OPPORTUNITIES FOR INNOVATION IN BATTERY CHEMISTRY

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Introduction

As countries strive to reduce their dependence on fossil fuels, battery technology is poised to take over as the future of sustainable energy.

With consumers and regulatory bodies pushing for improved battery sustainability in vehicle electrification and renewable energy storage, an alternative to current lithium-ion battery (LIB) technology is needed. LIBs dominate the market due to their high performance, but concerns over lithium and cobalt scarcity, combined with recycling complications, leave a need for novel chemistries to make more sustainable technology.

Battery developers can look to several routes for designing more sustainable and competitive batteries, including:

- Implementing chemistries with lithium and cobalt alternatives, such as sodium-ion, potassium-ion, and zinc batteries, as well as manganese cathodes.
- Developing novel recycling techniques and pipelines to increase battery life-cycle circularity and recycling efficiency.
- Redirecting into alternative battery chemistries such as olid-state or flow batteries.

With a rapidly evolving market, it is important for developers to have the full picture of the current landscape to know where to move next with battery sustainability research.

Barriers to battery sustainability

Battery sustainability pitfalls depend on the battery type. In recent years, traditional lead-acid batteries have been unable to provide enough power for emerging technology, including personal electronics and electric vehicles (EVs). While they still have uses in smaller battery-powered devices, the fast-paced development of these larger technologies has caused a huge surge in the demand for lithium-ion batteries and their alternatives.

However, in spite of the ever increasing demand for LIBs, they are largely considered unsustainable. LIBs rely on scarce raw materials, energy intensive manufacturing processes, and typically go unrecycled into landfill waste at the end of their <10 year lifespan.

Specific barriers to LIB sustainability fall into three categories:

Raw material scarcity	– Lithium and cobalt are rare elements needed for LIBs.
	– Cobalt is the most expensive raw material in LIBs due to its scarcity.
	– The use of scarce materials is unsustainable as:
	  – Environmentally, scarce, finite materials will run out.
	  – Financially, increasing demand and decreasing finite resources will drive up the cost of these materials.[3,4]

Recyclability	– LIBs are not recycled in any significant amount, despite the environmental and economic advantages.
	– Within the EU, less than 5% of LIBs are recycled in practice.
	– This lack of recycling creates increasing landfill waste with worldwide LIB waste predicted to reach 20 million metric tons per year by 2030.
	– These low rates of recycling are largely due to two factors:
	  – Lack of initiatives and infrastructure to channel LIBs out of landfill waste streams and into recycling pipelines.
	  – Lack of effective LIB recycling technology which can handle the high turnover created by increasing demand.[1,2,5]

Manufacturing processes and supply chains	– Different manufacturing processes can have vastly different energy consumption which affects battery sustainability.
	– Heat and electrical energy consumption differs between manufacturers.
	– How this energy is supplied also affects sustainability—either from renewable sources or fossil fuels.
	– The use of different methods to source raw materials has been shown to affect:
	  – Water consumption
	  – Energy consumption [6,7]

The lack of sustainability in the life-cycle of LIBs is in conflict with the growing demand for sustainability within the market they currently dominate. This creates an opportunity for either a new battery chemistry, manufacturing process, or recycling technology.

What's driving the change to more sustainable battery materials and manufacturing?

The push toward more sustainable batteries comes from across the globe and falls into three major categories:

- Consumer demand for sustainable products, including electric vehicles and renewable energy storage
- Concerns about unsustainable practices resulting in unstable supply chains
- Regulations in markets across the globe requiring sustainability, including China which dominates the EV market

The interplay between these driving forces will forge a path for the future of battery chemistry.

Consumer demand - Vehicle electrification

One of the main areas where consumers are pushing for battery sustainability is vehicle electrification. With consumers widely looking to reduce their reliance on fossil fuels, the electric vehicle industry is seeing a huge boom. In the last five years, the industry has seen a staggering 20-fold increase in EV sales to 6.6 million sold in 2021.

Disposable LIBs currently underpin the EV market, and their demand is expected to increase ten-fold by 2030, with an added 2-3-fold increase by 2050, driven by a predicted surge in EV sales. However, LIBs bring with them a host of sustainability concerns and consumers, looking to live more sustainably by purchasing EVs, will prioritize the most sustainable battery options available.[1,6,8]

Cumulative lithium-ion battery demand for electric vehicle and energy storage applications

