CONSORTIUM FOR
BATTERY
INNOVATION

A Technology Roadmap for Advanced Batteries

+ TECHNICAL NEEDS AND PERFORMANCE IMPROVEMENTS REQUIRED FOR 2035

+ Contents

1.1

Who is CBI?

The Consortium for Battery Innovation (CBI) is a global research organization for the battery industry. Our member companies consist of end-users, battery manufacturers, suppliers, research institutions, and universities. CBI conducts research on behalf of the industry, focusing on how to improve lead batteries and other technologies in various applications.

CBI undertakes a wide array of research initiatives focused on enhancing lead battery performance across multiple applications. These projects collectively represent an investment of $1.65 million per year and address critical performance and cost-efficiency challenges in these segments.

In addition to current programs, CBI membership grants access to a comprehensive archive of **35 years of technical research,** representing over **$50 million** in cumulative R&D investment.

By joining CBI, companies ensure they remain on par with key industry competitors—who are already leveraging consortium membership for strategic advantage.

The CBI Battery Roadmap focuses on the role of relevant technologies in various applications, describing the advantages, necessary improvement areas, and how applicable battery types align with the technical needs within an application. CBI believes in matching the best battery technology to the application, taking a holistic approach when looking at battery technology.

1.2

CBI Battery Roadmap: Expertise from Trusted Sources

The CBI Battery Roadmap market analysis is based on market reports from reputable sources such as KPMG and Avicenne Energy, focusing on well-established battery technologies, lead and lithium-ion. Zinc, flow, sodium, and nickel-based technologies are currently niche or exploratory. These technologies will be discussed when relevant.

Information on the markets, battery technology, application needs and engineering, and the performance indicators to focus on within each application were gathered through interviews and information gathering from CBI member companies, end-users, and representatives from the United States Department of Energy (DOE) and EU Energy Commission.

Furthermore, literature from reputable institutions like Pacific Northwest National Laboratory, IRENA, IEA, and EASE were used in the Energy Storage System (ESS) battery section.

Thank you to our CBI members who contributed to the Roadmap: Advanced Battery Concepts, Amara Raja, ArcActive, Banner Batterien, Black Diamond Structures, C&D Trojan, Clarios, Crown Battery, CSB Battery, East Penn Manufacturing, Enersys, Exide Technologies, GS Yuasa, Hammond Group, Hollingsworth&Vose, Hoppecke Batterien, Leoch, Luminous, Moll Batterien, Moura Group/ITEMM, Schweitzer Engineering Laboratories, SiliconJoule, Stryten Energy.

Thank you to the consultants who contributed to the Roadmap: Geoffrey May, Eberhard Meissner, Francisco Trinidad, Boris Monahov, and Eckhard Karden.

Thank you to East Penn, Gravita India, GS Yuasa, Hoppecke, Moura Batteries and US Battery for supplying the images used in this Roadmap.

CBI Members

- Abertax Technologies
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- Moll Batterien
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The Battery Industry Today and Moving Forward

This document uses publicly available information on macro-market trends and supportive market analyses from premier organizations in battery volume and demand forecasting, specific technical feedback from institutions such as the US DOE and EU Energy Commission (JRC) and gathered information and expertise from battery manufacturers and end-users around the world. In-depth information on lithium-ion, lead, zinc, nickel, and flow battery technologies are covered, including key performance indicators, necessary research areas, and state of the art.

Across the six applications, competitive technologies are described, below in Table 1 is an overview of the technologies covered in each application.

Automotive (Micro-hybrid, start/stop and Auxiliary)	Lead, Lithium, and Sodium batteries
ESS	Sodium, Zinc, Flow, and Lead Batteries
UPS	Lithium, Zinc, Nickel, and Lead Batteries
Telecom	Lead Batteries
Motive Power	Lithium and Lead Batteries
Low Speed Electric Vehicle (E-bike, E-rickshaw)	Lithium and Lead Batteries

Table 1. The battery chemistries discussed by application

The explosive growth of the lithium-ion industry, based on the ongoing strong industrialization push from China, has put the global battery industry (including the Chinese market) under pressure. Figure 1 shows the growth of the entire global battery industry.

The glut of lithium-ion capacity has driven the cell price to historic lows, with cells well below $100/kWh. At the same time, regional tax incentives are lifting up battery manufacturing in the US and Europe, financially bolstering current manufacturing. In large markets such as the US, tariffs are stimulating onshoring as well, disrupting legacy supply chains and establishing instability in applications including UPS for data centers and ESS. European battery markets are coalescing under new regulatory frameworks and a renewed industry support effort from national and EU government bodies. Indian battery manufacturers have experienced unparalleled growth, with lead and lithium-based battery production increasing at the fastest rate worldwide.[1]

Despite strong government and economic drivers, costs and pricing from manufacturers outside of China will be impacted by the current highly competitive battery market. This Roadmap describes the types of improvements and requirements for batteries should consider for further developments and innovation.

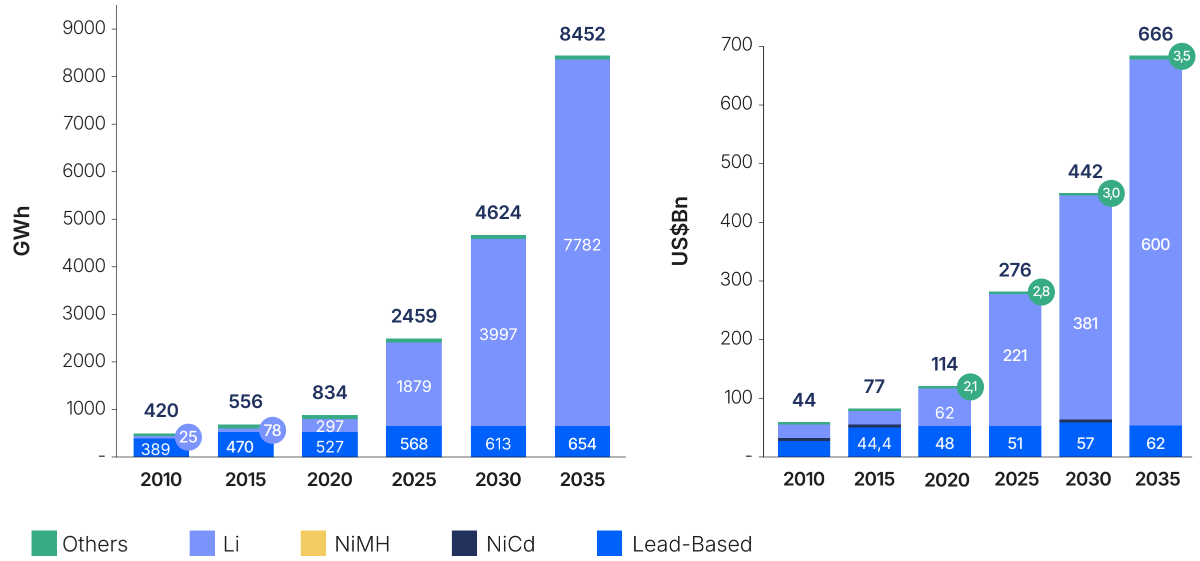


Figure 1. The global battery industry market by GWh and by value in USD Billions. The others category is flow, Zn-based, and sodium-based. Source from Avicenne Energy 2025.

The battery market has expanded and changed dramatically since the last CBI Roadmap four years ago, with the continued evolution of policies, supply chains, and manufacturing drastically changing the battery landscape. This Roadmap has historically focused only on the research areas, performance indicators, and market drivers for lead batteries, a robust and sustainable rechargeable battery solution.

Figure 2 shows the global battery market for lead batteries, with steady growth in many applications and explosive growth in auxiliary battery markets.

The Roadmap document also looks at the entire battery market for each of the major applications discussed: automotive (start/stop, micro-hybrid and auxiliary), ESS, Uninterruptible Power Supply (UPS), telecom, and low speed electric vehicle (motive power, e-bike and e-rickshaw). Furthermore, in order to fully understand the battery market and battery needs globally, a multi-technology approach has been used, focusing not only on lead batteries, but the contributions and required improvements for lithium-based, zinc-based, sodium-based, and in some cases nickel-based and aqueous flow batteries.

Evolution of lead battery market demand (Global, GWh)

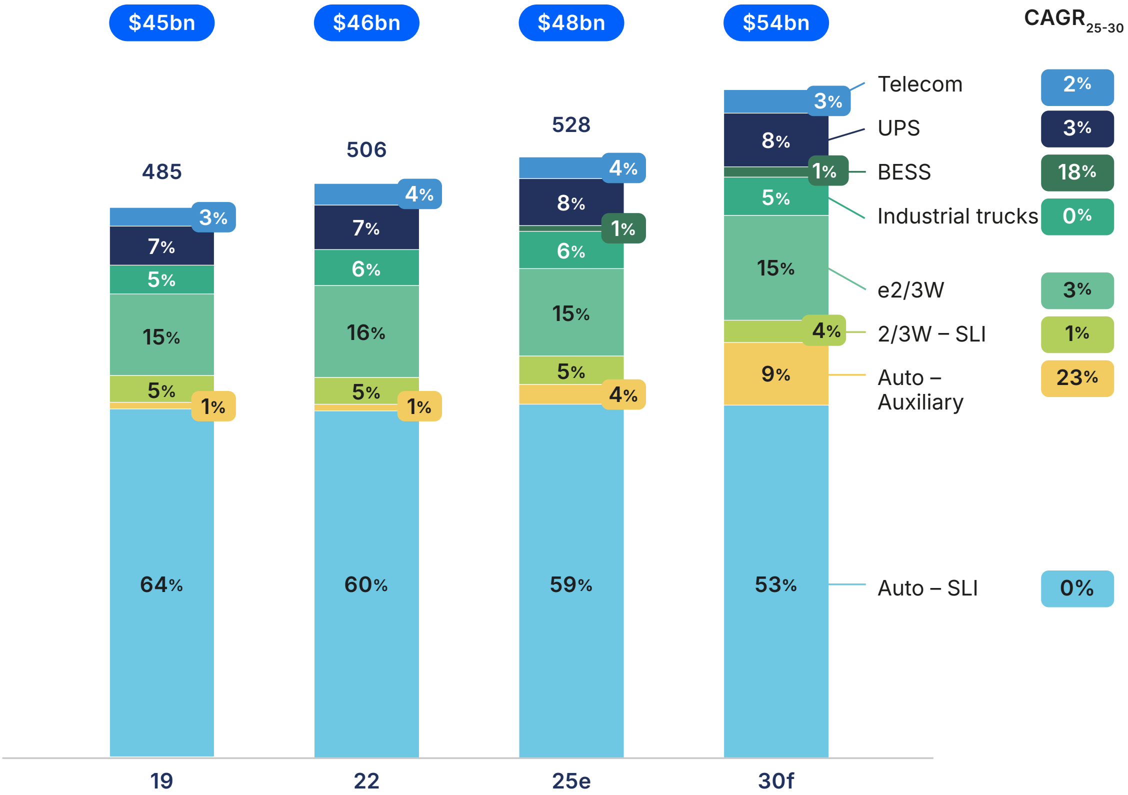


Figure 2. The global lead battery industry accounting for the major markets. Auto auxiliary applies to safety batteries for EV and secondary 12 V batteries for ICE. Source from KPMG 2025.

CBI uses our Roadmap not only as a resource for our members, but the outlined market directions, research areas, and key performance indicators directly influence the research our membership chooses to fund and pursue. In the past three years, 16 research projects have started with 8 ongoing. Table 2 below shows a summary of the topics and contributors, and research progress reports and findings are available to our member companies.

Research Area	Partners	KPIs
Use of bipolar batteries in residential applications	SiliconJoule®, Electric Applications Incorporated	System optimization, cycle life
Effect of $BaSO_4$ additives in ESS lead batteries	Hammond, East Penn, Eclipse Energy	Cycle life
Opportunity fast charging	C&D Trojan, EAI	Energy throughput, opportunity charging
In-situ analysis of lead battery materials	UNT, Ecobat, East Penn	Charge efficiency
Magnetic field monitoring	Villanova University	Cycle life
Metal silicate additives	Hammond, BAS, East Penn	Charge recovery, PPC, CCA
PAM and NAM variations	Fraunhofer ISC, Moll, Karden	Charge recovery, PPC, CCA
PAM additives	Jinkeli Power Technology	Cycle life
Mechanical properties	Villanova University	Cycle life
Electrode integrity	Black Diamond Structures, University of Texas	Cycle life
Charge operations in BEVs	Combatec, Karden	Charge recovery/efficiency
Charging strategies in BEVs	Röttger, Karden	Charge recovery/efficiency
Battery sizing tool	BatterieIng, Karden	PPC
Data analysis of Aux batteries over lifetime	Villanova University, Karden	Charge recovery, PPC
Analysis of discharge plateu uplift/pseudo-capacitance during charging	UL, Karden	Charge recovery
Reverse charge regulation	Combatec, Karden	Charge strategy

Table 2. Concluded and ongoing CBI Technical Program projects.

Progress since last Roadmap

In the last five years, since the last CBI Roadmap was released, lead batteries have innovated in step with other competitive technologies, pushing to higher service life, faster recharge times, and more energy throughput over life.

1. In safety critical applications for nuclear power plants, lead batteries are the only option. Lead battery producers have employed new state of the art devices prolonging the excellent operational life even further. CBI has worked with nuclear governance authorities to make them aware of the continued improvements from lead batteries.

2. Low voltage (12 V) automotive batteries have continued to improve. In micro-hybrid applications, quality and performance have increased, and the advanced products of 2021 are now commonplace in the market with lead battery producers leading the market.

3. For auxiliary applications, the automakers and battery producers have developed new understanding of the interplay of the main traction battery, the auxiliary battery, and sensors, leading to better systems solutions and longer service life.

4. Lead batteries for ESS have changed significantly, and CBI has developed innovative battery management protocols and systems engineering available to member manufacturers now. However, 99% of the ESS market is lithium-based battery systems mainly using NMC and LFP. Flow, sodium, and zinc technologies are currently being explored, but have no appreciable market presence. Lead is still an important technology for off-grid solar.

5. AI data centers, financial institutions, telecommunication networks, and substations use advanced Absorbent Glass Mat (AGM) and gel lead batteries. These batteries offer world class service life unparalleled by any other technology. Since our last Roadmap, our members have benefited from reports outlining new duty cycles, new devices developed in the industry to prolong life, resulting in added years to service life. Currently 70-75% of this market is met by lead batteries, with lithium-based technologies forming the rest of the market. There are instances of Ni and Zn based technologies in data centers, but they are currently not being used in significant amounts.

6. Motive power lead batteries have adapted quickly to the continuous use profiles needed in e-commerce warehousing. Advanced lead batteries with lower maintenance and faster opportunity charging are now present, a new development since the 2021 Roadmap. Lithium and lead act as equal market players now, and improving the total cost of ownership in the market is important for both battery technologies.

CBI Tech program and lead battery manufacturing improvements

5X Better Recharge Capability
0.4 → 2.0 A/Ah

3X Increase in Cycle Life
1500 → 4500 Cycles
10 → 15 Years

+40% Increase in Energy Density

Key lead Battery Energy Storage Systems (BESS) R&D to unlock their full potential:

+ **Decreased Levelised Cost of Storage**

Increase cycle life & utilization of lead batteries to reduce total cost of ownership and levelized cost of energy storage (LCOS).

+ **Standardization**

Create a standard for the different lead BESS systems, to improve their compatibility, decrease overall costs and increase adoption

+ **Advanced Monitoring**

Enhance lead-based BESS with advanced monitoring capabilities to boost battery cycle life and performance, on a par with lithium battery standards - compensating for the historical lack of needed monitoring.

Figure 3. Summary of the performance improvements for lead battery products over the last five years.
Source: Battery Energy Storage Systems (BESS) 2035 Market Outlook and Opportunities, KPMG, 2025.

2 Automotive Batteries: ISS/Micro-hybrid and Low Voltage EV Batteries

Current State of the Automotive Lead Battery

Over the past four years (2022-2026), the CBI innovation Roadmap (2022 version) has been the foundation for funded projects – helping direct research in our program and in the industry. Clear 2022 goals for the industry were set out regarding advanced lead batteries for start/stop (ISS) and micro-hybrid use. These include:

Dynamic Charge Acceptance (DCA)
A value of 1.5 A/Ah

High Temperature Durability (SAE J2801)
18 Units

Water Loss (EN)
Less than 3g/Ah

PSOC Cycle Life
2000 EFB

Innovations in carbon additives have pushed the boundaries of DCA, cycle life, and capacity over the last twenty years. In the past several years, Fraunhofer ISC has developed key insights into the impact of carbon additive properties like external surface area and micropore volume on the DCA enhancement offered by carbons. Ongoing research with Fraunhofer ISC and Wroclaw University of Science and Technology is adding to an increasingly detailed understanding of the intrinsic properties of carbon that contribute to performance enhancement. The focus of the current research is looking at the impact of functional groups (amides, amines, ketones, aldehydes, esters) on KPIs. Carbon additives contribute strongly to DCA improvement, and an understanding of carbon has resulted in measured DCA values in prototype products up to 1.0 A/Ah.

Lead batteries must operate in the extremes, from -30 to 100 °C, and high temperature durability is important for automotive batteries. AGM and Enhanced Flooded Battery (EFB) batteries are tested routinely in SAE J2801 and High-Temperature Endurance (HTE) testing, and major strides have been achieved in terms of durability. New materials, optimized additives, and novel battery grids have inhibited lead battery failure modes associated with high temperature operation. Advanced lead batteries routinely hit 15-18 units in the SAE J2801 and 20-25 units in the HTE.

ISS/micro-hybrid applications are a target for development; however, there are new avenues for 12 V lead battery technology in automobiles. Functional safety and other auxiliary battery functions are important for all types of vehicles including Full EVs, autonomous driving, steer assist, drive assist, and other advanced functions – and CBI is stimulating collaboration amongst OEMS and battery manufacturers to produce better understanding of the requirements necessary for auxiliary batteries. The starting lighting-ignition (SLI) and ISS/ micro-hybrid markets are largely stagnant now in Europe and have slowed to 2-3% CAGR in the US. Growth is higher in areas such as India and Northern Africa. However, 12 V automotive markets have diversified with the growth of auxiliary battery markets, stabilizing the decrease of lead battery growth. Auxiliary battery markets have several key segments and can be classified into three main uses as defined by IEC 60095.

The market in total, while a much lower revenue and volume market in 2026, is set to grow at the same pace as the EV traction market. Auxiliary batteries are the main solution to providing safe and critical operation of the vehicle when the main high voltage powernet is compromised. ISO 26262 and Automotive Safety Integrity Level (ASIL) levels require these kinds of solutions with 12 V lead batteries currently being the solution of choice versus another battery, DC-DC converter, or integrated solution. The market growth is approximately 20% CAGR, and this document will discuss the performance goals and research areas for keeping lead batteries competitive in this market space.

Currently in 12 V automotive applications, the market is still over 95% lead, with approximately 5% from lithium. Lithium adoption has slowed in the last two years, due to cost considerations and slowing penetration in auxiliary markets. However, lithium and sodium batteries offer superior service life and recharge capability. Sodium-ion, typically using Prussian blue or white, has been in development for several years. BYD and CATL have developed sodium ion analogs applicable in the heavy truck and EV market. The major area of development for sodium and lithium 12 V batteries is strengthening performance at low temperatures. Cold crank performance below 0°C is limiting the ability of these battery types to be used in conventional 12 V powernets.

Legend: Poor [red] [orange] [yellow] [green] Strong

	Cyclic Performance	Low temp. performance (up to -20°C)	High temp. performance (up to 60°C)	Cost	Safety	Recyclability[1]	Standardized Test Maturity	Battery Regulation
Pb-based AGM/EFB	[yellow]	[yellow]	[yellow]	[green]	[green]	[green]	[green]	Included
Li-ion: LFP	[green]	[orange]	[green]	[yellow]	[orange]	[red]	[green]	Included
Na-ion: Prussian blue/white	[yellow]	[green] [2]	[yellow] [3]	[yellow]	[green]	Experimental (lab scale)	Under Development [yellow]	Not included yet
Na-ion: Metal oxides	[green] [4]	[yellow]	[yellow]	[yellow]	[green]	Experimental (lab scale)	Under Development [yellow]	Not included yet
Na-ion: Polyanionic	[green] [5]	[green]	[green]	[orange]	[green]	Experimental[6] (lab scale)	Under Development [yellow]	Not included yet

Table 3. A current comparison of the technologies currently being developed for use in 12 V automotive applications. The performance and technical comparison will change as sodium ion technology matures.

1 Recyclability is based of not only the rate, but the use of Pb, Li and Na in resulting batteries. Li and Na are on track to follow Battery Regulation in the EU, but do not currently use secondary Li or Na at mass scale in batteries.
2 This type is often tested at -40°C and it faces challenges to be recharged at low temperatures. The vehicle requires an additional heating unit for the battery recharge.
3 Na-ion batteries are tested up to 60°C. Their performance at 75°C is currently unknown.
4 Due its high energy density and promising cycling performance, it might be a good candidate for EVs.
5 It provides a promising cycling performance but not better than LFPs and its cost is much higher (may not be suitable for EVs).
6 Na-ion batteries raw-material costs are aimed to be low, which might be a disadvantage for conventional recycling, requiring further study at both lab and pilot scales.

Sodium ion developments are also occurring within Europe and the US, with lead battery producers like Moll Batterien and Clarios currently developing sodium ion gigafactories. Sodium ion technology is slated to increase to 500 GWh in production capacity by 2030, according to Bloomberg NEF. The sodium ion market is immature and current market forecasts do not reflect the potential of the technology. Decreasing production costs and better BMS integration into low voltage (12-48V) battery packs as well as operational temperature window will be key areas of developments for sodium ion. Furthermore, the ongoing decreases in cost and wide availability and capacity of LFP will be a challenge for any emerging technology, like sodium ion, for low voltage automotive.

Market Forecast: Influence of Innovation

According to the battery market report of Avicenne Energy[2], lead and lithium-ion batteries will remain as the two most important markets in 2030. As seen in Figure 4, the worldwide battery market is expected to reach 4.6 TWh and US$ 440BN in 2030 and 8.4 TWh and US$ 666BN.

