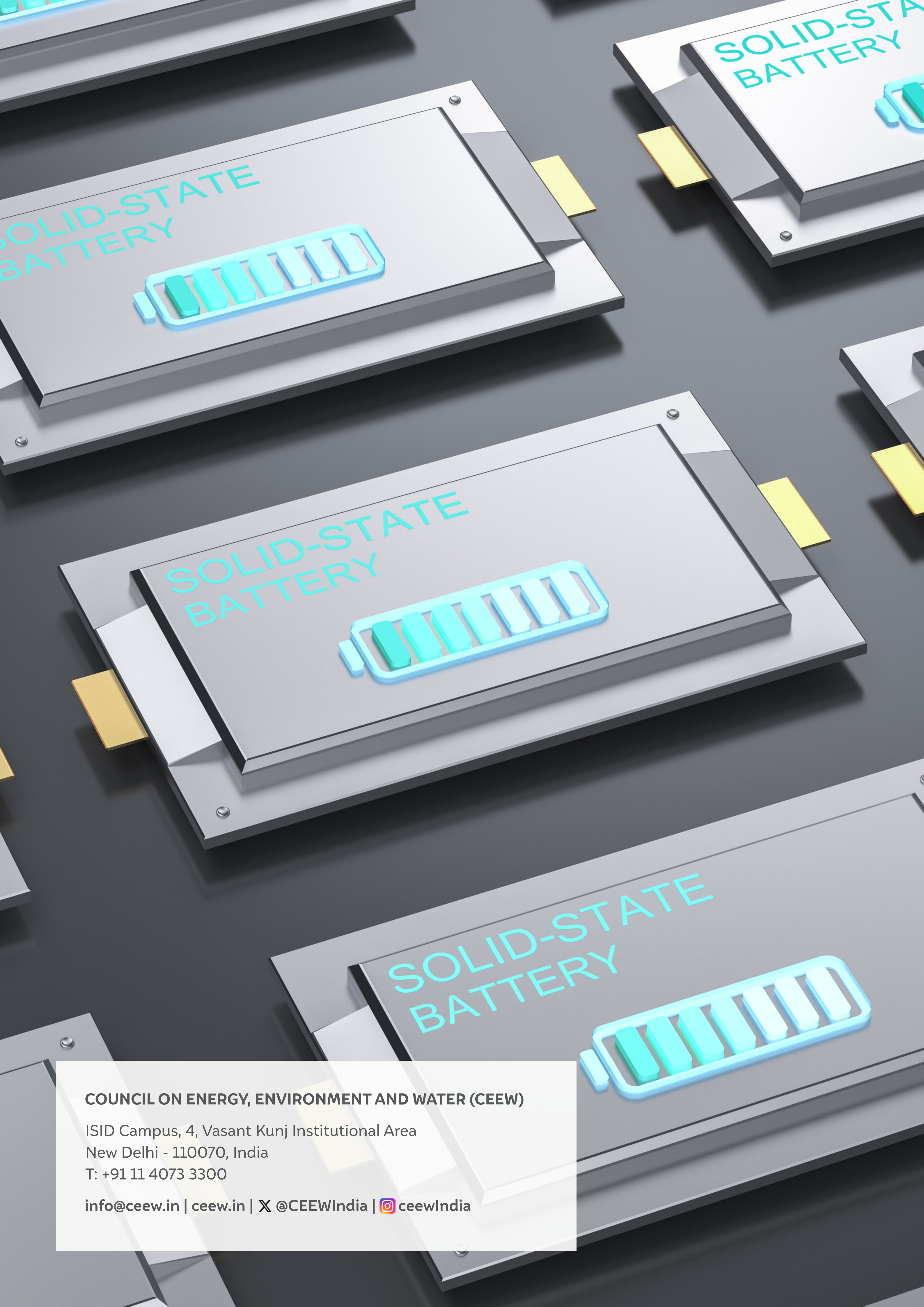

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