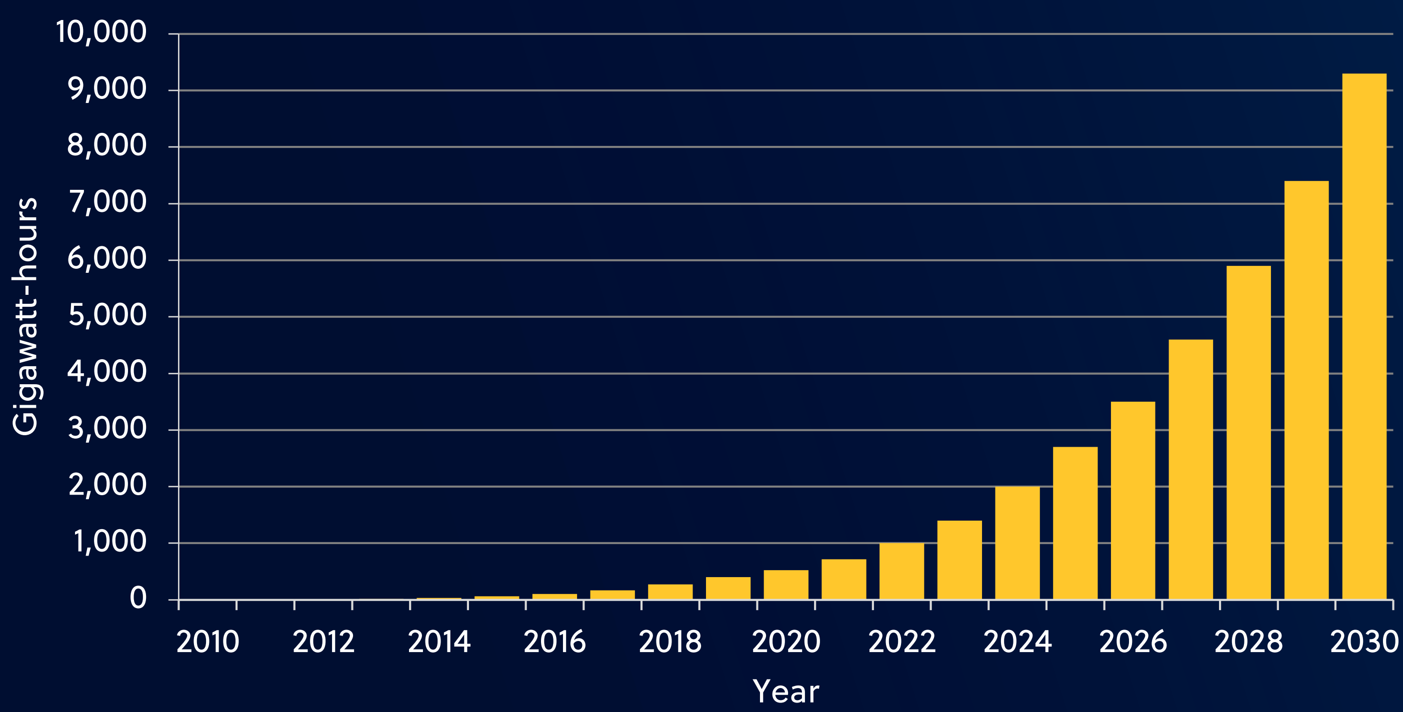


Figure 1. EV sales are expected to continue to rise steeply to 20.6 million in 2025, bringing with it a matching demand for batteries.[8]

Consumer demand - Storing sustainable energy

The sustainable energy sector also relies heavily on LIB technology. Renewable energy from wind or solar power is not consistently produced, with production rates affected by changes in the weather as well as the day-night cycle. Because of this variability, energy storage is a key component for renewable energy systems. In China, one of the world's leading sustainable energy markets, LIBs are the second largest energy storage system in use.[10]

Installed capacity of energy storage system in China in 2020

Pumped hydro
~93%

Lithium-ion batteries
~5.9%

Lead-acid batteries
~1%

Other
<0.1%

Figure 2. Renewable energy sources are expected to account for 60% of global energy generation by 2070, bringing an imminent need for efficient energy storage systems.[6]

As consumers increase their reliance on renewable energy, the efficiency and environmental impact of batteries are limiting factors in moving toward energy sustainability. With countries around the world pledging to increase their reliance on renewable energy sources in the next decade, demand for cost-effective large-scale LIBs is expected to soar.

Supply chain instability

A major push toward new battery chemistry and increased LIB sustainability comes from the need for cobalt, the rarest component of current LIBs. Not only does the use of a rare, finite resource threaten the longevity of LIB production, but cobalt is sourced in ways that threaten the stability of the entire LIB supply chain.