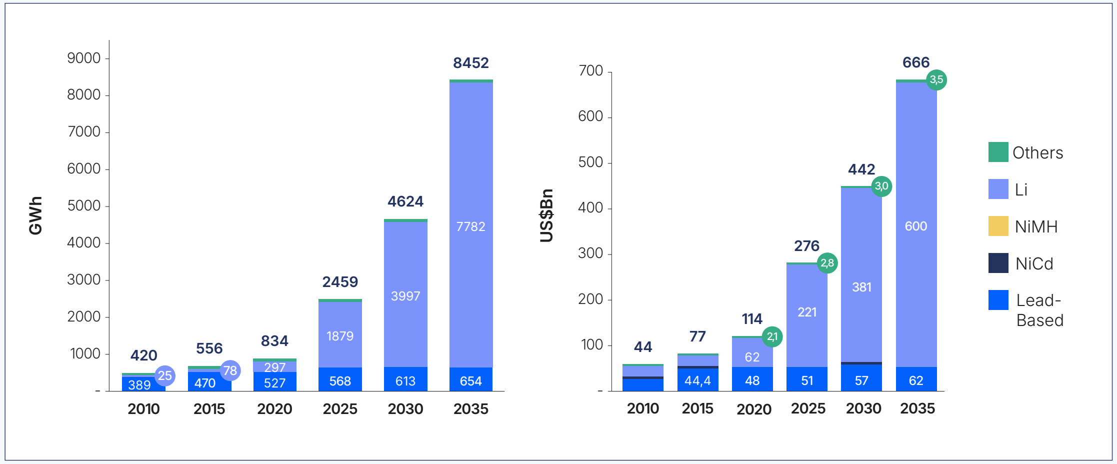


Figure 4.

Avicenne Energy battery market report 2025 showing a) worldwide battery market in value by chemistry in GWh and b) market value at Pack level (including cells, cell assembly, BMS, connectors – power electronics like DC-DC convertors not included) in US$Bn from 2010-2035.

If the lead battery market is focused according to the KPMG market report[3], lead batteries are anticipated to remain a steady presence across various industries. Automotive applications including auxiliary and starting-lighting-ignition (SLI) form around 60% of the market share worldwide, which highlights lead batteries will persist in providing a supporting role particularly for automotive applications. At a global level, demand for automotive battery applications will remain concentrated on internal-combustion-engine (ICE) and battery-electric-vehicles (BEV), in which a distinct decrease for ICE and remarkable increase for xEV by 2030 can be seen (Figure 5). Considering the battery breakdown in regions, China is expected to hold the dominant position in the EV market in terms of sales and production. Emerging markets like Thailand, Vietnam, India, and Brazil are witnessing a swift rise in EV adoption, indicating an expanding worldwide demand for EVs. Meanwhile, in Europe, the automotive market growth is anticipated to be fuelled by xEV, with a particular focus on BEV, especially for Europe. However, the current global political climate has resulted in a significant cooling in EV adoption in the last six months.

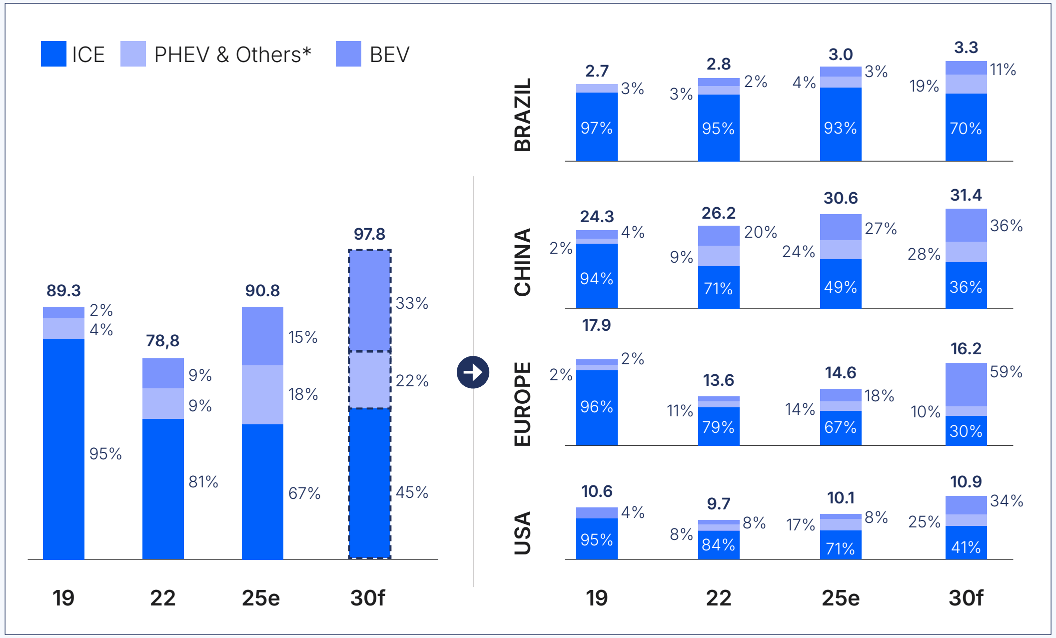


Figure 5.

KPMG battery market report highlighting passenger and commercial vehicle production by powertrain and by region in million units from 2019 to 2030.

As seen in Figure 6, lead batteries are forecasted to lose market share compared to other battery technologies, this is mainly due to the buildout of BEVs. Despite this prediction, demand for lead batteries is still foreseen to grow at a 2% CAGR between 2025 and 2030. Vehicle electrification is significantly increasing battery content per car, exemplified by Mercedes' integration of up to three non-traction batteries in its latest luxury sedan models. In response to uncertainties surrounding tariff policies, automotive OEMs are reassessing the role of lead-based technologies to mitigate supply chain risks.

Automotive industry leaders announced an interest in lead-based solutions, particularly for auxiliary applications, where forecasts expect lead batteries could account for 80-85% of future demand.

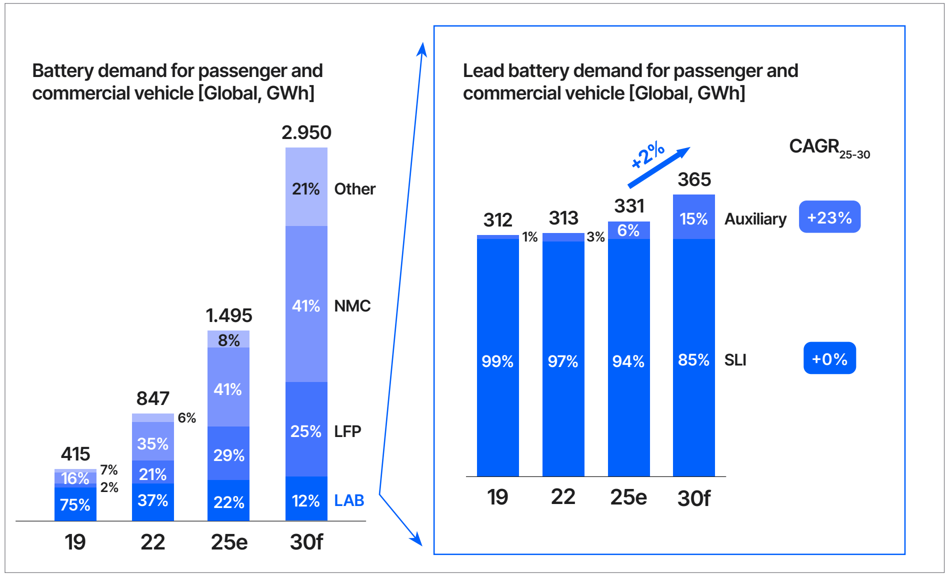


Figure 6.

KPMG battery market report showing battery demand for passenger and commercial vehicle in GWh from 2019 to 2030. Others is defined as a mix of sodium ion chemistries mainly Na Prussian Blue/White and their analogs.

The forecasts outlined above highlight a global transition to electric vehicles. As OEMs adapt and expand their portfolios, a significant market opportunity emerges for lead batteries, particularly in applications where safety, cost-effectiveness, and well-established production and recycling processes are crucial for creating stable supply chains. Electric vehicles typically use two different types of batteries, traction and auxiliary. In terms of auxiliary batteries, 12 V lead batteries are predicted to play a vital role owing to their reliability and superior performance at low temperatures.

In the 12 V automotive battery market very little penetration from other types of batteries (such as Li-ion) is expected based on the following assumptions:

1. The market consists of both the OEM demand and replacement market. Both of these avenues are heavily reliant on the known low cost of 12 V lead batteries.

2. The main competitive battery type, Li-ion, is heavily utilized in higher voltage platforms (48 V → full electric vehicles). The demand for Li-ion is such[4] that penetration is unlikely due to the inability of Li-ion to meet thermal durability and performance requirements. Sodium ion thermal durability and performance is currently being scrutinized by CBI.

3. The addition of auxiliary batteries to power safety functions in hybrids and EVs, as well as peripheral electronics and infotainment, has resulted in batteries being in the cabin of the car. Crash safety concerns exist for non-lead battery technologies.

Market forecasts for Li-ion penetration in the 12 V automotive market show that there will be minor (~5%) penetration (in market value) over the next ten years. However, there is speculation regarding 12 V Li-ion and Na-ion auxiliary batteries; market trends may change slightly depending on the market capture that occurs from these products. Since 2024, lead battery penetration in the auxiliary market has increased due to supply chain and cost issues related to smaller, lower volume 12 V lithium-ion battery packs, safety issues related to crash testing with non-lead technologies, and the poor low temperature performance of lithium and other battery analogs.

Research Areas for Automotive Batteries

Over the past 15 years advanced lead batteries in start/stop (ISS) and micro-hybrid automobiles have experienced rapid market adoption, resulting in an increase of AGM and EFB use in the global market. However, in recent years, government regulations on CO_2 emissions have driven a shift in the market trends, especially in the EU where BEVs have become a replacement for SS/micro-hybrid.
In 2022, the European Commission proposed strict CO_2 standards, requiring a 55% reduction in emissions from new vehicles by 2030, with the aim of achieving net-zero emissions by 2035[5].

Consequently, this regulatory shift has driven automotive manufacturers to focus predominantly on the development of full EVs rather than hybrid and micro-hybrid technologies because they offer less significant emissions reductions relative to fully electric alternatives. As hybrid vehicles still rely on combustion engines, they do not provide the full decarbonization that EVs do. As a result, automakers faced difficulties meeting the required emission targets by hybrid vehicles alone, prompting a stronger shift toward full EVs. In case of the U.S., EVs are poised to be the dominant application in the future, but micro-hybrids still offer value in the U.S. automotive market.

Furthermore, in certain regions of the world, such as India, the primary focus has shifted towards full EVs rather than hybrid models, leading to a reduction in the market share of hybrid vehicles. (Figure 7)[6].

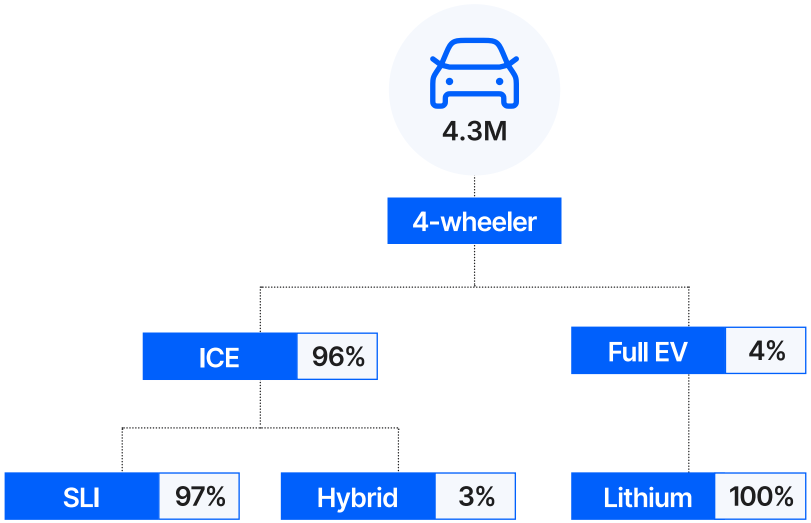
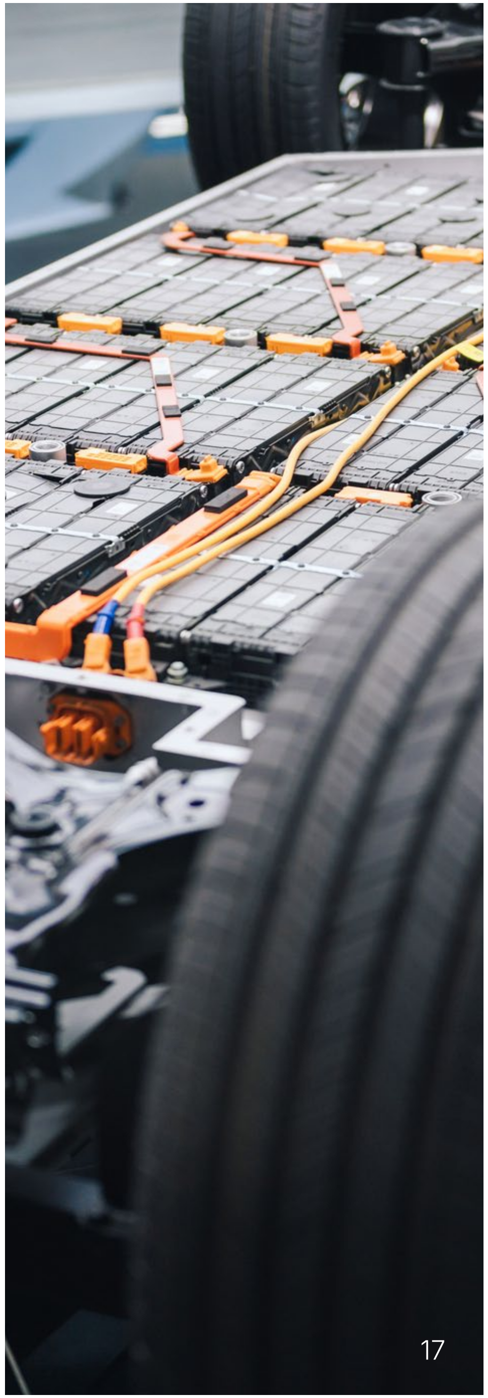


Figure 7.
Indian automotive market breakdown in IEC and full EV.



Despite this shift to full EVs, micro-hybrid applications continue to hold significant market share in areas such as Latin American and Southeast Asia[7] due to several reasons including infrastructure challenges and cost considerations. Therefore, this market segment according to the performance of lead batteries for start/stop and micro-hybrid applications is discussed in the following paragraphs.

Considering start/stop and micro-hybrid applications, the shift of battery design from conventional SLI to AGM/EFB coincides with an evolving understanding of desired performance for 12 V automotive lead batteries. As a baseline, SLI performance is typically described by DOD 17.5% of test methods, cold crank performance, and reserve capacity.

For advanced lead batteries, SLI tests still apply, along with a number of test sequences covered in depth in EN 50342. These tests include:

1. Micro-hybrid performance (MHT)

2. EN 50342:6 – 2015 Dynamic Charge Acceptance (DCA) testing or SBA testing (for initial insights)

3. Endurance in cycle test with 50 % depth-of-discharge (DOD) at 40 °C and preceded deep discharge – as outlined in EN 50342:2015 M1, M2, and M3 classification

However, as lead batteries advance in performance, so too does the demand on the battery. The start/stop function has a demonstrated positive benefit on fuel savings, but this differs depending on the real-life duty cycle, such as an urban or highway driving scenario. Scenario testing is an important methodology for fully understanding innovation for 12 V lead batteries.

Primarily, DCA and capacity turnover enhancements offered by carbon additives to the negative mass are compromised by water loss values measured in testing, such as the protocols outlined in the EN water loss test or the Volkswagen water loss test. Water loss restrictions are valid and based on the premise that energy from the battery is being forfeited in parasitic gassing reactions.

Scenario testing in both urban and highway drive cycles has demonstrated that water loss values are smaller than measured in simple overcharge benchtop testing used by automakers and battery manufacturers.

Ongoing disparity between field and laboratory testing has resulted in test development efforts focused on understanding impacts of innovations across multiple levels, highway/urban, different rest periods, charge sequences, and discharge/charge periods. This new approach to testing has initiated the development of several important test sequences.

1. HTE	2. Ford Run-in DCA
3. Worldwide Harmonised Light Vehicle Test Procedure (WLTP)	

These test sequences are a departure from conventional tests like DOD 17.5% testing and reflect field use more accurately.

Overleaf is a summary of the research priorities for automotive lead batteries, first in start/stop & micro-hybrid and then in auxiliary applications complete with relevant test sequences and descriptions of issues. Additionally, the performance metrics relevant for this market segment are described.

The most important qualitative improvement for ISS and micro-hybrid 12 V automotive applications is to maximize product quality and decrease warranty issues.

Dynamic Charge Acceptance (DCA)

This performance metric is required for energy recuperation function. DCA determines the ability of a battery to accept and store charge efficiently when subjected to rapid and short charging pulses, such as during regenerative braking or engine deceleration. DCA can be determined by standardized tests according to EN and SBA standards as mentioned.

In the past years, there have been several studies working on the improvement of DCA, such as screening of different carbon additives and optimization of negative active material formulations (lignin and carbon). Numerous studies reveal that high carbon content and low lignin concentrations in the negative active mass improve the charge acceptance.

The DCA performance of lead batteries has increased over the last 5 years, although DCA decrease over lifetime is still observed. According to several OEMs and battery manufacturers in Europe, focus is no longer to enhance the DCA values above 1.5 A/Ah, as new vehicles do not require this function.

High-Temperature Endurance (HTE)

This test simulates hot climate automotive service when the battery operates in a 12 V micro-hybrid vehicle with start/stop and brake energy recuperation enabled by alternator control as well as state-of-the-art premium car electric ancillaries. The test includes charge and discharge cycles comparable to those encountered in automotive service. Under such conditions at high temperatures (+60°C), service life of a battery can be expected to be determined typically by positive grid corrosion and positive active material loss. Furthermore, high temperature conditions increase water decomposition which lead to loss of electrolyte.

High-temperature durability can be tested according to the cycle life test at 75°C in SAE standard and HTE test in EN standard. Feedback from battery manufacturers and automakers suggest that 15 weeks is the aim for SAE J2801. For the HTE EN test, 20 units of performance is the goal. These high-temperature tests are often requested by OEMs in addition to their in-house HTE tests.

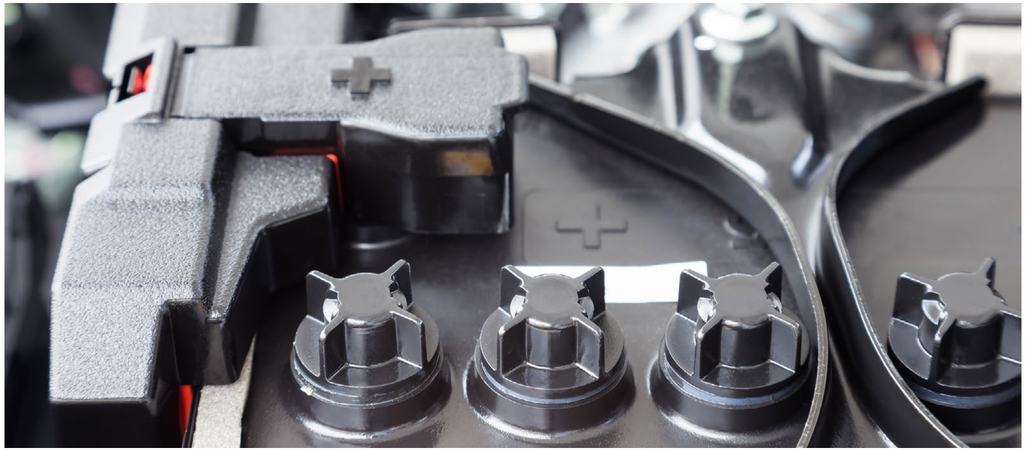
Previous CBI projects have shown that DCA enhancing additives often accelerate the water loss of a battery, which leads to a poor HTE. The subsequent effect is also the accelerated positive grid corrosion. Therefore, a balancing act between charge acceptance and high-temperature performance should be established.

Initial HTE testing of Na-ion has demonstrated strong high temperature durability for Na-Prussian Blue Analogs (PBA). Polyanionic and metal oxide testing is currently underway.

Cold Cranking Ability (CCA)

Cold cranking performance is the ability of a battery to start an engine in cold temperatures. It mainly determines how well a battery can deliver bursts of power in freezing conditions. CCA can be tested according to the IEC 60095-1 and EN 50342-1 standards. This performance metric does not require further optimization. The CCA value of a battery should be in line with OE requirements. Furthermore, while other performance metrics of a battery is optimized or improved, CCA must not be compromised.

CCA is currently being scrutinized at low temperatures by CBI. This includes the testing of lead, Li-ion, and Na-ion at -18°C, -29°C, and -40°C. Initial low temperature testing shows superior capacity retention from lead batteries.



Water Loss

Electrolysis of water in lead battery electrolyte comprises oxygen evolution reaction (OER) at the positive electrode and hydrogen evolution reaction (HER) at the negative electrode; rate of these reactions should be minimized by pure raw materials and proper battery operation. Oxygen gas molecules undergo recombination in AGM (to some extent also with flooded) products, reducing deleterious effects significantly in usual vehicle operation conditions.

Persistent water loss results in dry-out of the glass mat and, in time, of the active material, and increases in acid stratification and acid concentration (with subsequent sulphation). Energy used in OER/HER reactions is energy not being used in charge processes. This relationship means water loss is an indirect indicator of the efficiency of a lead battery. Lead batteries with low water loss most likely are more efficient, and vice versa. In field, start/stop batteries usefulness is dictated by how often the battery can provide the idle stop function. Batteries at peak efficiency provide hybrid functionality as often as possible. Conversely, a high-water loss (above 3 g/Ah) measurement suggests that the battery is spending energy on parasitic processes.

Water loss of a battery can be tested according to EN and IEC 50342 standards. The aim is to keep this value under 3 g/Ah. This is especially requested by for the OEMs based in Europe.

Research topics about water loss are highly concentrated on minimizing metal impurities in the electrolyte as well as in the active material components (such as lead oxide and carbon). Certain metal impurities (e.g. Fe and Sb) are known to accelerate the catalytic activity of the negative and positive electrode surface, which results in an increase of HER and OER. Furthermore, additives improving DCA are also known to intensify the water loss of a battery. Like the HTE, there needs to be optimization to improve certain performance metrics of lead batteries without increasing water loss values.

Key Performance Indicators (KPI) Table

The analysis of battery performance requirements has resulted in the definition of a small number of KPIs, shown below as the main objectives defined by the Technical Roadmap.

Performance Metric	2025-2030
DCA (EN) / A/Ah	1.5
Durability HTE (EN) / weeks	20
Water loss (EN)/g/Ah	<3
Cycle life at DOD 50%	EN 50342:2015 M1, M2 and M3 Classification
End of life (EOL) Internal Resistance (IR)	IR reaching 1.5x original indicates beginning of EOL
CCA (EN)	In line with OE requirements, must not be compromised

Table 4. KPI values for automotive Start/Stop and Micro-hybrid batteries

As seen in Table 4, the KPI values are the same for both 2025 and 2030, as no further improvement is necessary according to the feedback received from several battery manufacturers (BM) and OEMs in Europe and the US. For this market segment, there are no specific requirements stated by OEMs to improve performance metrics for the next years. In case the focus is shifted from EVs to combustion engines, this scenario might push the KPI values. All performance metrics listed in Table 4 are discussed in the previous paragraphs.

It is important to note that BMs are focused on cost reduction and weight savings, rather than solely on improving KPIs for Start/Stop and micro-hybrid applications.

There are two major performance metrics for ISS, high temperature durability (as defined by the impending HTE, WLTP, and SAE J2801) and DCA (as defined by Ford Run-in and EN 50342 – 6:2015, DCApp). All improvements in these two categories must not forfeit the performance of lead batteries in CCA or capacity. Contained in this document are research goals, KPIs, and the status and description of potential research pathways for the following KPIs:

1. Water Loss
2. High tempature durability
3. DCA (Ford Run-in and EN 50342-6)
4. DOD 17.5% and PSOC (MHT) performance

12 V Lead Battery Testing and Duty Cycles

Over the past 15 years advanced lead batteries in start/stop and micro-hybrid automobiles have experienced rapid market adoption, resulting in an increase of AGM and EFB use in the global market. The shift of battery design from conventional SLI to AGM/EFB coincides with an evolving understanding of desired performance for 12 V automotive lead batteries.

As a baseline, SLI performance is typically described by DOD 17.5% test methods, cold crank performance, and reserve capacity.

For advanced lead batteries, SLI tests still apply, along with a complement of new test sequences covered in depth in EN 50342. These tests include:

Micro-hybrid performance (MHT)	EN 50342:6 – 2015 Dynamic Charge Acceptance (DCA) testing or SBA testing (for initial insights)
Endurance in cycle test with 50 % depth of discharge (DOD) at 40 °C and preceded deep discharge – as outline in EN 50342:2015 M1, M2, and M3 classification	

However, as lead batteries advance in performance, so does the demand on the battery. The start/stop function has a demonstrated positive benefit on fuel savings, but this differs depending on the real-life duty cycle, such as an urban or highway driving scenario. Scenario testing is an important methodology for fully understanding innovation for 12 V lead batteries.

Primarily, DCA and capacity turnover enhancements offered by carbon additives in the negative active material are compromised by water loss values measured in testing, such as the protocols outlined in the EN water loss test. Water loss restrictions are valid and based on the premise that energy from the battery is being forfeited in parasitic gassing reactions.

Scenario testing in both urban and highway drive cycles has demonstrated that water loss values are smaller than measured in simple overcharge benchtop testing. Ongoing disparity between field and laboratory testing has resulted in test development efforts focused on understanding impacts of innovations across multiple levels, highway/urban, different rest periods, charge sequences, and discharge/charge periods. This new approach to testing has initiated the development of several important test sequences.

1. New Key Life Test (HTE)
2. Ford Run-in DCA
3. Worldwide Harmonised Light Vehicle Test Procedure (WLTP)

These test sequences are a departure from conventional tests like DOD 17.5% testing and reflect field use more accurately.

Functional safety offered by auxiliary lead batteries

The use of 12 V SLI or ISS/micro-hybrid batteries for safety and support functions on vehicles with higher levels of electrification is becoming more widespread. There are no major technical issues for batteries as such, but better SOH, SOF, and SOC estimation are becoming more important so that battery reliability can be assured when functional safety is essential. Specifically, this section will cover 12 V battery support to ISO 26262. This encompasses SLI, ISS, micro-hybrid, AUX, and any lead battery going into XEVs. The relevant definition for this is as follows:

Battery discharge into a safety-critical load (e.g., electric steering actuators, or autonomous driving functions) makes discharge underperformance a safety case or hazard, as opposed to "only" being a roadside assistance or warranty case, and thereby enforces additional verification by the vehicle OEM and component suppliers of both battery and pole-niche sensor.

There are no special research requirements but as for SLI, EFB or AGM batteries providing safety and support systems, better SOC, SOH, and SOF detection and failure prediction is needed for the highest levels of functional safety.

Lead batteries have provided safe function for hybrid vehicles for over ten years, and the need now is to harmonize SOF/SOF diagnostics to be tailored to specific safety-critical applications (i.e. autonomous driving).

While not strictly areas of battery science-based research, there are key focus areas of concern for 12 V auxiliary lead batteries. The areas include (see Table 5) testing scenario development, and the aforementioned development of the SOH, SOF, and SOC estimation.

Focus Area	Sub-Topic	Design Principles
Test Scenario Development	Benchmark Testing	The standardization of electrical test sequences to measure performance of auxiliary batteries
	Scenario Development	Identification of the load demands on auxiliary systems – functional relationship and response needs from auxiliary battery
Monitoring Methodology	Failure Monitoring	
	Data/Model development for "smarter" or better harmonized diagnostics from sensors – better SOH, SOC, SOF estimation	Moving toward an "off-the-shelf" solution for battery and sensor for multiple applications
Charging Methodology	Models and experimentation on the proper charge procedures for maximizing available capacity of auxiliary batteries in EVs and other auxiliary use.	

Table 5. An outline of focus areas for functional safety, applicable to all batteries. This table describes key topics to cover in auxiliary development and how design principles are influenced at the battery level.

Development of 12 V auxiliary batteries is currently approached through the adaptation of small UPS and automotive batteries, as well as other types, into the application. While functional, this strategy creates deficits in performance areas and high performance for irrelevant performance metrics, such as CCA.

Current progress toward many of these focus areas is being driven by cross-industry information sharing and method development between lead battery manufacturers and automotive OEMs. ASIL considerations have produced highly reliable sensors and redundancies for functional safety purposes. The ASIL approach lacks considerations for accuracy of information gathered by sensors and electronics, and a concerted effort to develop a correct methodology for SOC, SOF, and battery health is necessary.

Development of information on failure mode/incidence rate and scenario testing to understand the different conditions and variables that the system must operate in need are necessary. Failures in Time (FIT) rate information is sparse, and data sharing amongst OEMs and lead battery manufacturers is necessary to understand sudden battery faults.

CBI working groups gather data on FIT rate in micro-hybrid and SLI applications and are working with the industry to understand failure in auxiliary applications.

Lead batteries have clear technical advantages for functional safety, and a major hurdle for the technology is to make sure the advantages are clearly and accurately communicated and understood by the automobile industry. These advantages include (other than low cost):

1. No disconnect
2. Robustness against both overcharging and overdischarging
3. Internal safe bypass reaction
4. Superior low temperature (below -15 °C) performance

Again, these advantages must be continuously communicated, and active collaboration between lead battery manufacturers, supporting electronics (sensors, diagnostics), and auto makers is vital.

The major drive for the increased auxiliary battery market in recent years can be attributed to the growth of EVs. EVs heavily rely on traction batteries, which power the electric motor and provide energy for driving and propulsion, but they also require smaller auxiliary batteries to power non-propulsion systems such as lights, entertainment, climate control, and electronics. These auxiliary batteries are essential for managing energy efficiency and providing power to systems that don’t require the main battery’s full capacity. Additionally, auxiliary batteries can also serve as a back-up to ensure critical vehicle functions including making sure safety-relevant functions remain operational in case of failure of the primary battery or during maintenance periods.

Despite the growing demand for auxiliary batteries, the technology underpinning these batteries remains relatively immature from a product development standpoint. Recent products for this market segment were adapted from the UPS and motorcycle batteries. Before going into details about the performance metrics and standardized tests required for auxiliary batteries, it is worth mentioning the type of such batteries.

Battery Categories

According to the IEC 60095-8, batteries defined for auxiliary or back-up systems can be classified into one of the three categories outlined below:

Category 1

The 12 V central-storage (main) battery in modern vehicles performs a variety of functions typical of automotive battery systems, except for engine cranking for ignition. These functions include supplying power during vehicle idle or parking conditions, enabling vehicle activation and post-operation (after-run) processes, supporting over-the-air software updates, and facilitating transient power delivery and absorption. Additionally, it plays a critical role in voltage stabilization throughout normal vehicle operation.

Category 2

The 12 V backup battery stabilizes voltage and provides emergency power to critical, often functional safety-related, electrical components or sub-systems within the power supply network. These batteries are typically disconnected from the 12 V load when the alternator or DC/DC converter is not supplying power, such as during parking, to prevent discharge. In such instances, the state-of-charge (SOC) is generally maintained within a narrow range, typically near full charge, to ensure optimal performance and longevity.

Category 3

The 12 V auxiliary battery in start/stop and micro-hybrid vehicles stabilizes the system voltage during engine restarts, which are primarily powered by the starter battery. This application is analogous to the back-up battery scenario described above, but with the distinction that the auxiliary battery experiences more frequent discharge during normal operation.

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When discussing 12 V batteries in BEV applications, it is essential to clarify the distinct performance requirements relative to ICE vehicles. In auxiliary and back-up roles within BEVs, engine-start capability (i.e., cranking performance) is no longer required. The batteries are not charged via an alternator but instead through a DC/DC converter, enabling recharge at any time.

Moreover, because installation within the engine bay is unnecessary, the associated high-temperature durability specifications may be relaxed. These application conditions shift the design focus toward hardware reliability and battery monitoring, driven by functional safety requirements. At the same time, 12 V batteries in BEVs are typically downsized while loads continue to increase.

This combination can accelerate failure modes due to high throughput as well as undercharging or sulfation. According to the battery characteristics described, new performance metrics become relevant for lead batteries, outlined overleaf.

Pulse Power Characterization (PPC)

PPC is a power performance test used for auxiliary and back-up applications. As lead batteries for such applications are not used for engine cranking, traditional CCA test becomes irrelevant. Instead, PPC test is used as an indicator of general power performance.

According to the IEC 60095-8, the PPC test involves two different pulse profiles (PP1 and PP2) and is performed at the beginning of life (BOL) and at the end of life (EOL). The test is executed at different SOC levels (full or partial SOC) and temperatures (25°C or -18°C) with respect to battery categories (category 1 or 2 & 3). Voltage requirements stated in the IEC standard (Tables 18-21 of IEC 60095-8) shall be met.

Charge Recovery (CR)

For auxiliary and back-up applications, CR is prioritized over charge acceptance (CA), as the latter does not address power boost. CR is typically measured over time scales ranging from minutes to hours, in contrast to DCA, which involves repetitive charge pulses lasting seconds at 25°C, and static CA test, which is limited to 10 minutes at 0°C. In auxiliary applications, OEMs require testing for both SOF and SOC recovery following prolonged periods of low discharge rates at -18°C.

The charge recovery is the ability of a battery to recover from a discharged condition to vehicle-target levels of both discharge power and energy. New CR test according to IEC 60095-8 directly measures the restoration of power (SOF) and energy (SOC). Quick SOF recovery (discharge power capability) is required for auxiliary batteries due to modern functions such as electronics, assisted steering and braking. Also, such auxiliary batteries need to deliver good SOC recovery to prevent early failure due to sulfation or undercharging. In case of back-up batteries, charge recovery might be a lower priority if they are kept at high SOC levels. Still, battery monitoring is needed to predict the SOF boost after charging operation.

Considering the CR test based on IEC, SOC recovery is measured after total of 1-, 10-, 30- and 120-min charge, in which charge balance is recorded. In terms of SOF recovery, the measurement involves 10 s discharge pulses after defined charge time in which relative voltage uplift is recorded. Table 6 summarizes the characteristics of the new CR test and reveals the differences to the static CA test.

It is worth mentioning that accurate battery monitoring (e.g. voltage) of lead batteries in a vehicle during emergency or high stress conditions such as sudden high loads or electrical faults is essential, as the voltage behaviour is the real-time indicator of battery's available power and overall state. Reliable BMS ensures safety-critical vehicle functions, both SOF and SOC estimation as well as lifetime of a battery. It is known that lead batteries suffer at low SOC especially for extended periods, as lead sulfate crystals begin to grow into larger, are difficult to dissolve. This would lead to a decrease of electrochemical active surface area and increase of internal resistance which results in a limited charge ability and capacity loss. Ideally, a battery should be tolerating these conditions without a rapid degredation including maintaining reversible sulfation and preserving power capability. There is no standard measuring the robustness of batteries at low SOC levels, but the development of a representative test scenario should be considered.

Test Characteristics	New CR test (IEC 60095-8)	Static CA test (IEC 60095-1)
Pre-discharge	at 25 °C: 38% C_n in 7.6 h at -18 °C: 12% C_n in 72 h	at 25 °C: 50% C_e in 5 h
Soak to test-temp. when	before 72 h low-rate discharge	after pre-discharge
Test temperature	-18 °C	0 °C
Charging voltage	15.0 V	14.4 V
Charge test duration	2 h	10 min
SOC recovery	% C_n returned (30′, 120′)	instantaneous current (10′)
SOF recovery	ΔU_{10s} uplift (1′, 10′, 30′, 120′)	not measured

Table 6. Comparison of new charge recovery and static charge acceptance tests

To illustrate the data obtained from the CR test, Figure 8 presents the SOC and SOF recovery profiles of two distinct batteries. The aim is to enhance the total capacity gain for SOC recovery, which is achieved by incorporating carbon additives (Figure 8a). Such advanced batteries also appear to facilitate improved SOF recovery, as observed by the increased voltage uplift compared to the control battery (Figure 8b).

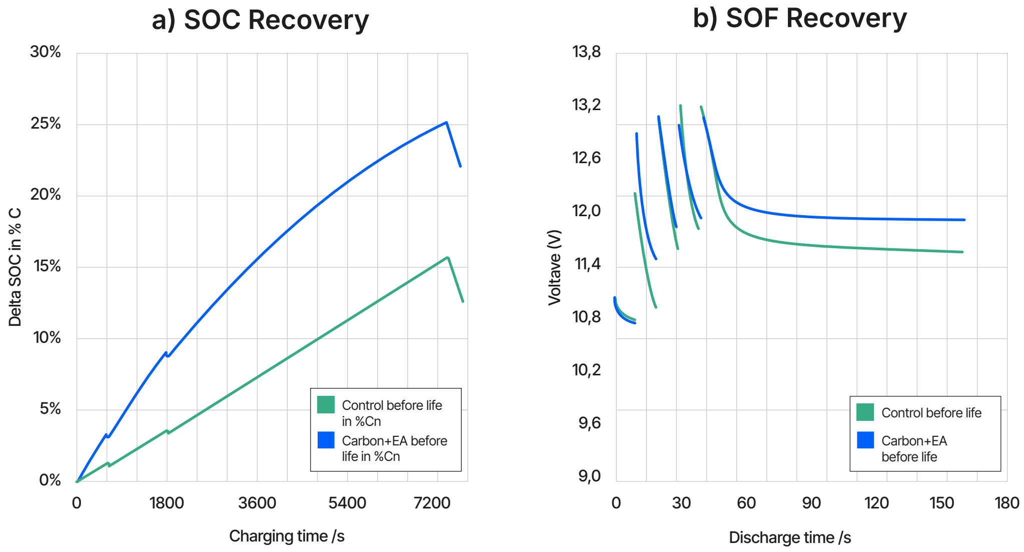


Figure 8. a) SOC recovery; b) SOF recovery of control and carbon containing batteries[8] during new charge recovery test according to IEC 60095-8.

In addition to the standardized CR test previously described, the IEC (IEC TC21X WG2) and ALBA working groups have worked on several CR testing protocols, namely CR-night, CR-weekend, CR-OTA, and CR-month. It is important to note that the CR-weekend test is the standardized version, which was conducted at both 0 °C and -18 °C. For comparison, the CR-weekend results were contrasted with the static CA test at 0 °C. All other CR test variations were carried out at -18 °C.

These tests were performed on various lead batteries, and the results demonstrated a clear dependency but consistent trends for different battery types (inc. JIS, SLI, EFB, EFB+C and AGM), test duration and temperature. Overall, the trends observed were consistent with the static CA test. Detailed results and correlation plots are provided in Annex C of the IEC standard.

The KPI table

KPI table (Table 7) for auxiliary and backup applications is divided into 2025 (current of the state-of-the-art automotive batteries), mid-term (2027) and longer-term (2030) goals. CR and PPC are main performance metrics that require further attention. Charge recovery can be further subdivided into two components, SOC recovery and SOF recovery, as previously described. Both are measured after certain charge time as stated in Table 7. KPI values for SOC and SOF recovery in 2025 are based on the typical performance of the state-of-the-art automotive batteries in IEC WG testing. Considering PPC, the voltage requirements are governed by the battery category and should be followed according to the IEC standard. In addition to CR and PPC, there are other performance metrics to be tested. These are typically regulatory requirements or supplementary tests that do not require further development. For instance, static charge acceptance test is recommended to be tested to compare its characteristics with respect to the new CR test. Further, various tests that are conducted on batteries for ICE vehicles are required for auxiliary batteries as well. Although auxiliary and back-up batteries do not provide the cranking function, it is essential to follow modified CCA test (called CCA-AUX) in the IEC standard due to battery labelling. Moreover, a service life of 7 years is aimed for lead batteries for such applications according to the feedback received from several battery suppliers.

Performance Metric		2025	2027	2030
Research Goals				
Charge Recovery IEC 60095-8*	SOF recovery (1′)	$\Delta U_{10s} \geq 0.2$ V	$\Delta U_{10s} \geq 0.4$ V	$\Delta U_{10s} \geq 0.5$ V
	SOF recovery (10′)	$\Delta U_{10s} \geq 0.5$ V	$\Delta U_{10s} \geq 0.8$ V	$\Delta U_{10s} \geq 0.9$ V
	SOF recovery (30′)	$\Delta U_{10s} \geq 0.7$ V	$\Delta U_{10s} \geq 0.9$ V	$\Delta U_{10s} \geq 1.1$ V
	SOF recovery (120′)	$\Delta U_{10s} \geq 0.9$ V	$\Delta U_{10s} \geq 1.2$ V	$\Delta U_{10s} \geq 1.4$ V
	SOC recovery (30′)	$Q(30') \geq 4\ \%C_n$	$Q(30') \geq 12\ \%C_n$	$Q(30') \geq 15\ \%C_n$
	SOC recovery (120′)	$Q(120') \geq 15\ \%C_n$	$Q(120') \geq 22\ \%C_n$	$Q(120') \geq 30\ \%C_n$
PPC IEC 60095-8	Category 1	Within tables 18-21 of IEC 60095-8 voltage requirements are suggested for PP1 and PP2 pulse profiles conducted at BOL and EOL and at 25°C (BOL) and -18°C (BOL, EOL).		
	Category 2 & 3			
Requirements, no longer need development				
Static charge acceptance at 0°C (IEC 60095-1)		Used as a comparison for charge recovery at 0°C.		
All charge retention, endurance cycling, vibration resistance, corrosion, water loss tests		Conform to requirements in IEC 60095-8.		
CCA - AUX		$U_{10s} \geq 7.5$V; must be on label		
Service life (50% nominal capacity loss or IR increase of ≥ 150%)		5 Years	7 Years	7 Years

Table 7.

KPI values for auxiliary and back-up applications

* For pure backup battery (category 2), charge recovery capability may not be required. In these use cases, the SOC window is higher, and the charging performance is not a priority to improve.

Auxiliary (AUX) battery innovation – Low voltage EV batteries and Additional Power Batteries in ICE/EV

Small (in capacity and form factor) 12 V lead batteries are used in both starting and non-starting functions. Section 2.8 will cover lead batteries that are used for some key safety areas (brake assist, drive assist, starting function) and will encompass AUX, SLI, and ISS/micro-hybrid batteries.

For this chapter, the discussion will be focused on AUX batteries that are:

- A secondary or tertiary 12 V battery in an ICE vehicle,
- Used in a hybrid with another battery that starts the engine,
- Or in a BEV without an ICE.

AUX batteries used in these cases power sound, radio, peripheral electronics, and additional equipment like dash cams and back up cameras. As described above, AUX (E) and AUX (P) products are preferred in these applications. Power is still necessary but not at the level commonly associated with CCA.

Function	Current Status	Research Priorities
AUX (E) battery in xEV (BEV, PHEV, HEV, 48 V) with no engine start function	Reasonably satisfactory, good cycle life needed and performance over a wide SOC window.	Lower priority. Requirements for higher performance at low SOC, better diagnostics for safe and secure operation and standardization as a route to lower costs.
AUX (P) battery for transient load response	As AUX (E) but with high performance at low SOC and fast charge capacity, power performance should be detailed by PSOC type pulses instead of CCA.	

Table 8. Summarizes the status for auxiliary (AUX) batteries

AUX (E) refers to a 12 V lead battery in an electric vehicle which has no engine start function. This can be on a pure battery electric vehicle (BEV), a plug-in hybrid electric vehicle (PHEV), a hybrid electric vehicle (HEV) or a vehicle with a 48 V battery which starts the vehicle so that the AUX (E) battery only supports other 12 V functions.

AUX (P) refers to a battery on a vehicle with a 12 V lead SLI, EFB or AGM battery for engine start, ISS/micro-hybrid capability and other functions which provides power for transient loads for safety and security functions to ensure a redundant power supply. Both types have reasonable performance at present.