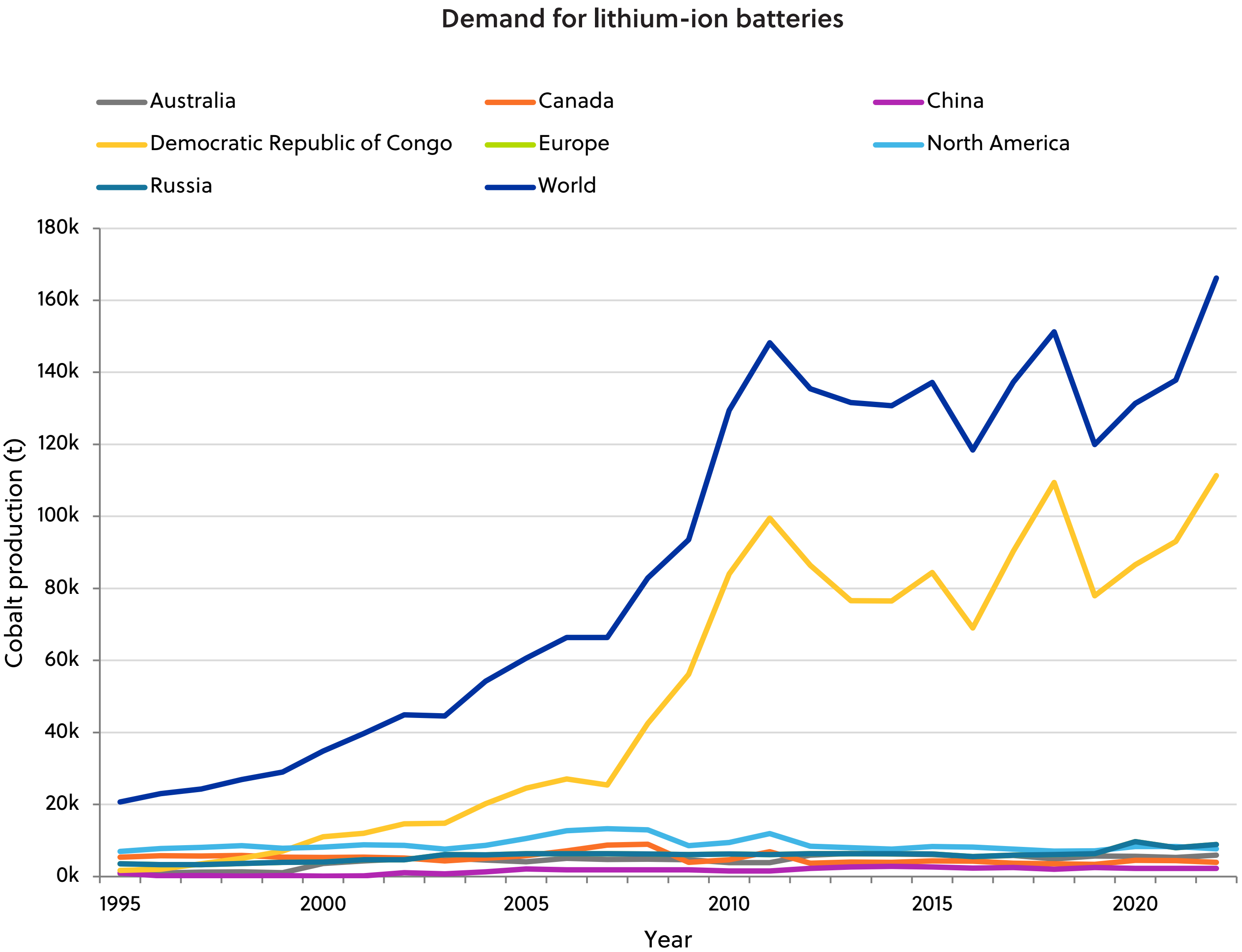


Figure 3. Over 60% of the cobalt in the industry is mined in the Democratic Republic of Congo.[4]
Source: Cutting cobalt. Nat Energy. 2020;5(11):825-825. doi:10.1038/s41560-020-00731-3

Political instability within the DRC has allowed cobalt mining to go mostly unregulated with child labour practices and environmental impact going unchecked. This means that cobalt, an integral element in current battery cathodes, is underpinned by environmentally and socially unsustainable practices, creating wide reaching ethical implications as well as concerns that access to this key material could be cut off suddenly.[4]

Global regulations

Battery sustainability frameworks have gained popularity across the world in recent years. Regulations have been developed in several countries to define the level of sustainability a battery must have to be sold. These regulations come from some key global players including China, the EU, and the U.S.:

Energy in China's new era	– In 2018, China announced clear interim measures including minimum standards for battery reuse and recycling plants. – These interim measures were tightened only a year later. – The 'Energy in China's New Era' development plan to 2030 was introduced at the end of 2020. This outlined even stricter regulations on battery supply chains, requiring recycling and a reduction in the carbon intensity of electricity used to power EVs.[12,13]
EU regulations	– In 2019, the European Union announced their new regulatory framework for batteries which focused on sustainability. – The regulations, a sorely needed update to the 2006 EU Battery Directive, will require batteries to be more sustainable in their entire supply chain. – The regulations will make the use of recycled materials in all batteries over 2kWh (which includes those used in electric vehicles) compulsory, along with other supply chain sustainability requirements.[12,14]
U.S. investments	– In October 2022, the Biden Administration announced a $2.8 billion investment into domestic battery manufacturing along with the 'American Battery Materials Initiative' which echoes the battery sustainability frameworks being introduced around the world. – In this announcement, Biden set a goal to have half of all vehicles sold in 2030 be EVs, a massive opportunity for growth in the U.S. battery sector.[12,15]

Currently, China, the world's largest EV market, is leading the globe with the strictest and most extensive regulations, with the EU not far behind. Given that China bought half of all EVs sold in 2021, and Europe is the second largest market for EVs, their influence in this market can make or break suppliers' businesses.[13,12,14]

With China and the EU making their stance on battery sustainability clear, and other countries set to follow suit, we can expect to see more sustainability regulations—and likely stricter ones—in the next few years. This will force battery developers and suppliers to invest in more sustainable battery practices to allow them to continue to trade in these markets.

Government regulations are likely to continuously target EV LIBs to install sustainable supply chains before the predicted market boom. This will result in opportunities for more sustainable novel battery chemistries, while also causing unsustainable LIB chemistry to become potentially obsolete and unsalable within the next decade.

Innovation opportunities

With the push from increased consumer demand and new global regulations, the development of new technology is evolving at an unprecedented rate. This fast-paced environment is both an exciting opportunity and a turbulent time for businesses to navigate. Up-to-date knowledge of current innovations can arm developers against the storm, giving them an advantage in the current market. Here we explore both the near-term and long-term options for moving towards sustainability.

Overcoming raw material scarcity

One of the obvious strategies to tackle the sustainability issues surrounding the use of lithium and cobalt is to design a novel, sustainable alternative.

Near-term option: Alternative metal-ion batteries can be used in place of LIBs.

While LIBs are overwhelmingly the most popular battery chemistry used today, other metal-ion chemistries including sodium, aluminum, and potassium have seen an increase in patent filings in the last decade. Along with this, there has been an upward trend in patent filings for alternative technologies such as flow batteries.[16] Shifting interest to existing alternatives like other metal-ion batteries is a way that companies can move toward sustainability immediately.

These metal-ion batteries are likely to increase in popularity in the near future. This will make their production and the development of more efficient versions a key area of interest.[16]