AUX (E) batteries need to have a good cycle of life and performance over a range of states-of-charge (SOC). AUX (P) batteries operate more in standby mode and so cycle life is less important, but good recovery after discharge is needed, and the duty cycle will usually require a moderately high discharge rate even at a low SOC.

There are several technical and design goals for this type of lead battery:

Focus Area	Sub-Topic	Design Principles
Productisation goals	Optimization toward energy: Aux(E)	The demand on the battery is based around DC/DC output vs. the need to maintain SOF and power output.
	Optimization toward power: Aux(P)	**Most likely** higher DCA is desired. ~1.5 A/Ah – responsive to quick charging across the SOC window.
	Smaller size	The AUX battery is now commonly placed in the cabin of the automobile or in the cargo space. Matching form factor to placement is key in providing a useful solution. As an example, manufacturing a battery that can provide the desired performance and fit underneath a seat is distinct advantage.

Table 9. Design concentrations for 12 V auxiliary batteries based on the categories covered in IEC 60095-8.

Summary of automotive battery innovation objectives

The principal research objectives for automotive batteries identified in section 1.8 required to meet the KPIs are summarized below (the activities in bold are the highest priorities):

Improve DCA and charge recovery and extend capability to lower temperatures

Understand water loss under cyclic/overcharge conditions to re-specify tests for durability

Increase corrosion resistance of positive grids

Increase intrinsic high temperature durability

SOC/SOH measurement techniques

Development of AUX battery to improve available capacity

Priority innovation areas for automotive batteries

In-depth discussions have identified several promising areas where research efforts should be directed for the current program. It is felt that work in these research areas is most likely to help meet the research objectives and KPIs for automotive batteries.

These are summarized as:

- Optimization of the beneficial effect of carbon in positive and negative plates is important.
- Studies of alternative additive materials (ionic salts, fibers, novel carbons) and their interactions.
- Understanding the effect of different histories (charge, discharge and rest) on DCA and charge recovery by examination of the active mass and electrical performance.
- Further work on how to optimize behavior for different duty cycles, specifically HTE and WLTP.
- Studies of how BMS/SOC/SOH measurement techniques improve charging and battery life.
- Harmonized interfaces and verification methods for SOF/SOH diagnostics in safety-relevant applications as an enabler for cost-efficient commodity solutions that reliably support driver-assistance and autonomous-driving functions.
- Na-ion batteries are relatively new in 12 V and more scenario testing is needed.
- Gas evolution studies should be considered for Na-ion. The strong thermal safety profile is encouraging, but the high under the hood temperatures in ICE vehicles and consistent use may produce gases.

OEM Battery requirements are moving rapidly, especially in Europe.

Overall, OEM battery requirements are moving rapidly, especially in Europe, to meet ever increasing emission standards. Lead batteries still retain most of the market both now and in the medium-term, but Li-ion and Na-ion batteries are getting less expensive. Na-ion shows promise in low and high temperature testing. The requirements are high and stable DCA, PSOC durability with fast SOC recovery to provide stable ISS/micro-hybrid capability over life and lower failure rates in hot climates.

More realistic high temperature tests are a key to improved DCA. More precise SOC, SOF and SOH information are needed for batteries supporting safety and vehicle functions.

Li-ion batteries are always fitted with a BMS and lead batteries need to have a similar capability if they are safety critical.

3 Batteries for ESS used in Utility and Consumer Services

Introduction: Batteries used in ESS

The energy storage market is dominated by lithium-ion batteries, with sodium-ion batteries beginning to emerge as an alternative in some applications. Currently 99% of the global ESS market comes from lithium ion batteries (NMC and LFP).

Lead batteries have demonstrated their ability to perform in a range of ESS applications while both flow and zinc batteries offer alternative chemistries to these more established ESS technologies. According to KPMG, the ESS market will be 864 GWh by 2035, representing the second largest global battery market next to EV battery buildout.

The ESS market represents dozens of individual segments ranging from residential to historical ancillary service markets for utility substations. Table 10 represents the market segmentation from the perspective of twelve broad categories.

This table outlines the need for six different KPIs: response time, discharge time, cycle life, safety, system cost, and power capability. These six KPIs are scrutinized differently within each category, and power capability and cost are the main drivers across all applications. System cost can be broken down and expanded into a much more thorough analysis, looking at not just ESS capital cost, but installation, integration, insurance, operational maintenance, and depreciation due to technical degradation.

These kinds of analyses known as Levelized Cost of Systems (LCOS) have become a crucial lens for viewing the efficacy of a battery technology in a given ESS application.

Criticality assessment of core KPIs for ESS applications

Legend: Weak  Strong

Type	Application		Response Time	Discharging Time	Cycle Life	Safety	System Costs	Power Capability
Front-of-the-Meter	Generation support & bulk storage	Firm capacity	Yellow	Yellow	Yellow	Red	Green	Green
		Demand response	Yellow	Red	Green	Red	Green	Green
		Arbitrage	Red	Green	Green	Red	Green	Green
	Transmission & Distribution	Upgrade deferral	Red	Red	Yellow	Red	Yellow	Yellow
	Ancillary services	Frequency regulation	Green	Green	Green	Red	Green	Green
		Spinning reserve	Green	Yellow	Red	Red	Green	Green
		Non-spinning reserve	Red	Yellow	Red	Red	Green	Green
		Black start	Red	Yellow	Red	Green	Yellow	Yellow
Behind-the-Meter	Residential	Bill management*	Yellow	Red	Yellow	Green	Green	Red
		Back-up / micro-grid	Green	Yellow	Red	Green	Green	Yellow
	Commercial & Industrial (C&I)**	Bill management*	Yellow	Red	Yellow	Green	Green	Yellow
		Back-up / micro-grid	Green	Yellow	Red	Green	Green	Yellow

Source: Desk research, expert interviews, World Bank, KPMG analyses

(*) self consumption, peal shaving, demand charge (**) incl. EV infrastructure

Table 10. Distribution of KPIs for ESS applications, showing the needed strength of performance across major market segments for utility BTM and FTM applications.

With LCOS and the rest of these drivers in mind, the performance of different available battery chemistries can be evaluated in different segments.

Table 11 shows the performance of seven noteworthy technologies in the twelve market categories. The rapid buildout of high-quality lithium-ion manufacturing, mainly in China, has resulted in lithium-ion being the dominant solution in most applications. The cross section of energy density (power capability), cycle life, and cost make lithium-ion highly competitive in both front of the meter and behind the meter applications. However, there are several applications spaces where other technologies demonstrate a competitive advantage or are better suited.

Flow batteries, especially the mature vanadium chemistry, have demonstrated exceptional life and LCOS in long duration applications, as well as in very large (+50 MWh) industrial systems for high load usage (i.e. AI data centers). In behind the meter applications there are two mass scale available options: lithium-ion and lead batteries.

Target areas for all battery chemistries

Within this Roadmap CBI aims to outline the pros and cons of each chemistry referred to in Table 11, demonstrating that there are application spaces with multiple chemistries offering good solutions. Furthermore, we will highlight the research and engineering pathways necessary to make each chemistry more competitive.

Technical and economical assessment* of current battery technologies for various ESS applications

Legend: Unsuitable (Red) – (Orange) – (Yellow) – (Green) Suitable for the application

Type	Application		Lithium-based	Lead-based	Sodium-ion	Sodium-sulphur	Nickel-based	Vanad.-based	Zinc-based
Front-of-the-Meter	**Generation support & bulk storage**	Firm capacity	Green	Yellow	Orange	Orange	Orange	Yellow	Orange
		Demand response	Green	Yellow	Orange	Orange	Orange	Yellow	Yellow
		Arbitrage	Green	Yellow	Orange	Orange	Orange	Green	Orange
	Transmission & Distribution	Upgrade deferral	Green	Green	Yellow	Yellow	Orange	Green	Yellow
	Ancillary services	Frequency regulation	Green	Orange	Orange	Green	Yellow	Green	Yellow
		Spinning reserve	Green	Orange	Orange	Green	Yellow	Red	Red
		Non-spinning reserve	Green	Yellow	Orange	Green	Yellow	Green	Yellow
		Black start	Yellow	Green	Yellow	Yellow	Orange	Yellow	Orange
Behind-the-Meter	**Residential**	Bill management*	Yellow	Green	Orange	Orange	Orange	Red	Red
		Back-up / micro-grid	Green	Green	Yellow	Yellow	Yellow	Orange	Orange
	Commercial & Industrial (C&I)*	Bill management*	Yellow	Yellow	Orange	Orange	Orange	Orange	Orange
		Back-up / micro-grid	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow

Source: European Commission, desk research, KPMG analyses

(*) See details in KPMG CBI Member Report

Table 11. Performance of different ESS battery technologies in key market segments. Lithium is dominant in FTM applications, but lithium and lead show promise in the BTM markets. Flow (Vanadium) shows strong performance in large (+100 MWh) applications.

Legacy Players

Li advanced	High energy density, High Cost, Long cycle life, Sustainability issues, Availability issues
Li LFP/NMC	Good energy density, Good Cost, Good cycle life, Sustainability issues, Safety Issues
Pb	Good cost/power, Sustainable, Safe, Low Cycle Life
Ni	Good power, Safe, Good High Temperature Life

On the Horizon

Zn	Good power, Cost and Production Issues, Safe, Sustainable
Na	Good energy density, Good cycle life, Cost and production issues
Flow	Great cycle life, High Cost, Low Energy Density
Fe	Great cycle life and cost, Very low energy density

Figure 9. Characteristics of the technologies used in ESS.

Lithium-ion battery-based ESS, mainly NMC and LFP types, are the dominant technology for ESS solutions. The dominance of lithium-ion is due to the exceptional performance and low cost. However, there are clear issues associated with the energy dense technology, with ongoing improvements in safety and low temperature performance being necessary to further performance. The global battery industry is watching the Chinese industrial push to better understand the long-term cost of the technology.

Recently CATL and BYD have introduced sodium ion batteries into the market. Containerized ESS solutions using the technology are slowly emerging as the technology is further optimized, creating a more sustainable alternative to lithium-ion ESS. Sodium enjoys a more stable supply chain; however, the technology at large is more expensive and lower performing versus lithium-ion analogs. Nevertheless, there will be some sodium ion growth in the next few years as manufacturing lines for the technology mature and issues related to lithium-ion battery materials evolve.

Vented lead batteries (VLA) have a long legacy of operating in float and standby applications, lasting +20 years in applications like substation backup, nuclear reactor systems backup, and telecom standby applications. Over the last twenty years, the reliability and robustness developed in VLA has been slowly transferred to VRLA lead batteries that require less maintenance, have greater power capability, cycling performance, and footprint. Currently the state of the art for lead VRLA products is 5000 cycles at ~70% DOD. However, lead batteries must improve in several ways, mainly in optimizing the systems cost, further improving cycle life, and ramping up manufacturing of more energy dense varieties. Bipolar batteries, an example of a more energy rich lead battery, hold special promise with exceptional power capability and cycle life comparable to LFP.

Flow batteries are well-suited to medium and long duration storage applications due to their ability to scale power and energy separately. Because of the dominance of lithium-ion batteries, particularly for medium duration storage, flow batteries face a variety of challenges to gain greater market share, especially around cost and performance. While there are a range of chemistries in this category of batteries, vanadium redox flow batteries have found the greatest commercial deployment, including the recent commissioning of a 1 GWh installation. Other chemistries in flow batteries include zinc-bromine, iron-chromium and a variety of organic compounds. Flow battery systems can be designed to be connected either in front of the meter or behind the meter and are frequently more cost effective at larger scale and for relatively longer durations, namely the 10–24-hour duration range.

Zinc batteries can be broadly classified into two main categories: static and flow batteries. Key chemistries within the static zinc battery space are Zn-Ni, Zn-MnO, Zn-air, and some configurations of Zn-Br. On the flow side, zinc-based flow batteries are most commonly Zn-Br or Zn-Ferrocyanide. The key technical challenges in zinc batteries are largely tied to dendrite formation and hydrogen gas evolution. Different zinc chemistries are appropriate for different system durations—with Ni-Zn batteries favored in shorter duration systems (up to 2 hours). Flow and hybrid flow zinc-bromine systems are more appropriate in the 4–8-hour duration, with some companies meeting an even broader range of system durations. Finally, the more novel zinc-air chemistries are expected to be used for long-duration energy storage systems, namely those with durations ranging from at least 8 up to 100 hours.

For both flow battery energy storage systems and zinc-based systems improving both cost and performance will be critical to unlock new market opportunities.

For flow batteries, improvements in mining and metallurgy, secondary sourcing and supply chain to battery improvements and market development are important. Battery improvements that could lead to significant reductions in cost and increase in cycle life and roundtrip efficiency include improvements to membrane selectivity and durability, novel active electrolytes, and bipolar plates. Market development could be supported through increases in demonstration projects, improved scalability and improvements to system design and packaging. Similarly, there are opportunities throughout the entire zinc-battery life cycle for improvements for cost and performance, from innovations in mining and metallurgy for battery-grade Zn metal to Improved cathode materials and electrolyte development and enhanced domestic recycling.

The energy storage market continues to grow ahead of analyst projections. Given this trajectory, it is important to consider a wide range of technologies to meet these energy and power demands. Zinc and flow battery technologies offer an interesting alternative to lead, lithium, and sodium for this use case. Across their offerings, they can provide storage at durations ranging from minutes to hours and even days through the development of zinc-air batteries.

Key Performance Indicators for All Technologies

Two distinct categories of KPIs have been developed for ESS: Longer duration (+8 hrs) and BTM for C&I, focusing on markets applicable to sodium, lead, zinc, and flow technologies.

Performance Metric	2025	2028	2030	2035
Research Goals – improve throughput, battery management to maximize cycles.				
Cycle life (60% DOD, PSOC) as an estimate for C_{10} or higher rates	5000	6000	8000	10000
LCOS ($/kWh energy throughput)	0.28	0.23	0.18	0.15
Round Trip Efficiency (system level)	75%	78%	80%	82%
Service Life (years)	13	15	16.5	+20
Sustainability, safety, and tolerance to abuse will be important in this application field.				

Table 12a. KPIs for battery technologies in FTM/BTM at +8hrs duration.

Performance Metric	2025	2028	2030	2035
Research Goals – battery management to maximize cycle life, maximize economic value.				
Cycle life (50% DOD, PSOC) as an estimate for C_{10} or higher rates	5000	5500	6000	7500
LCOS ($/kWh energy throughput)	0.25	0.20	0.15	0.10
ESS acquisition cost	350	325	300	275
Service Life (years)	10	13	15	+20
Sustainability, safety, and tolerance to abuse will be important in this application field.				

Table 12b. KPIs for battery technologies in BTM and microgrid applications.

Priority Research Areas for ESS

The single most important research areas for lead batteries, specifically developing ESS around batteries is optimizing the **SYSTEM** performance and cost. Optimization of performance focuses on increasing battery energy throughput as well as maximizing the impact of the inverter, battery management system, and other systems on the total serviceable life of the ESS. From a cost perspective, it is vital to establish the following:

1. An optimized inverter solution – appropriate voltage level, cost, and product design for the segment. As an example, an inverter should be sized to the market segment being addressed, such as a 500-kW inverter for C&I BTM.

2. Battery management systems need to be deployed to aid in string/cell charging and balancing, should be done at as low a cost as possible.

3. Balance of plant items such as circuit breakers, contactors, power supplies, and sensors need to be purchased with mature, effective procurement contracts to lower cost.

Indicator	ESS Battery Research Areas Difficulty Level and Possible Research Avenues
Service life, years	This metric is tied to both lifetime at float and under operation. Self-discharge has historically been an issue at float, but current innovations have helped mitigate this issue. Despite advances, self-discharge is very important process to control. Further extension of service life would be increased directly by increasing capacity turnovers. Zinc, lead, and flow-based batteries must improve self-discharge issues.
Cycle life (80% DOD)	Improving overall cycle life is **THE MOST IMPORTANT METRIC from a battery product perspective**, and high DOD cycle life is a problem area with some innovation pathways: 1. Bi-polar configurations have been developed for other applications. These types of batteries have shown superior performance, especially in high DOD duty cycles. Adapting the technology to ESS applications could easily lead to performance enhancement. Zinc, nickel, and lead variants are possible or in the market. 2. Additives including carbons, lignosulfonates, and salts have been utilized in other applications. Optimization and further discovery could be beneficial for cycle life. 3. Charging algorithms could directly assist in improving battery total capacity turnovers in ESS applications.
Energy Throughput	Smart charging and cycling improvements would directly assist in increasing energy throughput. Understanding and establishing how batteries want to be treated is important. Damage accumulation can be controlled by ensuring proper charge and depth of discharge control, allowing for maximum energy throughput.
Energy Density	Energy densities in commercial lead and zinc battery products range from 30-60 Wh/kg, 80 – 120 Wh/l. For flow batteries energy density is even lower at 10-30 Wh/kg depending on the specific type. 1. Increasing current density and active material utilization through bi-polar configurations has already resulted in energy density improvements, however further optimization and developing manufacturing processes for thinner electrodes could lead to even higher energy density. 2. Improving the lead battery electrode lead oxides through semiconductor particle doping or alloying may increase active material utilization. 3. In flow batteries optimization of the ancillary equipment and streamlining footprint are of major concern.
Round Trip Efficiency	The real-life implications of round-trip efficiency with solar and wind generation are particularly important due to the inconsistent energy delivery. Systems configuration between the controller, generation, and battery could be optimized as well.

Table 13. Key research areas for batteries used in ESS.

The KPIs for lead batteries in ESS were formed based on technoeconomic goals declared by stakeholders in the US and EU. The research area table summarizes some high-level areas that would attend to specific performance metrics. However, lead batteries are only a minor player in ESS. Zinc-based, Flow, and nickel-based batteries are currently niche players as well. These non-lithium chemistries will become more and more relevant as BTM segments develop near communities and safety becomes a priority. Long duration ESS opens the door for flow-based batteries, where in these duty cycles the longevity of the technology maximizes the economic benefit.

The improvement of non-lithium battery energy efficiency, throughput, and density will lower the overall cost of the unit.

Research Areas for Lead Battery ESS Batteries

Cycle life, Energy Throughput, Capacity Turnovers

The overall life expectancy of the battery is the most important metric to improve through innovation – with production cost being a special consideration during research. Many different products across a wide price range are currently offered in the ESS space, making average $/kWh/cycle cost calculations of a lead battery difficult to determine.

Carbon Additives

Distributing current and voltage uniformly through active material is a pathway toward controlling crystal expansion, growth, and dissolution processes. Various carbons have demonstrated a transformative effect on the overall behavior of the negative electrode, and the added electrochemical conductivity, advantageous change in pore size and volume, and stronger cohesion of the active material offered by carbon indicate the additive would benefit lead batteries in ESS applications.

There are many advanced lead battery products using carbon additives in the negative electrode already, however, there are very few detailed reports of the impact of specific carbons on the performance of lead batteries in IEC 61427 and SANDIA/PNNL 22010 5.3.2 endurance testing.

Understanding the impact of carbon loading, carbon type, dispersion method, surfactant agent in the dispersant, carbon particle size, and a host of other materials characteristics on ESS battery performance is uniquely difficult due to the outstandingly long test periods required in currently accepted test sequences.

Increasing Active Material Utilization (AMU)

Increases in AMU are not correlative with operational life directly. However, utilizing the electrode more uniformly will decrease the likelihood of sulfation differences across the negative electrode. Carbon is known to promote a finer, more cohesive structure in both the NAM and PAM.

New battery electrodes and designs (bi-polar, carbon felt, advanced 2V AGM) have greatly increased active material utilization, but what of carbon?

1. Initial hypotheses from the 1618 ALABC Narada Power Project Final Report Addendum document stated that carbon helped decrease the creeping polarization occurring on the positive electrode during IEC and SANDIA/PNNL test sequences.
2. Carbon has known beneficial impacts on PSOC performance in automotive batteries, and this is especially important for shorter duration ESS applications.
3. The impact of carbon on energy density, on active material utilization is not well characterized.

Long duration storage is becoming a more highly scrutinized application space for ESS, mainly due to high profile instances of thermal runaway related incidents from lithium-based storage. The shallow cycling and slow charge and discharge rates from long duration applications are well suited for lead batteries. With shallow cycling in mind, carbon additives have been well described as benefitting lead batteries in these duty cycles.[9]

Expanders

Expander materials have been heavily researched in automotive applications and to a lesser-degree standby application. Lignin is highly beneficial and necessary for all lead battery applications, enabling high discharge power for CCA, providing uniformity to lead sulfate growth, and supporting the overall durability of lead battery negative electrodes.[10] Power is important for ESS applications, but depending on the specific application (long duration vs. short duration) high DOD cycle life, PSOC cycle life, and/or recharge capability should be the governing KPIs for tailoring expander materials to ESS.

$BaSO_4$ size and surfactant treatment significantly impact the structure and resulting performance of a lead battery negative electrode. CBI is working with Hammond Group to understand the impact of $BaSO_4$ on the electrical performance of test cells and analogous 2 V AGM products in IEC 61427-2 testing. In isostructural and isoelectronic analogs to PbSO4, such as SrSO4 and $BaSO_4$, small molecules and ionic compounds directly impact growth and dissolution.[11] Work from Andrew Stack et al. at Oak Ridge National Laboratory demonstrated effective control of a key mechanistic growth step for $BaSO_4$ through use of interfering ions of different sizes and concentrations.[12] Additionally, the functional group density (carbonyl group for instance) can positively impact cycle life.[13]

Battery Design

There are basic design principles that aid in improving cycle life for flooded batteries – dropping the specific gravity, increasing the thickness of battery electrodes. Changing these simple parameters lengthen operation life at the cost of energy density. In VRLA, large plates are used to great effect in improving cycle life. Combined with a "pancake" or side-on orientation to mitigate acid stratification, these simple design principles significantly impact lead battery performance. Each manufacturer has a specific approach to paste production, compression in AGM, and of course different additives and separators.

There are several high profile bi-polar technologies that promise a step-up in energy density (close to a 100% increase, 35 to 65 Wh kg^{-1}), primarily by eliminating lead content and using plastic or silicon as a main support of the active material. This increase in energy density is part of the energy storage performance need, opening avenues for lead battery to meet the $/kWh metrics and smaller footprint. There is a paucity of information on bi-polar lead battery performance, primarily total energy throughput, in stationary or ESS applications. CBI is currently looking into bi-polar technology for battery packs representative in size to residential applications. These 24 V low capacity monoblocs provide a solution with high energy density and small footprint, easily managed by simple BMS components. The currently offered monoblocs for bi-polar technology range in voltages from 12 – 48 V and capacities of 8 – 25 Ah.

Developing bi-polar technology to larger systems may be best done from a different form factor, using higher capacity electrodes (larger in terms of geometric surface at least, more active material), and different electrolyte concentration. Increasing the capacity of the monoblocs provides two advantages in ESS systems (include BOP, cabling, connectors): smaller number of monoblocs and a lower number of parallel strings. This would result in smaller cost related to circuit breakers, cables, terminal connections, racks, and other elements of the system relative to smaller capacity bi-polar monoblocs. The presented example of a design strategy for improving bi-polar technology toward ESS applications has a drawback, however. Increasing the size of the electrodes could decrease the aforementioned energy density step-up. Design optimization studies at the monobloc and total systems level are vital to introducing bi-polar technology into ESS systems.

Beyond bi-polar there are other technologies that hold promise for ESS applications, and are used in other lead battery applications. Carbon negative electrodes, specifically carbon felt current collectors, are a promising technology for ESS. Carbon felt results in an increase in energy density, an increase in DCA, and higher PSOC cycle life. Alternative current collectors are a valid pathway to attaining the desired technoeconomic performance, as long as the manufacturing process and materials cost are not significantly higher than current baselines.

Structural Effects
Understanding Damage Over Time

Fundamental understanding of electrode change over time is key to improving lead battery technology performance for ESS, and the following section of this document will discuss an ongoing issue with lead battery technology: balancing energy throughput with high DOD activity. ESS lead battery technology has improved significantly over the last ten years. Best in class products are able to reach 5000 cycles at 70% DOD.[14] There is still a well-known issue for lead batteries past ~80% DOD, cycle life drops sharply as 100% DOD cycle life is approached. An accurate representation of this general trend is described in the 1618 ALABC Narada Project and has also been presented as various papers by Herbert Giess.[15]

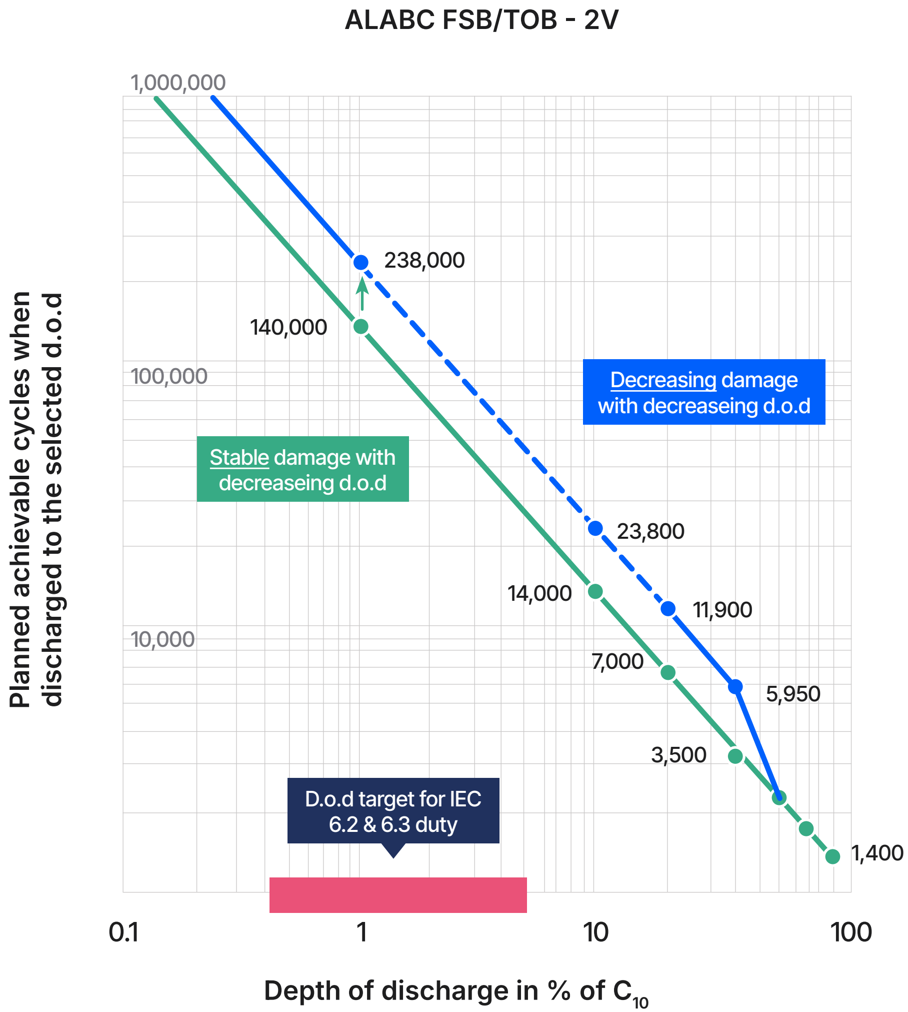


Figure 10.

The relationship between cycle life and DOD, as exemplified by the 2V test cells used in the 1618 ALABC project with Narada Power.

Understanding the applications duty cycle requirements is key to developing effective management (and treatment) of the lead battery technology in the system.

As demonstrated in Figure 10, the DOD range for IEC 6.2, 6.3 renders a wide range of possible cycle performance, ranging from 500,000 (less than 0.5% DOD) to 50,000 cycles (5% DOD).

Improving Acquisition Cost - Innovation in Energy Density - $/kWh

Acquisition cost is an important comparative metric for ESS systems. **This term, acquisition cost, in this section of the document will be directed at the cost of battery monobloc per kWh.** Total AC and DC system acquisition cost are typically the two categories discussed in reports from PNNL, LAZARD, and IRENA.

Improvements to energy density, and the innovations that lead to them, are suggested primarily to lower the production cost of lead batteries associated with lead materials cost. Before discussion of research areas, there are manufacturing methodologies and market considerations useful for lowering acquisition cost.

- For most lead battery manufacturer members, ESS batteries typically overlap with UPS offerings. High volume mass production of ESS specific products would lower cost.
- The manufacturing process could use optimization:
  - Active material production relies on paste production, curing/drying, and formation. What if PbO_2 and Pb could be chemically prepared on mass scale?
  - Alternatively, curing and drying and formation are intensive and a major cost of production. Curing/drying takes time, energy, and the process is prone to many issues. Making the process higher in throughput and continuous could benefit overall.

There are several research areas that may further improve energy density (volumetric and/or gravimetric). Increases in volumetric energy density, while secondary to gravimetric, provide improvement to footprint – allowing for more batteries in a single enclosure, benefitting overall system cost.

Battery design - maximizing energy density using new designs and materials

Bipolar ESS batteries

As mentioned earlier, Bi-polar design offers a distinct advantage in energy density for lead batteries. Current estimates of bi-polar energy density are 120-130 Wh/l, 60-65 Wh/kg, an estimated 50% increase in energy density compared to conventional VRLA batteries. The current collectors and electrodes used in available lead bi-polar technologies are thin foils or wafers supported by a plastic border. The thickness of lead "grid-like" material is approximately 100-150 microns, lowering internal resistance and providing efficient, high-power batteries. High charge acceptance, +2000 cycles at 50% DOD, and PSOC cycling in IEC/EN 50342 testing suggest bi-polar technology could provide suitable performance for ESS applications.

The impact of higher energy density is more batteries in single enclosure, resulting in a lower system cost for enclosures, racking, and HVAC.

Novel Electrodes

Over the last twenty years, Ti mesh, carbon felt and carbon capacitance layers, and ceramic electrodes have been studied as alternatives to lead-based grids.[16]

- Ti mesh is a viable option and potentially recyclable. Initial capacity testing and cycling at low DOD have been conducted. Electrodes developed by Kirchev et al. at CEA Liten using Ti mesh with Sn/Pb conducting layers have been produced.
- Carbon-based electrodes are effective at PSOC and high C rate applications. UltraBattery® technology and now the GEM battery has demonstrated the effectiveness of these innovations in ESS applications.
- Different silicon electrodes have been developed, and remain untested in ESS applications.

Grid weight is the most significant contributor to electrode weight, and the substitution of lead with other materials could be disruptive to lead batteries, dramatically improving energy density.

Advantages and Disadvantages to Different Lead Battery Products

The array of different lead battery products offered for stationary and ESS applications is best discussed from several perspectives: weight, BOP cost, footprint, and power conversion (relative to the inverter) advantage. These metrics will be discussed relative to the two most prevalent monobloc voltages: 2 V and 12 V. Distinctions will be made also on flooded vs. AGM or Gel.

Note: These are examples put together to demonstrate the systems implications of different products – this is not necessarily the case for all types of 2 V or 12 V lead battery technologies. Control and power conversion product also have a significant impact on systems design.

Battery Type	Advantages	Disadvantages
Flooded 2 V	▪ Long history of great performance in stationary applications, low DOD use. ▪ Long cycle life for float and shallow cycling. ▪ Lowest incidence of thermal runaway of all battery types and chemistries. ▪ Very low BOP cost.	▪ Maintenance is an issue – all batteries need maintenance, but watering of batteries is a possible added issue. ▪ Low energy density.
AGM/Gel 2 V	▪ Long cycle life – depending on the product, highest for lead batteries. ▪ Higher energy density. ▪ Very low BOP cost can be attained by maximizing serial string voltage – continuing advantage as PCS products with high voltage continue to become more popular. ▪ Robust across a broad spectrum of duty cycles.	▪ Wide spectrum of products and prices, hard to judge the true technoeconomic performance. ▪ Can be expensive.
AGM/Gel 12 V	▪ Products that use TPPL and other advancements (carbon, for instance) have been shown to have high performance. ▪ Least expensive. ▪ Small unit size (higher energy density) – lower footprint.	▪ Relative to 2V, BOP can be significantly higher for smaller systems (below 1 MWh). ▪ Cycle life is still in need of improvement for most products.

Table 14. Comparison of prevalent lead battery types – all lead batteries are safe, reliable, and inexpensive – this a strict look at some issues that must be considered for ESS.

Flooded Batteries

There are several advantages and disadvantages to flooded lead products. This specific type of lead battery has been utilized in other stationary applications for decades – it is the natural comparison in telecom and authorities having jurisdiction (AHJ)s and utilities have a lot of experience with the technology. However, the typical application for most flooded products requires high float life with only minor high DOD performance. Across the energy storage systems that are tracked by CBI, none use flooded batteries. The long lifetime at shallow cycling regimes means flooded batteries are attractive for long duration applications, but the maintenance issue presents a problem.

Flow Batteries for ESS

Introduction

Flow batteries have emerged as an important technology for grid-scale stationary energy storage systems, especially over the past decade. Their unique capability to scale power separately from energy due to their design enables them to be a potentially important player in the medium and long duration storage market, particularly in front of the meter or in large commercial and industrial applications. Several key references[17,18,19,20] provide an overview of the chemistry and technology alternatives in this space as well as significant developments over the past decade.

Overview of Flow Battery technology

As with other energy storage systems, the flow battery itself is only one piece of the overall storage system. The DC portion of the system is comprised of the flow battery itself which includes tanks, pumps and stacks, with the battery's stacks defining the maximum power of the battery and the size of the tanks (and associated electrolyte) determining the capacity of the battery. In order to be compatible with the AC grid, power from batteries must be converted from DC to AC through the use of a power conversion system (PCS), commonly called an inverter. Another important layer to the system is its controls. A battery management system monitors and manages the battery to ensure its safety, performance, and longevity.

There are two main types of flow batteries: traditional or hybrid. Traditional flow batteries have "two electrolyte tanks containing dissolved active species are separated by a membrane. The active species undergo redox reactions during charging and discharging. A hybrid flow battery system employs a solid anolyte active species in addition to a dissolved catholyte active species, providing extra capacity and higher energy density." Most flow batteries that have been deployed are classified as traditional redox flow batteries and largely utilize all-vanadium as their active species. Other common redox flow battery chemistries include iron-chromium, vanadium bromine, and organic. Hybrid flow batteries are commonly zinc-based (zinc-bromine has been most commercially available thus far), but all-iron, all-lead, and organic species have been developed or are under development.[21] These types are summarized in the following table (Table 15), based on the table from the Technology Strategy Assessment Findings from Storage Innovations 2030 Flow Batteries Report.

Type	Solvent	Solute	RFB System
Traditional	Aqueous	Inorganic	Vanadium
			Iron-Chromium
			Vanadium-Bromine
		Organic	Anthraquinone-Benzoquinone
			Phenazine-Ferrocyanide
			Fluorenone-Ferrocyanide
	Non-Aqueous	Organic	Ruthenium Complexes
Hybrid	Aqueous	Inorganic	Chromium Acetylacetonate
			Zinc-Bromine
			Zinc-Cerium
			All-Iron
			All-Lead
	Non-Aqueous	Organic	Lithium-Anthraquinone
Redox Targeting	Aqueous		Zinc-Ferrocyanide

Table 15. Types of flow batteries present in the market today and historically.

Particular types of flow batteries will be described briefly here, but the remainder of the report will focus on vanadium redox flow battery energy storage systems as these are the most commercially available redox flow batteries. Some unique research and development areas will be described where appropriate, but much of the market discussion will be based on projections for VRFB technology.

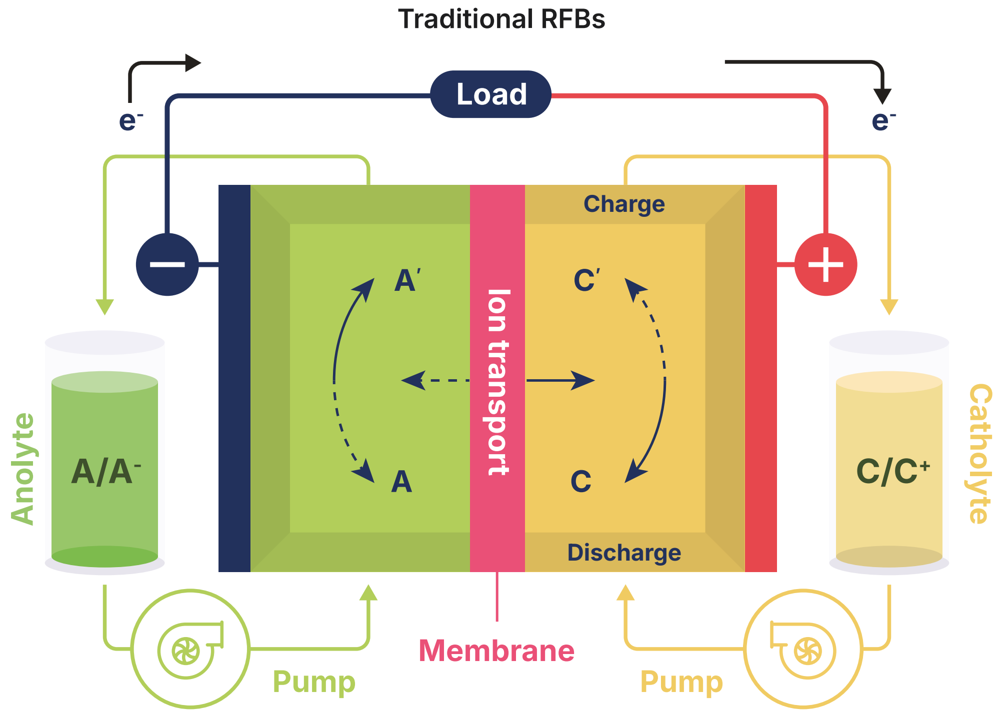


Figure 11. Example scheme for a traditional redox flow battery, such as vanadium flow technology.

Within the traditional flow battery structure, shown in the Figure 11, we see both inorganic and organic chemistries. A traditional RFB has an anode and a cathode divided by an ion-selective membrane. The anolyte and the catholyte are kept in separate two distinct reservoirs and pumped through the battery to charge/discharge them[22].

Currently, the largest fraction of deployed flow batteries are vanadium redox flow batteries. The largest vanadium redox flow battery companies are Invinity Energy Systems, VRB Energy, Sumitomo Electric, V Flow Tech, and Rongke Power. Other organizations, like Storion Energy (a Stryten and Largo Company) have specialized in the development of an "integrated supply chain for vanadium and vanadium electrolyte manufacturing in the United States."[23]

Iron-Chromium batteries, such as those commercially available from Redox One, are another traditional flow battery chemistry. They were initially developed by NASA in the 1970s and have since been refined and commercialized. In these batteries, during charging the iron is oxidized (+2 to +3) while the chromium is reduced (+3 to +2), and the reverse happens during the battery's discharge. According to the company, "Mixed Species Electrolytes Eliminate Crossover – Both tanks have equal concentrations of Iron Fe and Chromium Cr ion so there's no net diffusion across the separator during battery operation[24]."

Vanadium bromine flow batteries are a variation of the all-vanadium flow battery technology described above. They employ “a vanadium(II)/vanadium(III) couple in the negative half-cell and a Br^-/Br_3^- couple in the positive half-cell, using a mixture of vanadium bromide, hydrobromic acid and hydrochloric acid as the electrolyte”[25] with the advantage being that the addition of the halide would enable a higher concentration of vanadium and increase the energy density of the system. One of the challenges with this technology is the tradeoff between the additional energy density gained from the addition of bromine and the additional cost because of the greater vanadium content.

Organic flow batteries encompass a range of chemistries including quinones, phenazine-ferrocyanide, and fluorenone-ferrocyanide. Quinones for flow batteries have been widely researched[26] and companies like Quino Energy have licensed the technology developed at Harvard University; this company has recently reached a manufacturing readiness level (MRL) 7 for their battery active material pilot production line.[27]

Hybrid RFBs

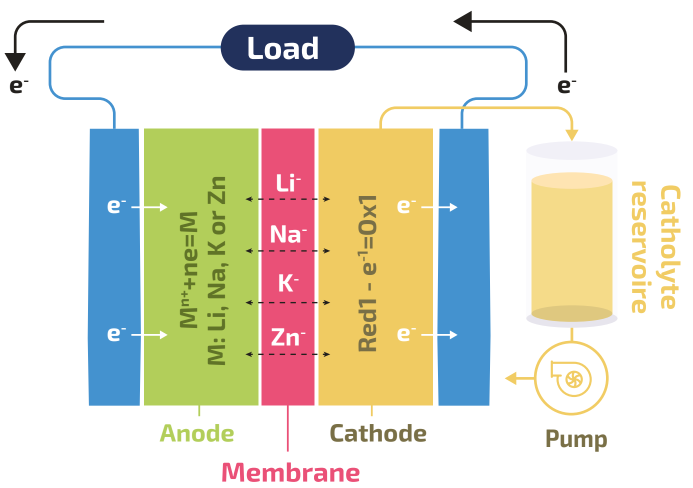


Figure 12. Example scheme of a hybrid redox flow battery.

Hybrid Flow batteries are those in which the energy is stored partially in the electrolyte and partially in the metal anode.[28] This offers the advantage of increased energy density. One such example of this setup is with the zinc-bromine hybrid flow system, the most commercialized of the hybrid flow batteries, and it was first developed in the 1970s. Zinc-based flow batteries will be discussed briefly in this section and additionally in the section on zinc-based batteries. Additional chemistries that fall into this category include chromium acetylacetonate, zinc-cerium, all-iron, all-lead, and lithium-anthraquinone hybrid flow batteries.

The largest zinc-bromine hybrid battery manufacturer is EOS Energy, which has offered several generations of products. Their current offerings focus on meeting storage durations of 3-12 hours and a product lifetime of 20 years or more. According to product documentation, their technology is “highly tolerant of significant variation in operational requirements[29]” including variability in the depth of discharge to maximize roundtrip efficiency. Other zinc-based providers include Gelion which focuses on the manufacture of a zinc hybrid cell. It is important to note that Redflow (out of Australia) operated in the zinc-bromine space for several years until challenging economic conditions and limited ability raise capital resulted in its closure in 2024[30]. Its difficulties highlight the challenges in the scale-up of novel technologies for energy storage technologies when the price of incumbent technologies continues to drop.

All-Iron flow batteries, such as those sold by ESS, Inc., target the long-distance storage space, offering durations ranging from 8-22 hours. Their three product scales range from the Energy Warehouse which offers hundreds of kWh in capacity up to the scalable Energy Base which incorporates building blocks offering 800kW apiece, with suggestions that this offering is able to be integrated into systems at the GWh size. Significant research opportunities remain to develop the all-iron aqueous flow battery system as described by Gong, et.al[31] among others.

In all lead flow batteries (soluble lead redox flow batteries or SLRFBs) "the same set of redox couples Pb/Pb^{2+} and Pb^{2+}/PbO_2 [as lead acid batteries] are being used at negative and positive electrodes, the active material Pb^{2+} ion is stored in a dissolved state in an aqueous acid electrolyte, which is circulated through the cell using a pump[32]. There remain significant challenges for the commercialization of this chemistry of flow batteries due to its tendency to form dendrites[33] and the costs and challenges of scale up of a novel technology when conventional lead acid batteries remain cost effective and meet performance requirements; however, research is ongoing[34].

Lithium-Anthraquinone flow battery development has been driven by work out of Pacific Northwest National Laboratory but not widely commercialized[35].