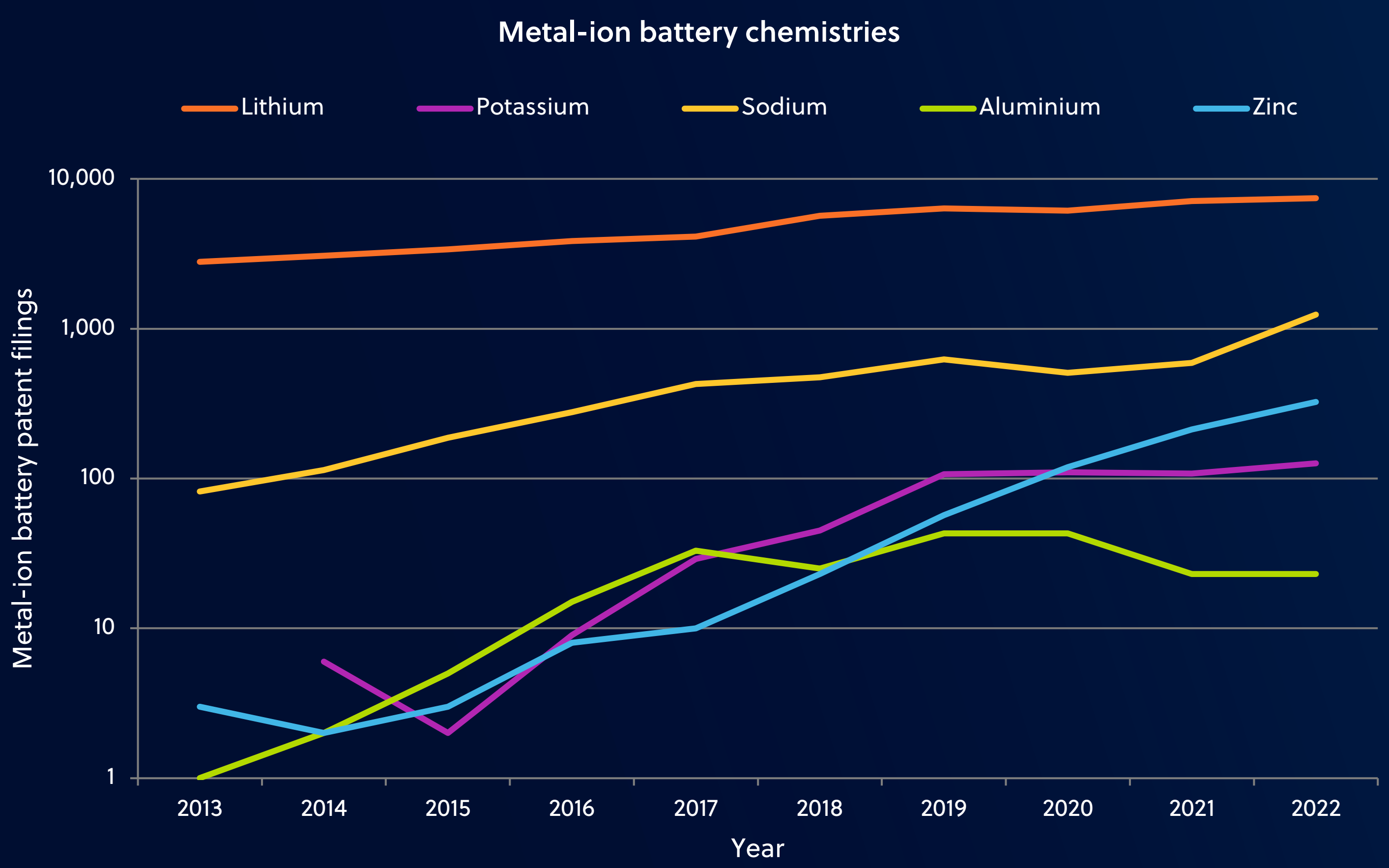


Figure 4. Metal-ion battery chemistries.

Long-term option: Zinc battery research can overcome dendrite formation and side reactions.

While sodium, potassium, and aluminum batteries are already in use, another option is the development of novel metal-ion batteries. Zinc is a key player in this research and an element to watch in the longer-term. Zinc batteries are intrinsically safer and more cost effective than LIBs. However, they have two major problems:

1. Dendrite formation which threatens the cycling stability
2. Side reactions which shorten the battery lifespan

These issues mean that zinc batteries in their current state are not a viable alternative to LIBs, despite their financial and environmental advantages. However, recent research has made interesting progress. Since dendrite formation and side reactions are a consequence of the zinc cathode reacting with the water in the aqueous electrolyte, the use of highly concentrated or non-aqueous electrolytes has been the focus of research. Unfortunately these alternative electrolytes bring new challenges in the form of increasing costs, low ionic conductivity, and safety concerns.

Recently, the design of the $Zn(BF_4)_2$/EG electrolyte for use as a non-flammable, hydrous organic electrolyte in zinc batteries was shown to have high efficiency under a wide range of temperatures. The electrolyte combines a hydrated $Zn(BF_4)$ salt with ethylene glycol and manages to suppress dendrite formation and side reactions. This kind of progress promises to position zinc batteries as a serious contender to LIBs in the future.[16,17]

Long-term option: Manganese cathode development offers an alternative to cobalt use.

Creating batteries which do not rely on cobalt is arguably even more pressing than lithium replacements. This is due to the scarcity and supply chain stability issues surrounding the metal. Luckily, there is a clear frontrunner here for battery developers to target: manganese.

Manganese is generally considered the element of choice for replacing cobalt, and has shown great versatility with promise in lithium, sodium, and potassium-ion batteries. Manganese is an abundant metal with low toxicity, so it can avoid the common pitfalls of scarcity and low safety. Unfortunately lithium-ion and sodium-ion batteries adopting the technology have suffered from performance fading issues, making them uncompetitive with LIBs.[18]

Research into overcoming the performance fading of manganese cathodes is a longer-term solution for battery developers moving towards sustainability. Recent studies have produced two novel manganese-incorporating cathode designs that do not show the same performance issues:

1. Changing the cathode topological structure to protect the cathode from lattice oxygen loss by encouraging reversible lattice oxygen redox reactions.[18]
2. A cation-engineered surface on KMnF electrodes to tune the redox properties and reduce distortion and the dissolution of Mn^{2+} ions.[19]

Optimize battery performance

Increasing the performance and safety of LIBs is another way developers can step toward battery sustainability. Improving performance can extend battery lifespans and reduce energy wastage, creating longer-lived and less wasteful batteries.

Near-term option: Increasing LIB performance is key for large-scale energy storage.

Improving LIB performance is most important when talking about large-scale energy storage for renewable energy. While LIBs are widely used for small, portable electronics, scaling them up to the large batteries needed for sustainable energy storage comes with a huge price tag. Companies including Tesla, Samsung, and LG are racing to reduce manufacturing costs of LIBs to corner the large-scale energy storage market. The world's largest battery energy storage facility is based in the U.S. and sets the scene for LIBs to be a practical solution for the future of large-scale energy storage, with a capacity of 730MW.[10,20,21]

Near-term option: Flow batteries enable large-scale energy storage for stationary applications.