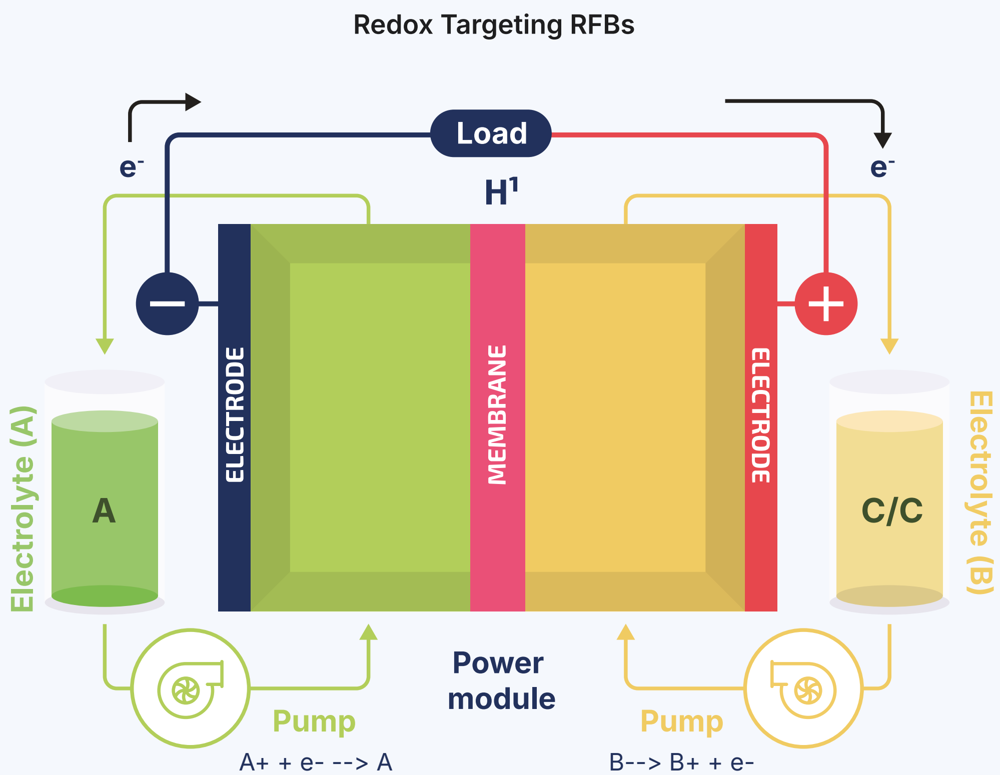


Figure 13. Example scheme of a redox targeting flow battery.

The third major type of flow batteries are redox-targeting flow batteries.

A redox shuttle design battery stores solid active materials in multiple tanks and a separate tank with a redox shuttle to transport the active species between the solid active tanks. This design enables higher energy density and a reduction in the volume of electrolyte required.

This type of battery has not been as widely commercialized as traditional or hybrid flow batteries, but the battery offers significant potential.[36] One of the specific chemistries in this space utilizes the zinc-ferricyanide redox couple.

Flow Battery Market Overview

Flow batteries have been sold at a range of sizes and scales, but as the market develops, trends toward large-scale and long duration systems have emerged. Trends in the flow battery industry have swung from smaller, more modular systems, designed to minimize one-off engineering to larger, more custom systems that minimize batteries and have landed somewhere between the two scales. For instance, Invinity Energy Systems offers three scales of products—the Endurium line offering 3-100 MW and 12-500+ MWh, the Endurium Enterprise line which offers 1-20 MW power and 4-80 MWh capacity, and the Invinity VS3 line which offers 0.7-10 MW power and 2-40 MWh in capacity[37]. Sumitomo Electric offers a range of energy capacities across their product lines[38] in building blocks of 250kW power and between 750kWh to 2500kWh capacity. The modular design of the product is flexible to enable efficiency and reliability across applications. Another company reflecting this range in scale is Rongke Power which offers the UPower Series[39] which is designed to be a flexible, plug-in-play offering with 10kW/40kWh building block that is scaleable; the SPower series is containerized and offers 240kWh and is scalable to gigawatt hours through stacking[40].

Given the range in scale available in the flow of battery industry, systems can be designed to be connected either in front of the meter or behind the meter. The point of connection will frequently be determined by the system's owner; utility-owned systems are more often deployed in front of the meter while privately-owned systems are often connected behind the meter. Earlier in the deployment of energy storage systems, point of connection limited the scale, but there is more flexibility for large systems behind-the-meter now than in previous eras.

Flow batteries are unique among battery technologies in their ability to scale power and energy separately. Their cost profiles tend to improve with larger and longer durations. In particular, systems meeting the 10–24-hour duration are particularly appealing. They are less relevant for durations greater than 24 hours due to the limitations of parasitic loads within the system (e.g. heating, cooling, and pump motors). These systems are also useful for time-shifting of renewable energy production, associated with one full cycle daily.

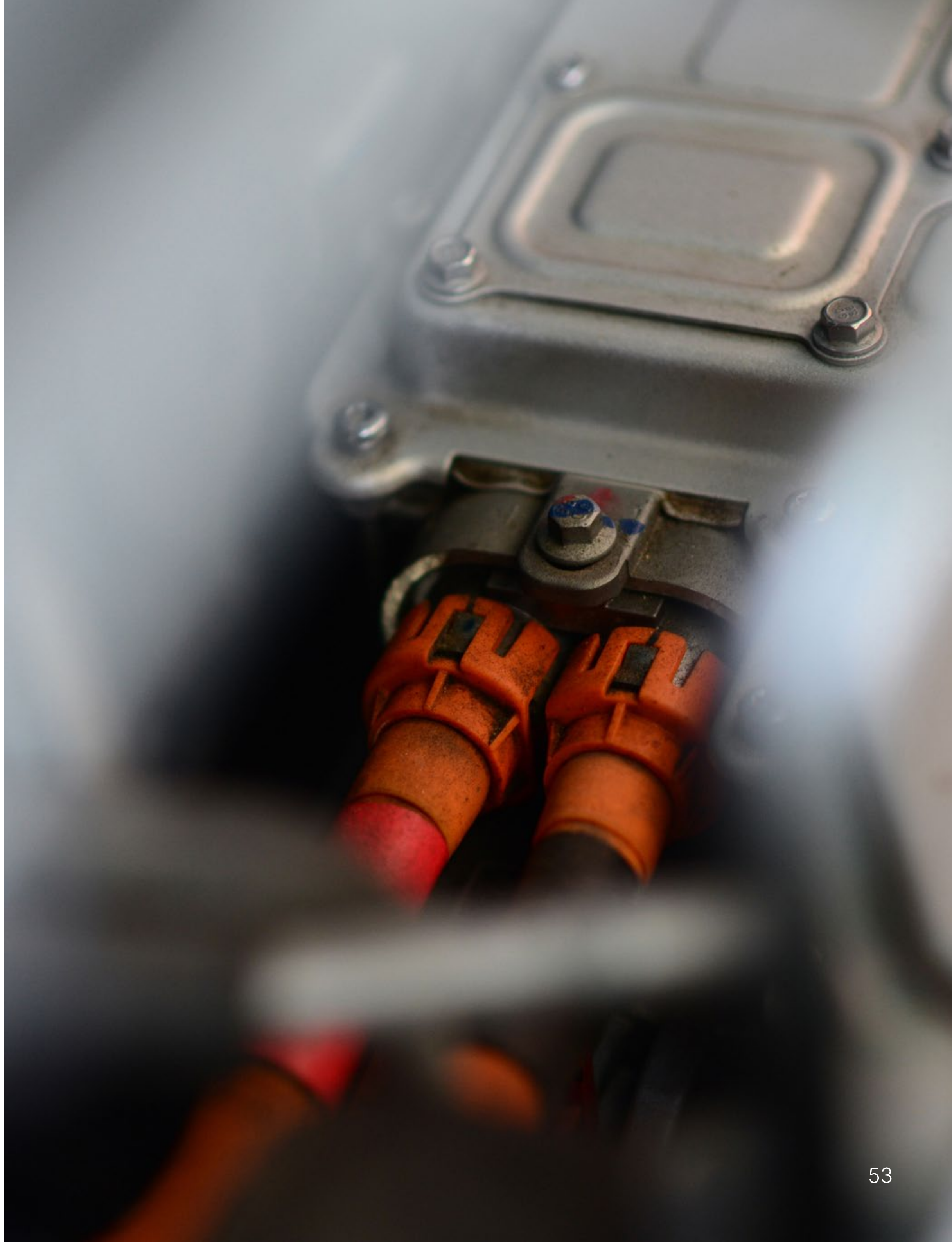
One of the key challenges to the development and expansion of the flow battery is the existence of competitive alternative chemistries. Both lithium-ion batteries and lead acid batteries are well-established commercially available alternatives for energy storage, with significant advantages in scale and bankability compared to many flow battery alternatives. Specifically, for lithium-ion batteries, they are competitive due to their relatively low prices and the slower than expected growth of EV market in the United States and Western Europe which keep lithium-ion battery costs low can be competitive at low-end of flow battery durations, particularly the 8-10 hour duration range. Lead batteries also have a substantial market share, relative to other technologies, and have the advantage of an established supply chain. Again, they are most competitive at lower durations.

Areas for Research and Development

Flow batteries have several areas to improve traction in the energy storage space. First, market development will be critical to compete against incumbent energy storage technologies like lithium-ion batteries and lead-acid batteries. This will hinge on identification of the use cases and markets that are best suited to leverage the capabilities of flow batteries, namely very large systems with longer durations than lithium-ion batteries are suited for. Additionally, companies will need to be seen as bankable to secure large system orders. On a related note, there will also need to be improved cost and performance within the battery, as described in the Technology Strategy Assessment Findings from the Storage Innovations 2030 Flow Batteries Report. Specific areas of research and development are described below; some of these are relevant across chemical species while others are unique to a particular redox pair.

Within a flow battery energy storage system, there are ways to improve the cost and performance of the system ranging from improvements in mining and metallurgy, secondary sourcing and supply chain to battery improvements and market development. Battery improvements that could lead to significant reductions in cost and increase in cycle life and roundtrip efficiency include improvements to membrane selectivity and durability, novel active electrolytes, and bipolar plates. Market development could be supported through increases in demonstration projects, improved scalability and improvements to system design and packaging.

Within flow batteries, material compatibility is critical; there is lots of research to be done. While vanadium-based flow batteries are the most established flow technology; there are a lot of other chemistries out there, however, as these chemistries develop, we must acknowledge that —even switching molarities can affect battery performance, corrosive behavior, iron transfer, and other factors. Additionally, when working with membrane development, it is often a balancing act—to increase membrane lifetime may be in opposition to ion transfer through the membrane.



Performance Targets

The 2022 Grid Energy Storage Technology Cost and Performance Assessment (published by Pacific Northwest National Laboratories)[41] projected vanadium redox flow battery costs among numerous other technologies. Based on their assessment, they estimated a cost per kWh ranging from $300-$800 with smaller, shorter durations expected to see a higher per kWh cost and lower costs achieved as scale and duration increase for their reference year of 2021. Their projections for 2030, based on assumptions of improved cost and performance, see this range decrease to approximately $250-$700. Performance targets for a system in 2030 are to achieve a calendar life of 12 years for the stacks and pumps, 10,000 cycles for the cycle life of the electrolyte, and a system-level round-trip efficiency of 65%. There are not projected to be significant gains in performance parameters according to the assessment during the 2021-2030 period.

Other current expert assessments[42] cite similar limitations for flow batteries, specifically vanadium redox flow batteries. In particular, they expect to inspect battery pumps every couple of years and replace them every five to ten years. Other key aspects of BESS include the power electronics of the system. Many real-world installations have observed challenges with the durability of this part of the system; this is reflected in the fact that the chips within the equipment get hot as the system operates. With regular cycling of the equipment (i.e. on a daily basis or more frequently), it is expected that a lifetime of five to ten years is expected and an improvement in this part of the system would be an opportunity to improve overall performance and durability of the battery energy storage system. This is an opportunity across a range of technologies, not just flow batteries.

Rongke Power is a well-established flow battery company whose performance guarantees appear to significantly exceed those cited by other experts as well as the 2022 Grid Energy Storage Technology Cost and Performance Assessment.[6,7] Their published performance metrics[43] describe a cycle life of 20,000+ cycles without degradation, a 20 plus year battery life expected and 100% state-of-charge (SOC) availability as well as an 80% energy efficiency for DC components not including self-consumption for both their SPower and UPower product lines. Other key flow manufacturers like Sumitomo Electric[44] describe an operational life of greater than twenty years as well. Another key component of a vanadium redox flow battery is its stack, particularly its polymer membranes. These membranes can clog and so it is critical to monitor stack performance (i.e. ensure that membrane is not becoming resistant to flowing ions).

As described above, there is a significant difference between the projected lifetime of system components and the performance guarantees reported by a number of VRFB manufacturers. This highlights the important role of maintenance and monitoring throughout the lifetime of flow battery and other BESS products. In summary, current performance and projected performance metrics are summarized in the table overleaf.

Metric	Current Performance	Projected 2030 Performance
Cycle Life	9125	10000+
Pump Life	10	12
Warranty	20	25
Round Trip Efficiency (Overall)	65%	65%
Round Trip Efficiency (DC-DC)	71-80%	71-80%

Table 16. KPIs for flow batteries in ESS applications.

Summary

Flow batteries are a critical battery technology, along with lithium-ion and lead-acid batteries, for energy storage systems. Their capability to scale power and energy capacity separately makes them an appealing choice for large, longer duration energy storage systems. Flow batteries, particularly vanadium-redox flow batteries, are an emerging technology and the third most commercialized battery energy storage technology but face numerous challenges to gain a larger market share within energy storage, specifically regarding system costs. Future research directions will need to focus on reducing system costs and developing the supply chain to build capacity to produce large scale systems.

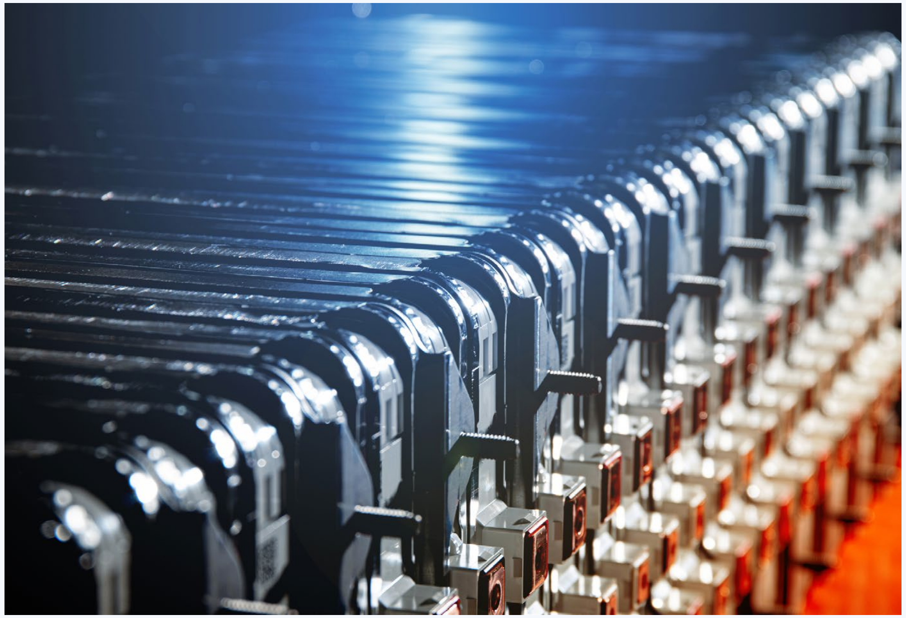
Zinc Batteries for ESS

Introduction

There is a wide range of zinc battery chemistries on the market currently serving a number of key applications in the ESS space. They range from more familiar technologies like nickel-zinc, zinc-manganese-oxide, and zinc-bromine to more novel chemistries being explored in the lab, particularly zinc-ion and zinc-air systems. As with many chemistries, challenges in the ESS market include competition with the strong cost and performance metrics established with lithium-ion battery systems and difficulty in capturing market share, leading to difficulties in bankability for some of the companies in this market. The following sections provide a description of the types of batteries in this chemistry type, their expected markets, areas for research and development and the proposed performance targets reflected in the Energy Storage Grand Challenge Cost and Performance assessment.[45]

Types of Zinc Batteries

Zinc batteries can be broadly classified into two main categories: static and flow batteries. Common chemistries within each of these battery types are described below alongside a summary of their key characteristics and development and commercialization. Key chemistries within the static zinc battery space are Zn-Ni, Zn-MnO, Zn-air, and some configurations of Zn-Br. On the flow side, zinc-based flow batteries are most commonly Zn-Br or Zn-Ferrocyanide.



Static Batteries

Nickel-zinc batteries "use an aqueous solution of KOH as the electrolyte and zinc as the anode material, with the same fundamental anode reaction during discharge ...the cathode in this case is nickel oxyhydroxide (NiOOH), which converts to nickel hydroxide.[46] These batteries are most frequently used for relatively shorter durations (ranging from a few minutes to a few hours). Their development began in the early twentieth century with significant efforts in the 1970s and 1980s. They are relatively energy dense[47] and the batteries available on the market have completed UL 9540A testing demonstrating that these batteries do not exhibit thermal runaway, making them non-flammable and non-reactive to air and water. Additionally, "the aqueous electrolyte lacks the flammability and reactivity of organic solvent-based electrolytes used in lithium batteries[48]. Companies in this space include ZincFive and Enzinc. Enzinc has recently announced[49] a joint venture with an unnamed lead-acid battery partner to continue the commercialization of their product and leverage existing talent, equipment and materials. This initiative highlights the interconnectedness and multi-chemistry thinking present in the energy storage industry.

In addition to nickel-zinc chemistries, zinc-manganese oxide batteries (zinc-alkaline), which have long "dominated primary applications"[50] have expanded into the rechargeable market. Notably, they are low cost, high safety, and easy to manufacture, but have been historically limited by challenges in achieving high enough cycle life for rechargeable applications. This results from the formation of irreversible species during discharge. Recent advancements in the prevention of dendrite formation by some companies and researchers have enabled their use in stationary applications, with products offered at the commercial-industrial and utility scale[51].

Zinc air batteries (ZABs) offer a high relative energy density along with being made out of earth abundant materials and utilizing an air cathode. A conventional ZAB is composed of an alkaline electrolyte, a negative Zn electrode, a membrane separator, and a positive air electrode[52]. In spite of these benefits, the technology has faced a range of challenges to commercialization, in particular: "high polarization and fast degradation of the air cathode, low interfacial compatibility and stability of the electrolyte, and poor electrochemical irreversibility of the Zn anode"[53].

Zinc Bromine batteries come in two varieties—hybrid and hybrid flow. In a hybrid configuration, the battery stores electrical energy through zinc deposition and utilizes a typically aqueous electrolyte enabling ions to move from one electrode to another creating flow. The most commercialized version of this chemistry is produced by EOS Energy[54]. The company was founded in 2008 and has had products in the field for over 12 years; this includes 444 MWh of installed capacity and a pipeline of over 1 GWh[55]. Individual projects have ranged in capacity from large installations for microgrids (i.e. MW-scale) down to kW scale for commercial and industrial and other behind-the-meter applications[56]. Unlike conventional flow batteries, the capacity of a zinc-bromine hybrid flow battery is "dependent on the anode surface area and the overall size of the electrolyte storage reservoirs"[57] meaning the power and energy is not fully decoupled. While some companies have found success, others have been challenged by the process of commercial scale-up, manufacturing, and warranty claims. For instance, Redflow[58], an Australian company, struggled with scale-up and warranty claims in spite of multi-MW deployments and orders for systems up to 20MWh in size. It was reported that "batteries sold with 10-year warranties were sometimes failing within months of installation. According to financials in a recent administrators' report, the company was spending more on repairing and replacing batteries than it earned selling them."[59] Primus power continues to advertise its Energy Pod 2 which offers 25kW/125kWh modules featuring the zinc bromide flow battery chemistry.[60]

Other potential chemistries in the zinc battery space include zinc-ion including zinc ferrocyanide alternatives. Zinc-ion chemistry has shown significant promise in the laboratory and in the literature[61], but has not yet been widely commercialized, and some attempts to do so have been met with significant challenges, evidenced by the recent filings by Enerpoly AB in Sweden[62].

Market for Zinc Batteries

Because of the growth of the energy storage industry and its projected continued growth, there is interest in diversification of storage technologies, particularly in applications not well-suited to the incumbent lithium-ion technologies.

As such, zinc batteries offer an attractive alternative to some applications in the energy storage space. Most installed energy storage systems in the zinc battery space are nickel zinc or zinc bromide based. They range in size from tens of kilowatts to megawatt scale installations.

Their duration is closely associated with the chemistry utilized—with nickel-zinc tending to meet the demands of shorter duration systems while zinc bromide and zinc air are targeted toward longer duration systems[63]. Market projections suggest that the demand for zinc for batteries for energy storage is expected to reach 43 kilotons by 2030[64].

Target applications for zinc-based batteries are heavily intertwined with their chemistry. In the shorter duration space, for backup and peak shaving, systems are more likely to be nickel zinc, while load shifting and longer duration applications, including long duration storage, is expected to be dominated by zinc bromide and zinc air chemistries.

Areas for Research and Development

In order to compete with incumbent energy storage technologies, zinc-based batteries for energy storage will need to be improved both in its cost and performance.

As discussed in Gong, et al., Xu, et al., and Rana et al., the key technical challenges in zinc batteries are largely tied to dendrite formation and hydrogen gas evolution. Dendrite formation "decreases battery efficiency and potentially causes flow channel blockage. Short circuits can also lead to internal heating with a potential for battery fires."

Hydrogen evolution in zinc-bromine batteries is also of critical importance; as hydrogen ions are consumed, pH increases in the electrolyte which can impact zinc deposition quality on the negative electrode. Use of carbon materials, including carbon nanotubes and doped materials have shown promise in reducing dendrite formation and enhancing lifetime of zinc-based flow batteries, but continued work is needed.

The 2023 Technology Strategy Assessment for Zinc Batteries also highlights the current state of the science as well as identifies key areas for these technologies to improve to progress towards the Department of Energy's "Long duration storage shot" pricing of $0.05/kWh for 10 hours duration[65]. In summary, there are opportunities throughout the entire zinc-battery life cycle, from innovations in mining and metallurgy for battery-grade Zn metal to Improved cathode materials and electrolyte development and enhanced domestic recycling. In this report, "technical innovations included electrolytes, cathodes, and separators, which again correlate with the prioritized impact of the components that impact cycle life efficiency and lifetime," noting that the different zinc chemistries require different cathode developments.

In addition to technical needs to improve battery performance, the report also highlighted the challenges that the zinc battery industry (among other chemistries) has faced with regard to funding for capital purchases and the difficulties in financing scale-up, especially in light of the current tight capital markets.

Performance Targets

Current zinc performance targets have been summarized in the Energy Storage Grand Challenge Cost and Performance Assessment from 2022[66] based on evaluation of the current state of science[67] and expected progress over the next several years through 2030. There is significant complexity in estimating cost and performance parameters for zinc batteries given the variation between types of chemistry, system duration, and other aspects, including depth of discharge.

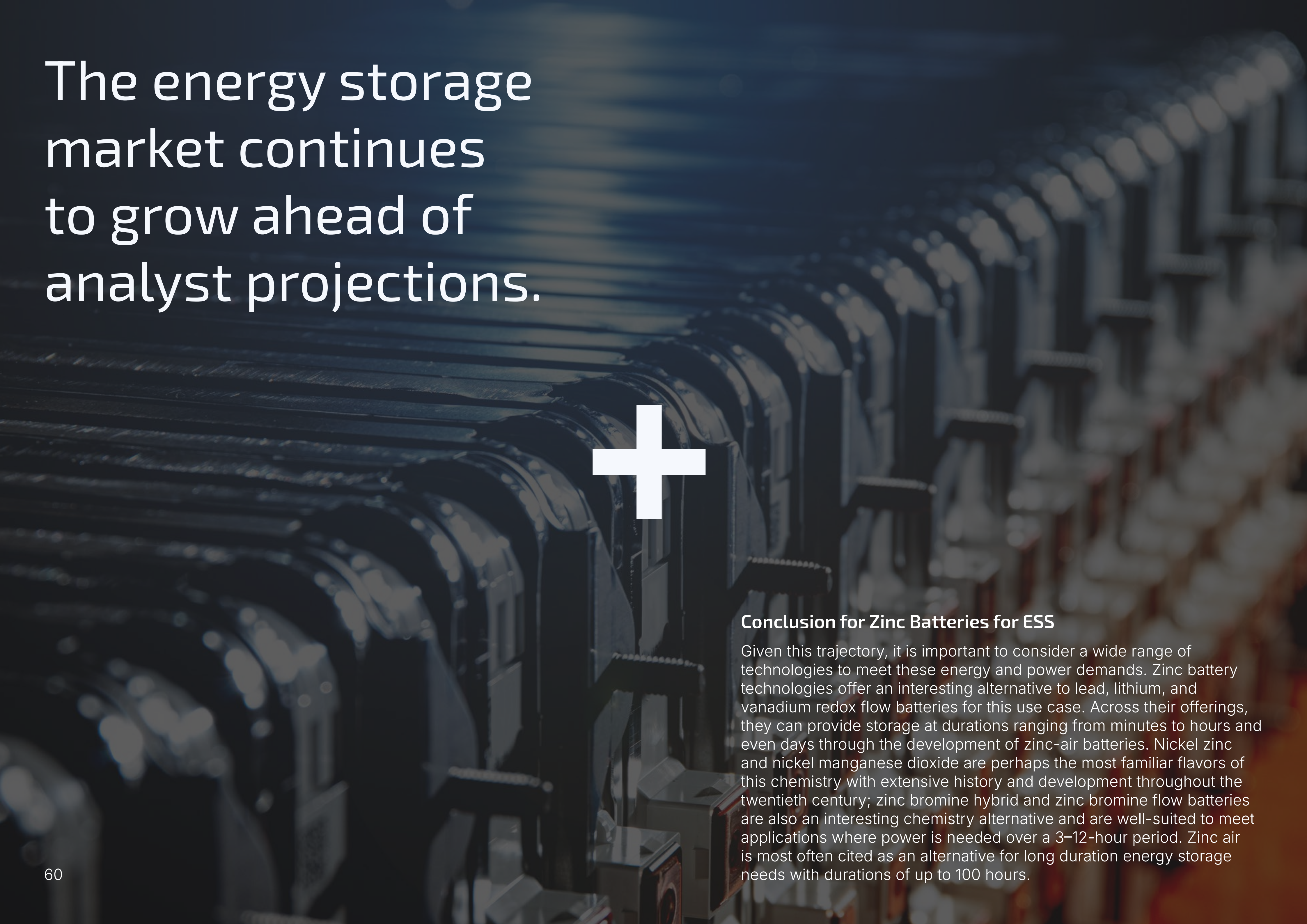
Different zinc chemistries are appropriate for different system durations—with Ni-Zn batteries favored in shorter duration systems (up to 2 hours). Flow and hybrid flow zinc-bromine systems are more appropriate in the 4–8-hour duration, with some companies meeting an even broader range of system durations. Finally, the more novel zinc-air chemistries are expected to be used for long-duration energy storage systems, namely those with durations ranging from at least 8 up to 100 hours.

Total installed system cost is described in Figure 4 of the Energy Storage Grand Challenge Cost and Performance Assessment from 2022 and highlight the range of expected costs for different durations and system scales in both 2021 and projected for 2030.

Ranges are provided for reference for both 1MW and 10MW sized systems. Due to limitations in data provided to the report, larger system sizes do not have cost estimates provided; given the growth and development of certain chemistries, it would be expected that systems of larger power and capacity would come online by 2030 to inform a range of durations, especially in the 4-12 hour range.

Size (MW)	Duration (h)	DOD	Required Rest Time (h)	2021 Cycle Life	2030 Cycle Life	2021 total Installed Cost ($/kWh)	2030 total Installed Cost ($/kWh)
1	2	80%	0.68	2146	2360	494-767	355-575
	4	80%	1.21	3066	3372	432-629	337-499
	6	80%	0.70	1800	1980	411-424	329-341
	8	80%	0.59	6000	6600	400-667	323-538
	10	80%	0.11	6000	6600	394-627	321-508
	24	80%	0.03	6000	6600	365-463	314-429
10	2	80%	0.68	2969	3265	450-767	336-556
	4	80%	1.21	3854	4240	398-603	302-484
	6	80%	0.70	2000	2200	383-392	297-317
	8	80%	0.59	6000	6600	375-667	292-527
	10	80%	0.11	6000	6600	703-627	291-498
	24	80%	0.03	6000	6600	367-523	305-420

Table 17. The performance goals for zinc batteries based on the technoeconomic assessments covered in the “2022 Grid Energy Storage Technology Cost and Performance Assessment” published by Pacific Northwest National Laboratory.



The energy storage market continues to grow ahead of analyst projections.

Conclusion for Zinc Batteries for ESS

Given this trajectory, it is important to consider a wide range of technologies to meet these energy and power demands. Zinc battery technologies offer an interesting alternative to lead, lithium, and vanadium redox flow batteries for this use case. Across their offerings, they can provide storage at durations ranging from minutes to hours and even days through the development of zinc-air batteries. Nickel zinc and nickel manganese dioxide are perhaps the most familiar flavors of this chemistry with extensive history and development throughout the twentieth century; zinc bromine hybrid and zinc bromine flow batteries are also an interesting chemistry alternative and are well-suited to meet applications where power is needed over a 3–12-hour period. Zinc air is most often cited as an alternative for long duration energy storage needs with durations of up to 100 hours.

3.7

Key Performance Indicators for ESS batteries

Improvements to energy density and cycle life are key to lowering the LCOS of lead batteries. Energy density is directly tied to acquisition cost and cycle life is a major factor for operating cost. A quantitative KPI for operating cost is still in development due to the rapid change in guidance from end-users like the EU Energy Commission and USDOE. As an estimate, **0.02 $/cycle/kWh for a desired operating cost** is reflective of feedback from US DOE, Office of Electricity.

3.9

Summary of ESS battery research objectives

This document outlines the suggested research pathways and areas to ensure lead batteries can deliver on the KPIs set out:

Improve cycle life and energy throughput via additives and materials– lower operational costs.	Battery management tuned to lead, zinc, sodium batteries specifically to maximize cycle life.
Increase intrinsic high-temperature durability using advanced materials – a step in increasing cycle life.	Optimize new battery designs, such as bipolar, to ESS applications.
Increase energy density by using new electrode designs– lower acquisition costs in well-established manufacturing.	Productize lead battery solutions with properly controlled charge algorithms and configured control and power conversion systems.

3.8

Priority research areas for ESS batteries

Energy storage for utility and consumer services has existed for decades. Only over the last seven years has the ESS market become a high growth area for batteries and the growth is only predicted to continue into 2050. Lead batteries are uniquely suited for ESS but have not gained appreciable market share in new applications. Zinc, flow, sodium, and nickel-based ESS are in an exploratory and development, and each technology offers unique advantages and improvement areas. CBI believes for non-lithium batteries to stay competitive in ESS applications there must be a concentration on **improving cycling (energy throughput) and volumetric energy density** in conjunction with cost decreases associated with mass scale production.

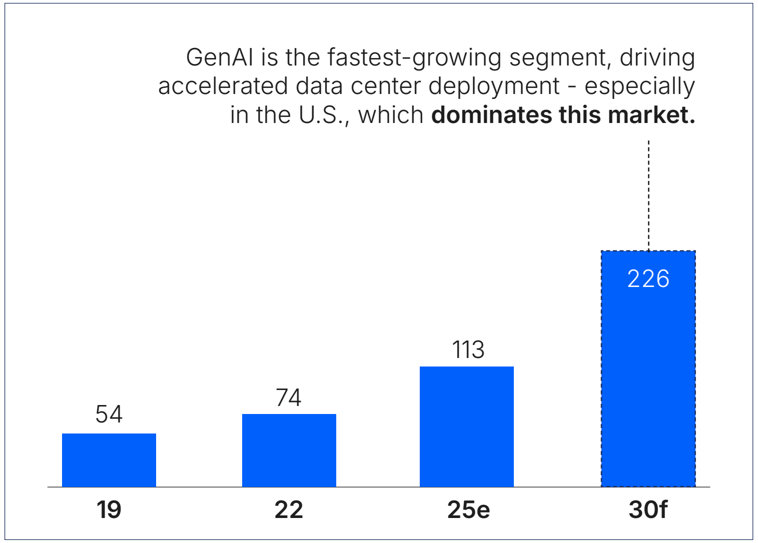
4 Batteries for Telecom and Standby Applications

UPS Applications Introduction

Market Overview

Hyperscale data centers have driven the UPS and distributed battery resources market to new plateaus, demanding batteries of all types to meet the demand and desired performance across the many use cases within a data center. Figure 14 shows the predicted growth in data center capacity until 2030, and the generative AI (GenAI) shows the greatest deployment, especially in the US which contains 45-50% of all data centers.

Estimated datacenter capacity evolution [Global, GW]



Estimated lead battery demand for UPS [Global, GW]

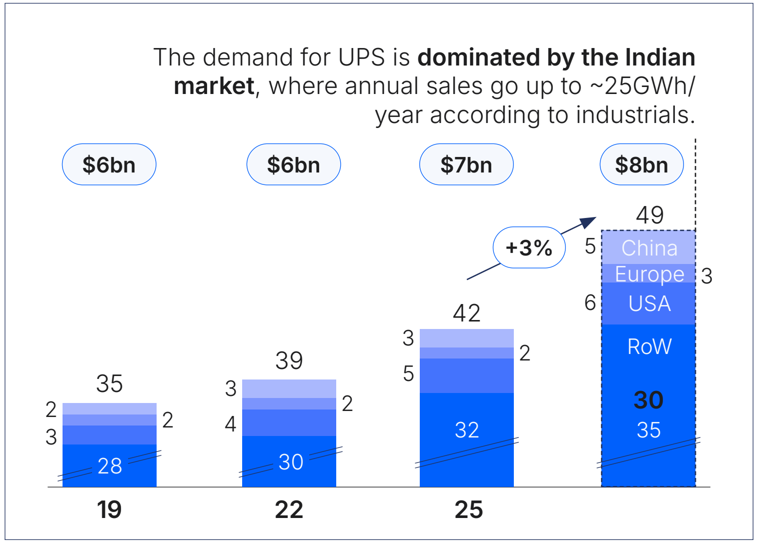


Figure 14 Figure 14 shows the estimated datacenter buildout over the next four years for GenAI, examples would be data centers for AI efforts such as Microsoft's ChatGPT.

The UPS battery growth predicted for lead batteries, does not account for GenAI use as the current backup solutions are difficult to track. Lithium-ion batteries and hybrid supercapacitors are the technology of fastest growth in this segment, but more risk averse users have also chosen to use very large VRLA systems in recent data center corridor designs.

UPS battery growth in GenAI is difficult to predict as individual data centers and users are utilizing different strategies to provide backup power. This includes in-rack distributed energy resources, grid-tied ESS, and traditional battery back-up (such as in battery rooms onsite).

Battery demand will grow at a ~3% CAGR in traditional markets as replacement cycles and modest growth in consumer level UPS, UPS/inverter, and data backup is forecasted until 2030. Within the traditional UPS markets, UPS/inverter is the market to watch as growth is directly correlated to power quality. Demand within India is approximately 90% of this market, and as utility grid stability has improved markedly over the years users have started to invest past small UPS/inverter system toward rooftop solar and residential UPS+ or ESS systems.

Traditional data center backup is dominated by VRLA batteries, and lithium is the only contender in this market. Zinc technology has made inroads, showing superior high temperature performance. However, the technology is still developing and optimizing manufacturing and currently only represents a niche part of the market.

Product Overview – UPS/Inverter Market (India and other Markets)

For the purposes of this discussion, the market and products will be Indian-centric, but 10% of this market is spread across Bangladesh and Southeast Asia. There are also niche markets in North America, Europe, China, and Brazil. These markets are characterized by household UPS systems, blurring the lines between residential ESS and residential UPS, and these niche markets are summed up in the ESS Section of the Technical Roadmap.

Power quality issues are becoming less common as Indian national utility grid is further developed, nevertheless, the 25 GWh market is still a crucial solution for power continuity at the residential level across India. The segment is dominated by tubular, tubular-gel, and to a smaller degree AGM lead battery technology. The main driver for the dominance of lead-based UPS/inverter preference is cost, availability, and safety. For perspective, these units are typically located in the home as small wall mounted or floor mounted units connected to incoming power from an outside wall. Lithium based UPS have been produced, but their role in the market is unclear due to concerns for cost and about fire safety in the very dense urban centers where these UPS/inverter systems are most common. Tubular gel systems are most popular and have proven to be robust, long-lasting, and cost-effective systems. Furthermore, there are many quality producers across India, such as Luminous Technologies and Exide. Tubular batteries are also offered but are less preferred by users due to the need to add water to the battery after a year of use. Advanced AGM and bipolar batteries are being scrutinized for UPS/inverter as they offer a smaller footprint and faster recharge capability – opening the opportunity to change the UPS/inverter market more toward a hybrid residential UPS/ESS. The integration of UPS/inverter system with solar rooftop systems is also a major recent development and is provoking hybrid UPS/ESS type systems as well.

The Roadmap describes the differences in lead battery technology, research areas at the battery and system level, and CBI efforts to create simple controls to integrate with solar rooftop systems.

UPS/Inverter

In the UPS/inverter market warranty period is key as the market is a consumer market, but the technical performance goals center around abusive conditions. It is common for the tubular gel batteries used in these systems to be disconnected and left at open circuit voltage or left under discharged for long periods of time (i.e. months). This condition is damaging to lead batteries (potentially dangerous for other types of batteries) and attempts to regulate this detrimental activity have been through oversizing the battery by 20% and employing controls capable of reserving capacity. Nevertheless, creating UPS/inverter systems capable of more robust activity after long periods of open circuit/rest is important.

Increasing available energy in the UPS/inverter system is a main performance driver. The energy density increases must not compromise the robust durability and long life offered by tubular gel products common in these applications. Furthermore, these systems are located within the home or business typically or on rooftops, and long-term safe operation is crucial. In congested city centers, rooftop solar buildout also means any performance enhancement must also take the partial state of charge operation profiles common in solar-battery system use. Bipolar lead batteries are being studied in these applications due to their high tolerance for abuse and much higher energy and power density. These enhancements come with all the relative advantages inherent to lead battery technology: sustainability, robustness, and safety. Specific performance goals can be found in Table 18.

Lithium-ion UPS systems have made headway in this application, but cost and safety still need to be optimized. KPIs for the major technologies are shown in Table 19.

Performance Metric		2025	2028	2030
Research Goals – improve footprint, simple management systems to improve abusive conditions				
Service Life	Years	5 years warrantied life	6 years warrantied life	7 years warrantied life
	Cycles	1800 (50% DOD) 5000 (20% DOD)	2100 (50% DOD) 6000 (20% DOD)	2500 (50% DOD) 7000 (20% DOD)
Energy Density (Volumetric)	Wh/L	90	100 (for tubular/gel) 135 (for bipolar lead)	100 (for tubular/gel) 150 (for bipolar lead)
Notes on other performance indicators		Create a battery with low maintenance and low cost, effective management. Preserve high temperature performance, safety, and sustainability.		

Table 18. KPIs for tubular gel used in UPS/inverters, energy density goals for bipolar included.

Product Overview – Conventional UPS - Safety Critical (Medical and Utility), Conventional Data Center and Consumer Level

The UPS market is comprised of many different segments, and historically UPS systems market developed around critical services like utility infrastructure and healthcare. Lead batteries, especially VLA, serve as the primary solution in utility infrastructure backup power, extending from substations to the backup for safety critical systems in nuclear reactors.

Consumer level UPS is now dominated by lithium battery-based systems due to higher energy density and the low cost LFP and NMC products available from the ongoing battery industrialization push from China. However, lead batteries are present in many different segments, especially for outdoor UPS due to superior climate tolerance especially at low temperatures. Consumer market segments operate at a commodity pricing level and the ultimate key performance indicator for this segment is cost-balanced by acceptable service life. This segment will not be covered in the Roadmap as the market is dominated by price. Additionally, safety critical back up for nuclear reactors will not be covered, as international standards like IEEE 535, 344 and IEC 60896 directly dictate how lead battery technology should be tested and the performance metrics required in the application.

Conventional UPS Performance Metrics

VLA and VRLA, as well as lithium-ion products, are offered as solutions for the wide array of segments offered in conventional UPS. There is a myriad of use cases, but typically a total cost of ownership model best describes the approach for product acceptance for technologies that meet a given specification. An example of this would be looking at a battery backup installation for a financial institution data center. Discharge times are slower by two orders of magnitude when compared to the new GenAI super high-rate discharge use cases. VLA and VRLA are highly capable of meeting the specified performance requirements, but the cost of the DC system is only a piece of the puzzle. The battery system must provide long life, good discharge performance, and a viable footprint for the facility. The system must also be safe, and not prone to thermal runaway. Installation and maintenance, as well as the cost of the cables, circuit breakers, and racks must be considered. Furthermore, fire walls (if needed), other passive fire protection, active fire protection, floor preparation, and other infrastructural needs like sensors, ventilation, and structural integrity must be taken into account.

In this document, CBI has scrutinized lithium and lead based technologies for this segment, as well as rising, currently fringe technologies like NiZn (preeminent example of a Zn-based battery in UPS). Performance indicators will be discussed in the GenAI/ data center segment. This section of the Roadmap covers utility ancillary services and conventional data center, two markets dominated by long life VLA and VRLA. For lithium it is important to continue to develop safer UPS systems, especially as cell architecture is changing to higher capacity LFP (such as the +2000 Ah variants currently in development). Lithium recycling rates must also increase, as the sustainability profile is poor relative to lead battery technology.

Performance Metric		2025	2028	2030
Research Goals – improve footprint, simple management systems to improve abusive conditions				
Service Life	Years	5 years warrantied life	6 years warrantied life	7 years warrantied life
	Cycles	500 (80% DOD) 1500 (50% DOD) 5000 (20% DOD)	600 (80% DOD) 1800 (50% DOD) 6000 (20% DOD)	700 (80% DOD) 2100 (50% DOD) 7000 (20% DOD)
Energy Density (Volumetric) Specific to lead and zinc	Wh/L	100	110	110
Notes on other performance indicators		Create a battery with low maintenance and low cost, effective management. Preserve high temperature performance, safety, and sustainability – lithium must improve safety and sustainability.		

Table 19. KPIs for lead and zinc batteries in UPS applications

Product Overview – Generative AI (GenAI) Datacenter

Lead batteries have served as the preferred technology in UPS systems, backing up financial institutions, data centers, residential, and medical services. The evolution of the technology has driven lead battery solutions for UPS applications toward faster charging, higher power, and better footprints in AGM and gel VRLA based systems. VRLA serves as a well known solution for many UPS applications. However, the proliferation of much higher power data centers for edge computing and GenAI has changed battery requirements, and nickel based and lithium-based technology have become necessary solutions.

Conventional UPS applications commonly require discharge times on the order of 15 minutes to several hours, offered by a UPS supported by a battery bank housed in a battery room within the facility. Lead batteries provide a good cross section of performance, safety, cost, and ease of use in these applications. In AI and edge computing cases faster discharge times below 15 minutes are required, and sub-minute discharge times are becoming common. Below a 5-minute discharge time, available lead battery capacity becomes limited, characterized by Peukert type behavior. Advanced lead batteries, such as pure lead products, offered by many manufacturers, combat this issue, but still have limited capacity at such fast discharge rates. Lithium based batteries have proven to be a higher performing technology, with a much smaller Peukert effect observed. However, while the performance of lithium batteries is superior to other battery types, the safety and liability issues associated with the technology combined with the burden of fire and safety codes for the technology have made UPS using this technology problematic in certain jurisdictions and use cases.

Furthermore, AI battery backup needs extend out of the conventional battery room approach, and added reliability comes from energy storage systems outside of the facility and server rack level battery distributed energy resources are now being used. UPS discharge rates are becoming faster, and power quality and disturbances are more frequent. Hybrid supercapacitors are being scrutinized within individual server racks as a complement to larger scale backup.

Nickel based batteries, mainly NiZn and NiCd, serve as viable solutions in UPS and concerted product development from companies like SAFT and ZincFive have created a foothold for the technology in conjunction with lithium and lead solutions. Amongst the three main technologies there are distinct advantages and disadvantages to consider, and each technology offers solutions for ESS and UPS battery room needs. Furthermore, lead batteries, lithium batteries, and lithium hybrid supercapacitors offer in-rack solutions. Table 20 compares Ni-based (NiCd and NiZn as distinct separate technologies), Li-based (LFP and LiTi2O7), and Pb-based (advanced VRLA, VLA, and bipolar lead) in UPS applications. Within these tables there are six main considerations: performance, footprint (especially in lieu of NFPA 855 2026/IFC 2024 restrictions), cost, safety, product maturity, and sustainability (from the perspective of recyclability, supply chain, carbon footprint).