It's not just LIBs which are likely to be in demand in large-scale energy storage, though. Flow batteries, an increasingly popular technological alternative to LIBs in the industry, offer longer life cycling than LIBs as well as lower costs and increased scalability. These advantages are especially important to large-scale energy storage and will likely result in increased demand.[10,16,22]
Flow batteries work by an electrolyte flowing through a power cell where chemical energy is converted to electrical energy. Currently there are three flow battery chemistries in use for large-scale energy storage:

1. Sodium bromide (NaBr) from Regenesys, UK
2. Vanadium bromide (VBr) from VRB Power Systems, Inc., Canada
3. Zinc bromide (ZnBr) from ZBB Energy Corporation, U.S.

Vanadium redox batteries (VBRs) have been most extensively developed in China, where they currently account for just under 1% of large scale energy storage, and have been successfully implemented in wind farms.[10]

Since flow batteries have a relatively low energy density and a large footprint, they are not competitive for portable applications. However, for stationary large-scale energy storage, they offer a more sustainable alternative to LIBs due to:

- The use of a vanadium-based electrolyte that is more environmentally friendly than LIB components.
- Increased safety over LIBs.
- Increased lifespan of ~30 years compared to ~8 years for LIBs.
- A hypothetically unlimited life-cycle by adding electrons to the battery.[23]

Long-term option: Solid-state LIBs promise improved performance of today's technology.

Promising improved safety, decreased performance deterioration, and increased energy density, the development of solid-state LIBs has dominated the most recent patents. Alongside offering increased performance, solid-state batteries also remove the need for a liquid electrolyte, eliminating the risk of toxic electrolyte leaks from batteries.[24] In 2023, there was an influx of solid-state battery patents including:

- Mechanical milling to form crystalline Li_6MgBr_8 [25]
- A novel method to manufacture an all-solid battery electrode[26]
- A gelable system to create a solid-state LIB[27]

While still in development, solid-state batteries represent an opportunity to jump forward from current LIB performance.

Long-term option: Battery sensing technology is key to optimizing current technologies.

It is not just the physical battery chemistry which matters in optimizing battery performance. To truly understand how to make batteries sustainable we must first understand where current battery performance is falling short. The development of more accurate battery sensing technologies is one answer to this.

Fiber optic sensing techniques present an opportunity for the development of sophisticated battery sensing systems, which will give rise to large quantities of data. This data can increase our understanding of battery performance and quicken the pace of novel battery chemistry development.[28]

Improve recyclability

Increasing demand for LIBs, along with government regulations around recycling targets, makes it impossible for the industry to continue working under the disposable model for LIBs. In the EV sector, for example, manufacturers offer a warranty of eight years on their batteries. This creates both a constant demand for battery replacement in EVs and a substantial waste problem. Under current regulations, this battery waste will need to be recycled. Thus, research has invested into reusing, repurposing, or recycling LIBs to create a more circular life-cycle.[1,6,8,29,30]

Near-term option: Reuse and repurpose LIBs.

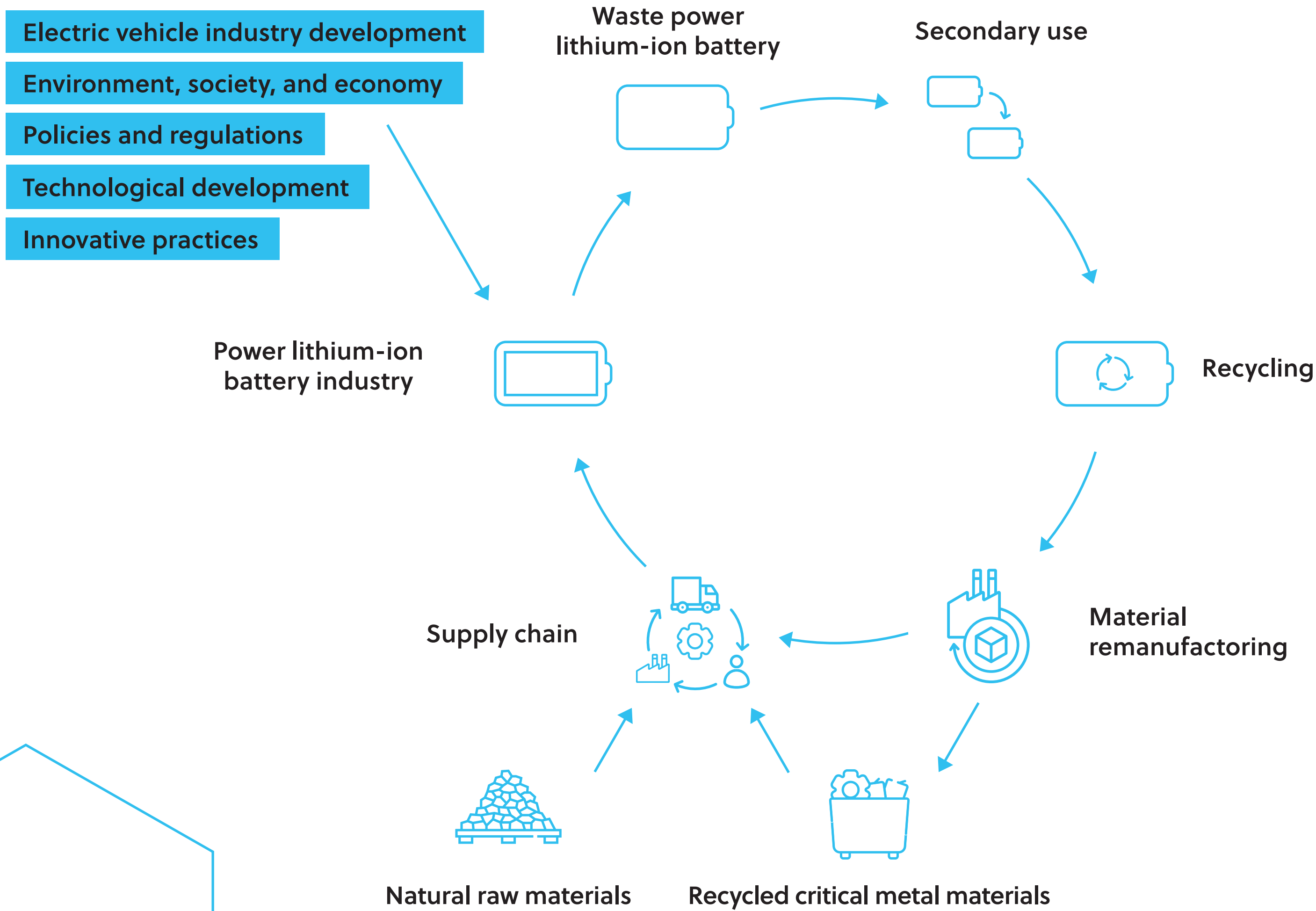
Before recycling, many LIBs (especially those from EVs) can be reused in an application where battery performance is not as critical. Reuse is an option that can be implemented immediately with little to no development. This repurposing of batteries could create a revenue stream of value which could even be channeled back into recycling costs.[1,6,8,29,30]

Long-term option: Establish novel recycling methods and pipelines for LIBs.

The LIB recycling industry is currently small in comparison to the production industry, but it is expected to grow rapidly in the coming years. In 2019, the U.S. Department of Energy announced the opening of their Battery Recycling R&D Centre along with a LIB Recycling Prize totalling $5.5 million. Government investment of this kind will help drive the growth of battery recycling R&D.

As there is currently no standard for recycling LIBs like there is for lead-acid batteries, the development of new recycling pipelines is needed to both handle the large quantities of waste LIBs and encourage consumer recycling with easier access.[1,31]

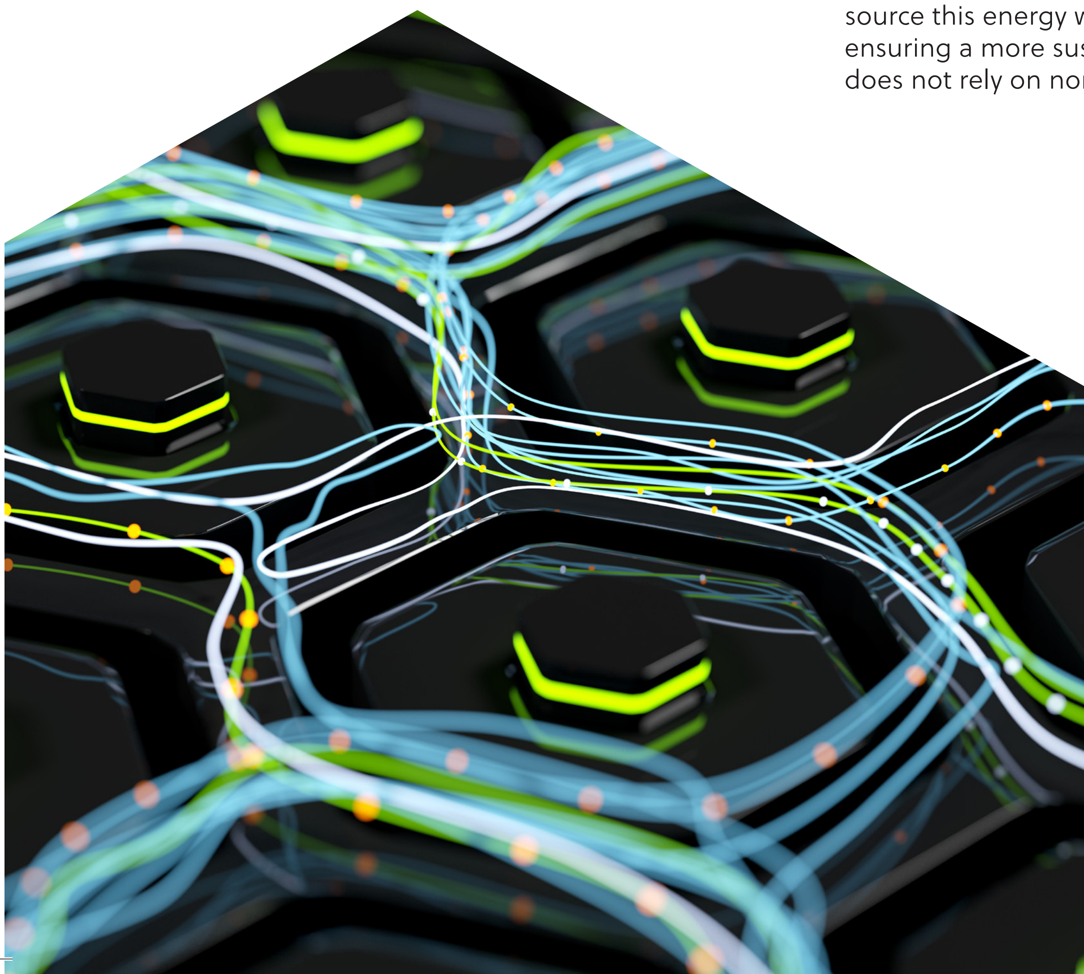
Recycling opportunities in the LIB lifecycle



In addition to developing the recycling pipeline, novel recycling methods can be incorporated for higher recovery yields and decreased environmental impacts. New technologies for recycling cathodes that contain cobalt and lithium are of particular interest. Recent developments in lithium and cobalt recovery include:

- Using deep eutectic solvents yielding leaching efficiencies of over 90% for both metals.[2]
- A novel ultrasonic enhanced leaching process for an efficiency of over 98% for both metals.[32]
- An improved oxalate process with hydrogen peroxide which reduced energy consumption and environmental impacts and increased cost effectiveness.[33]
- Early development of an electrolysis-based

  approach to cathode metal recycling recovered over 50% of $LiCoO_2$ from spent mobile phone batteries in a single step. This process has the added advantage of not needing the harmful chemicals or high temperatures usually required for cathode recycling.[34]
- The application of vacuum metallurgy for in-situ lithium recycling which resulted in a recovery rate of over 80%.[35]



Refine manufacturing processes and supply chains

Battery developers also have the opportunity to increase sustainability in their manufacturing processes and supply chains for LIBs. The source of lithium and energy consumption for cell manufacture are key moments in supply and manufacturing where more sustainable choices are possible.

Near-term option: Source lithium from filtering geothermal waters.

Lithium in LIBs is usually obtained by mining with vast quantities of water in Argentina or Chile or exposing material to high temperatures in China or Australia. These processes contribute to the unsustainability of LIBs with the excess use of water and energy. Recently, more sustainable ways to source lithium have been piloted in the UK and Germany, including filtering from geothermal waters. Sources like these can help battery developers make the most sustainable LIBs which will be more competitive in the market and avoid sanctions from global regulations.[7,36]

Long-term option: Reduce manufacturing energy needs and use renewable sources.

There is convincing evidence that energy cell manufacture has reduced its energy supply needs drastically over the last decade. However, by increasing energy efficiency and improving production processes, manufacturers could further reduce their energy costs. Factories could also consider replacing fossil fuels to source this energy with renewable energy options, ensuring a more sustainable manufacturing process that does not rely on non-renewable energy.[6]

Next steps

With a global push toward decarbonisation of transport and sustainable energy storage solutions, the battery industry is expected to see unprecedented growth in the next decade.

Leading governments across the world have made battery sustainability a priority and have been introducing increasingly tight regulations surrounding how batteries can be produced and raw materials sourced. This will force developers to move toward sustainability to remain competitive in those markets. As the need for sustainability continues to grow, battery developers will need to:

- Invest in chemistries using cobalt alternatives such as manganese cathodes.
- Ensure lithium is sustainably sourced or perhaps replaced altogether by sodium, potassium, or zinc chemistries.
- Create closed-loop battery recycling life-cycles.
- Optimize batteries for increased safety, energy storage, and performance.

A combination of these approaches will help lead battery chemistry into a new era of sustainability.

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