Legend: Poor (pink) Inferior (orange) Good (yellow) Strong (green)

	Performance				Footprint		Cost	TCO	Safety	Product Maturity	Sustainability		
Battery Technology	Power Density	Energy Density	Ridethrough	Microcycling	Fire Code Enforced	No Fire Code	$	$	Thermal	Production Capacity	Supply Chain	Recyclability	Carbon Footprint
LFP	Good	Strong	Good	Good	Inferior	Strong	Good	Good	Inferior	Strong	Inferior	Inferior	Inferior
$LiTi_2O_7$	Strong	Good	Strong	Strong	Inferior	Strong	Poor	Good	Strong	Strong	Inferior	Poor	Good
Li Hybrid Super Capacitor	Strong	Inferior	Strong	Strong	Inferior	Strong	Poor	Good	Strong	Inferior	Inferior	Poor	Good
Advanced Pb-VRLA	Inferior	Inferior	Inferior	Inferior	Good	Inferior	Good	Good	Strong	Strong	Strong	Strong	Strong
Pb-bipolar	Good	Inferior	Good	Inferior	Good	Good	Inferior	Good	Strong	Strong	Strong	Strong	Strong
NiCd	Inferior	Inferior	Inferior	Good	Good	Good	Inferior	Good	Strong	Strong	Strong	Poor	Inferior
NiZn	Good	Inferior	Inferior	Good	Good	Good	Inferior	Good	Strong	Inferior	Inferior	Good	Strong
Na PBA	Good	Good	Good	Good	Inferior	Good	Inferior	Good	Good	Inferior	Good	Inferior	Good
Na PVF	Good	Good	Good	Strong	Inferior	Good	Inferior	Good	Good	Inferior	Good	Inferior	Good

Table 20. Comparison of common battery technologies in UPS applications. Capacitors and other forms of storage are not considered in this discussion.

GenAI Research Areas and Key Performance Indicators

There are dozens of different technologies currently being scrutinized for use in energy storage backup (capacitors, flywheels, batteries, mechanical) for UPS applications, this document focuses on the main battery technologies used in three distinct UPS categories: UPS/Inverter, Conventional UPS, GenAI UPS.

The explosive growth of GenAI has resulted in three use cases: distributed energy resources at the server rack level, large scale battery backup, and integrated ESS. Differing performance metrics were developed for the three use cases, and the BTM ESS KPIs detailed in the ESS section are applicable in the GenAI ESS use case. For the other two use cases safety, power density, and response time are important metrics.

There are clear technical, economical, and supply chain related concerns for all the different technologies in the stationary battery application space. In the chart below are highlights of the different issues that need to be addressed for LFP/NMC, $LiTi_2O_7$, NiCd, NiZn, VRLA, and other technologies.

GenAI battery solutions

$LiTi_2O_7$	High cost, supply chain reliant on relatively rare and expensive titanium. Availability issue and poor manufacturing based outside of China.
LFP	More distributed and sustainable supply chains. Explosion and fire issues still relevant.
VRLA	To gain market share, must increase life. Must improve discharge capacity below five minutes.
Ni	Good value principle, best high temperature performance, needs to be optimized. Nickel based batteries with better energy density could be disruptive.
Zn	Maturation of production, product quality inconsistencies, could benefit from BMS. Locations outside of China would assist with cost and supply chain.

Figure 15.
Improvement areas for each battery technology in GenAI UPS. For KPIs refer to Table 13 for ESS and Tables 18 and 19 for UPS.

Telecom Applications

Cable, broadband, and conventional telecom standby battery needs have been supplied by lead batteries for decades, and recently lithium-ion battery solutions have come into the market. In these applications, lithium has become a popular choice for 5G buildout due to its lower weight and higher energy density, while lead batteries continue to be the primary choice for building-base installations. The better safety, lower infrastructure needs, and superior float life of VLA and VRLA lead batteries allows them to go where lithium cannot. NFPA 855 also allows an exclusion for nickel and lead based batteries in telecom due to the better safety profile.

Within the telecom market there are many segments, such as outside and inside plant, cable, 5G buildout, and communication networks. Lithium-ion batteries have replaced lead batteries in several where energy density is a key determining factor.

For telecom applications the principal requirement is calendar life on float. A life of 15 years at 20°C or 10 years at 25°C is a fair description of the current overall state-of-the-art. Cyclic life is of secondary importance unless the power quality is very poor and improved service life at higher temperatures is the key to improving the competitive position of lead standby batteries in this sector. Telecom equipment is often installed in outside cabinets and air conditioning is expensive to operate. As a result, lead batteries in outside plant ends to have a shorter life because of high ambient temperatures.

Performance Metric		2025	2028	2030
Research Goals – improve footprint, simple management systems to improve abusive conditions, maximize float life.				
Life on Float	Years	15 years at 20°C	17 years at 20°C 10 years at 40°C	20 years at 20°C 10 years at 40°C
	Cycles	400 (80% DOD)	500 (80% DOD)	600 (80% DOD)
Shelf Life	Years	2	2	2
Notes on other performance indicators		Create a battery with low maintenance and low cost. Preserve high temperature performance, safety, and sustainability.		
Cost must be driven toward $175/kWh				

Table 21. KPIs for batteries in telecom applications.

Research Areas for Standby Lead Batteries

Lead batteries' footprint in UPS applications, such as data centre back-up, are not currently limited by International Fire Code (IFC) or National Fire Protection Agency (NFPA). Authorities having jurisdiction (AHJs) over data centres strongly consider fire codes, and in cases when fire codes are enforced lead batteries have a smaller footprint when compared to lithium ion. Li-ion batteries are restricted in footprint and battery packs and must be spread out to mitigate fire risk.[68]

However, lead battery innovation must occur to further minimize the overall space requirement for sufficient data centre back-up. Lead battery Peukert behavior negatively impacts the capacity of standby batteries at the currently required 15-minute charge rate, requiring for larger battery banks to accommodate for the drop in discharge capacity.

An example of the drop in discharge capacity is represented in the Figure below:[69]

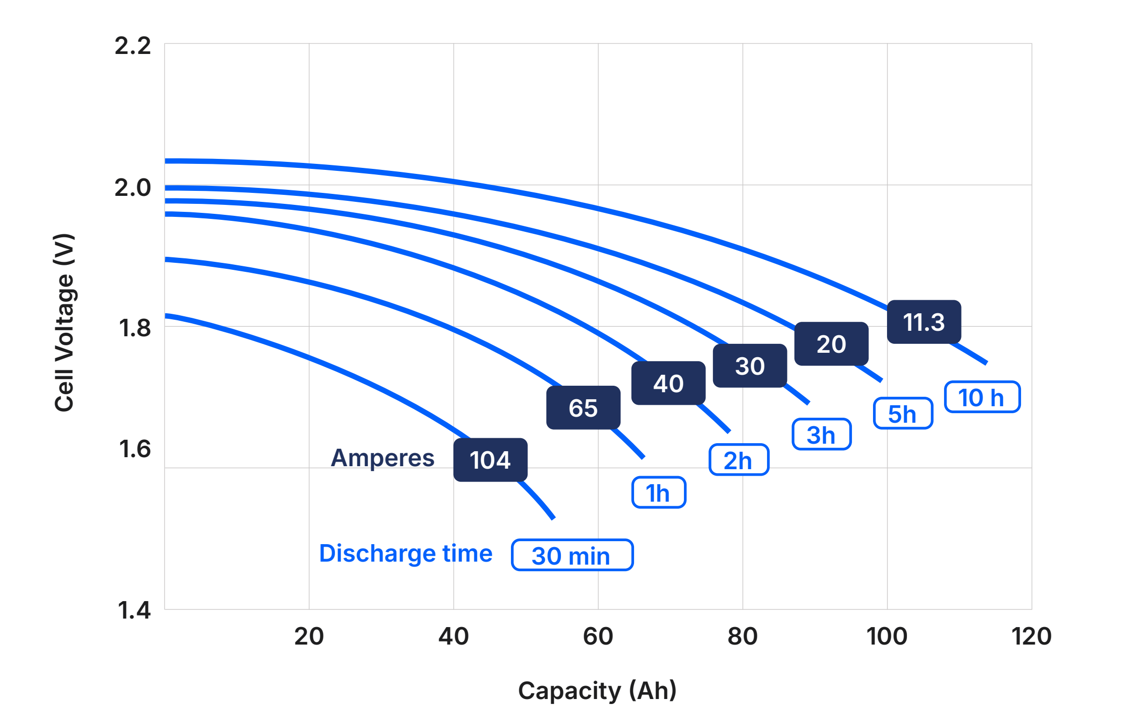


Figure 16. Example of the impact of discharge time on available capacity in lead batteries due to Peukert effects.

Potential areas and developments that may assist in this drop in discharge capacity common to some types of lead battery technology include:

- Carbon additives, specifically conductive carbon blacks and graphites that increase electrochemical surface area.
- Thin, pure lead electrodes result in a lower internal resistance and better utilization.
- Bi-polar products.

For standby batteries, irrespective of application, the service life on float is dependent on the corrosion life of the positive grids. These are either pure lead or lead-calcium-tin alloys. Pure lead grids tend to be a proprietary product offer as much of the technology needed to manufacture products efficiently is unique to a limited number of suppliers. Pure lead may be alloyed with tin to improve cyclic performance. Most of the industry uses lead-calcium-tin alloys which have evolved to higher tin levels and lower calcium levels over several years to reduce corrosion, improve cyclic behaviour and improve the age hardening response. Automotive applications will also benefit from more corrosion resistant alloys and the effects of barium and silver as alloying elements have been highlighted in the corresponding Roadmap.

The grid manufacturing process is also important. Conventionally cast positive grids are widely used for standby batteries. Improvements to corrosion behaviour would result from the use of wrought strip and punched grids but the diversity of plate sizes used for standby batteries limits the use of this technology because tooling costs and short production runs need to be considered. For pure lead grids, punching is invariably used as very soft grids can only be handled in this way.

Innovation in manufacturing technology is likely out-of-scope for a pre-competitive research program but any studies on new alloys should recognise the manufacturing processes that will be used.

There is no 2025 interim milestone set for research on standby batteries as the focus of product development is on long term durability. Testing should follow IEC 60896-21/22.

The KPIs indicate that cycle life should be a target. Some of the research areas identified to improve high temperature durability for automotive batteries may benefit standby batteries but will need to be adapted for other applications. In practice, most standby batteries see very little cycling unless the local utility is unreliable and it is difficult to justify this as a priority KPI in this sector. Suitable research pathways to improve VLA batteries are studying the impact of catalytic recombiners and vents on service life and watering frequency. Also, auto watering systems may be a useful addition to VLA, mitigating the need for routine watering maintenance.

Much of the research directed at the understanding and use of advanced carbons for automotive and ESS service will have applications for hybrid UPS applications as these have a shallow cycle duty. It may be useful in studies directed at ESS batteries to include hybrid UPS.

Another area which could be considered is charging strategies. Telecom and UPS batteries are maintained on float with the load for telecoms supplied by a rectifier and for UPS, the load is supplied from a rectified DC supply through an inverter. In both cases, there is a true no-break supply but it may be possible with innovations in electronic control systems to charge the battery intermittently which would improve life but maintain full security for the power supply.

For hybrid UPS applications, the research areas defined for ESS are applicable.

Summary of Telecom and UPS Battery Research Objectives

- Improve the corrosion life of positive grids to extend life at higher temperatures.
- Increase cycle life in all duty cycles using additives.
- Maximize life at float for UPS using pure lead materials.
- Improve shallow cycle life for UPS batteries for hybrid applications.

5 Batteries for Motive Power Applications

Motive Power and Industrial Equipment Batteries Market

The motive power lead battery has been key to the electrification of lift trucks, providing a cost-effective, reliable solution. Lead batteries have been the dominant chemistry in this market for many years and 60% of the current motive power market is fulfilled by lead batteries, in applications such as forklift trucks, mining vehicles and other warehousing vehicles. With the market predicted to grow to ~35 GWh by 2030, this is a significant sector for lead and lithium batteries.

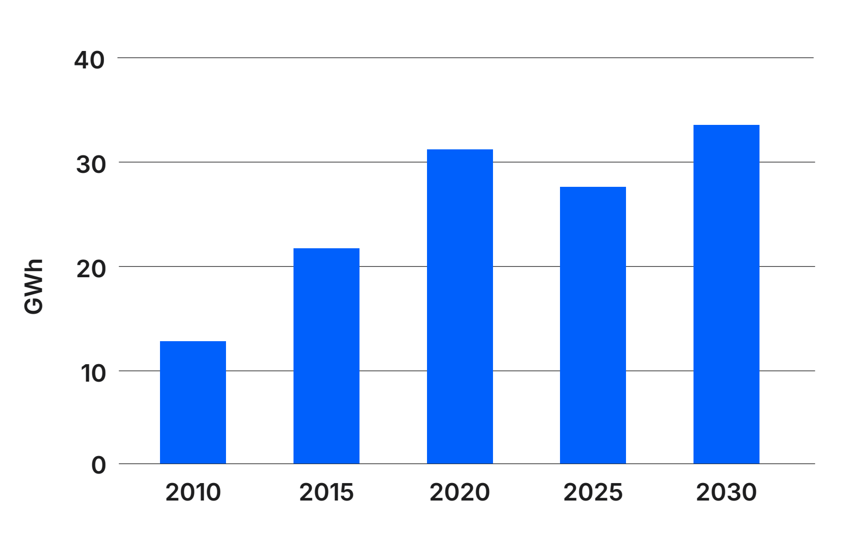


Figure 17. Lead battery motive power battery demand to 2030.

The performance expectations for motive power batteries are formed around a harsh usage profile with high DOD duty cycles, intermittent charging, and differing charging equipment.

The research areas covered by this Roadmap for motive power applications are directly applicable to lead batteries for Class I, II, and III lift trucks, and small recreational vehicles, such as golf carts. Although scrubbers and sweepers are not directly addressed in this Roadmap, many of the research areas and performance goals are relevant for innovation for that application.

Motive power batteries are also used in e-bike/e-trike/e-rickshaw markets particularly in China and India, but the market drivers and performance needs differ and batteries for these applications will be covered separately. Across the many types of equipment that may use lead batteries, lift trucks and golf carts for instance, there are commonalities:

In lift trucks there are a wide array of solutions – batteries (lead and lithium), ICE (diesel, propane, natural gas), and hydrogen.

Significant penetration from lithium-ion solutions into the market, mainly as LFP.

An evolution in warehousing, 24/7 use or multiple shifts are much more common for lift truck use.

Significant predicted growth, with Total Cost of Ownership (TCO), driving more of the mindset for end-users of motive power batteries.

Taking all of these factors into consideration, CBI has constructed KPIs focused on Total Cost of Ownership and market driven end-user requirements. The key focus of future work in this area is to lower TCO by increasing cycle life, recharge time, and producing maintenance-free batteries.

Motive power batteries offer a range of performance in high DOD duty cycles, with products operating between **500-1500 80% DOD cycles** based on BCIS-06 testing. Higher performing motive power lead batteries are much more competitive with lithium-ion in terms of TCO.

Another behavior of some lead motive power batteries is as capacity falls a corresponding drop in power happens, experienced as a drop in performance as the battery reaches low SOC. Currently, most off the market offerings are flooded batteries that require maintenance and may require the customer to have watering/change out rooms for lead battery powered forklifts.

Performance Metric	2025	2028	2030
Cycle life	1800 (50% DOD) 1100 (80% DOD)	2250 (50% DOD) 1250 (80% DOD)	3000 (50% DOD) 1750 (80% DOD)
Service life	Forklift (OE requirement in most regions): 5 years E-rickshaw: 2 years	Forklift (OE requirement in most regions): 5 years E-rickshaw: 2 years	Forklift (OE requirement in most regions): 5 years E-rickshaw: 2.5 years
Energy density (specific to charge efficiency)	35 Wh/kg - lead 150 Wh/kg - lithium	35 Wh/kg - lead 150 Wh/kg - lithium	35 Wh/kg - lead 150 Wh/kg - lithium
Charge time to 30 – 80% Opportunity Charging	1.5 hrs	1 – 1.5 hrs	1 hr or less
Technology requirements	▪ Lower maintenance products present ▪ Management of the battery[a] ▪ Harmonize with Chargers[b] ▪ Few products capable of opportunity charging	▪ Low maintenance more common ▪ Management and monitoring of the battery[a] ▪ Harmonize with Chargers ▪ Capable of opportunity charging	▪ Low maintenance typical. ▪ Management and monitoring of the battery[a] ▪ Harmonize with Chargers ▪ Capable of opportunity charging

Table 22. KPIs for lead and lithium batteries in motive power - forklift and E-rickshaw applications.

E-rickshaw battery KPIs

While the KPIs for motive power batteries for forklift and e-rickshaw are similar, there are huge differences in service life, field usage, testing and TCO needs.

Lead and lithium batteries for e-rickshaws experience notably abusive use conditions consisting of high temperature (+35 °C), high utilization use cases combined with routine overdischarge and undercharge. These usage scenarios are common and result in lead battery product designs towing the line between robustness/longevity and high charge acceptance/smaller footprint. Reaching warrantied life is difficult for most lead e-rickshaw batteries in these highly abusive conditions resulting in a gradual migration to lithium e-rickshaw batteries from major providers. Tubular gel lead batteries have continued to innovate and major KPI for e-rickshaw batteries (lead and lithium) is to routinely deliver at least 2 years of service life. For lithium batteries, it is important to provide good service life of more than 2 years, but to also provide a safe system capable of being routinely abused. BMS and simple control systems need to be purpose built and reliable to inhibit potentially dangerous overdischarge conditions.

Currently in the market lead batteries are used in the replacement market and in lower tier models, and lithium-ion (LFP) is being introduced primarily in newer, more expensive models. Lithium-ion packs are currently under scrutiny by standards bodies in India, and future products must be compliant to AIS-156 from 2027 onwards. Audits and certifications (such as the IATF 16949 which may be adapted into this market) will be important to conduct in 2026, making sure both supply chains and safety systems adhere to local regulations.

There is still potential market growth and runway for lead batteries for e-rickshaw applications. Currently lead batteries experience highly abusive overdischarge and undercharge with no thermal incidents. Moving forward simple, integrated BMS devices, inhibiting these extreme conditions could greatly benefit lead batteries used in the e-rickshaw market. Lead batteries currently use IEC 63193:2020 for performance and safety testing. Also both lead and lithium must adhere to the Bureau of Indian Standards (BIS) and Federation of Indian Chambers of Commerce and Industry (FEMA) requirements for safety, labelling, and auditing.

CBI has developed KPIs focused on keeping motive power lead batteries the dominant battery for electric lift trucks and small recreational vehicles like golf carts. The KPIs in Table 22 are based on market-driven requirements forming in these applications. Cycle life for traction (motive power) batteries is tested currently using BCIS-15 and IEC 60254. The KPIs for 2025 - 1800 (80% DOD) - are introduced in this document. These targets were chosen with these test sequences in mind, in addition to the impact of higher cycle life on TCO. Like ESS, increasing energy density in motive power batteries would translate to higher capacity batteries at the same product weight. Lead batteries are still the best option for single shift operations or intermittent use cases for forklifts and other traction applications. In the case of multiple shift or 24-hour warehousing operations, lead batteries fall behind and the following KPIs are necessary for lead batteries to be the best solution in this environment:

1. The maintenance required for antimonial flooded traction batteries contributes to higher cost of ownership. Watering and charging/change-out rooms (or areas) are typically necessary when these batteries are used. Other battery types, like lithium-ion, do not require the extra space and maintenance. Therefore, a major area of development should be in **maintenance-free lead batteries.**

2. Charging time to a "fast" charge (80% SOC) is an important consideration when choosing a product for electric forklifts. Like new automotive battery requirements, lead batteries in traction and motive power applications must have both fast recharge times to ~80% SOC and be able to be "opportunity" charged. Long equalization charges are burdensome and an issue for some lead battery products.

3. Both battery management and monitoring have become standard in lift trucks. These added components offer an alternative pathway to maximizing battery life.

Low Speed Electric Vehicle Applications (LSEV)

Traction batteries for low-speed vehicles are an important market in Asia, and millions of lead-based and lithium-ion based battery packs are produced annually to meet the needs of the market. E-rickshaws in India use lead battery packs, typically two 12 V tubular or tubular gel batteries, or in more recent years lithium-ion battery packs. In China, e-bikes and e-scooters are popular, with VRLA lead (typically AGM) and lithium-ion solutions available. The Chinese e-bike market has undergone several iterative evolutions, first starting as a lead battery market, swinging to lithium-ion as the main solution, and then due to a high number of fire incidents and relaxed regulation back to a lead battery dominated market.

Markets in Vietnam, Thailand, Philippines, and Bangladesh are growing, but the global market is dominated by consumption from India and China.

5.3

E-rickshaw Batteries

The lead battery market in India for E-rickshaws is fundamental to the transportation sector, powering millions of LSEVs across the country. Main providers include Exide, Eastman, Luminous, and Livguard. The market is estimated to be 1.21 billion USD in size, although due to the many different distributors of both batteries and E-rickshaw market evaluations differ.

The usage profile of E-rickshaws is highly abusive, with routine overdischarge and high temperatures being characteristic in the duty cycle. Undercharge is common as well, as end-users routinely opportunity charge to continue use. Tubular gel batteries excel in these conditions but still suffer from premature end-of-life. Negligent overdischarge and routine undercharging are damaging for batteries, and the employment of equipment to disable overdischarge would be helpful for lithium and lead batteries in this application.

Opportunity charging is important, and poor charging behavior from lead batteries has opened the market to lithium-ion batteries. Similar to motive power applications, improving opportunity charging will help lead batteries stay competitive in the market. Lithium-ion on the other hand, while possessing superior performance, must focus on safer operation especially at high temperatures. KPIs for lead batteries in E-rickshaw batteries are shown in Table 22. Additionally improving service life in E-rickshaw to 2-3 years is crucial for all battery types.

5.4

Current Status of Forklift Batteries

The motive power lead battery has been key to the electrification of lift trucks, providing a cost effective, reliable solution. The performance expectations for motive power batteries are the harshest amongst all the applications, with high DOD duty cycles, intermittent charging, and consistent use typical for batteries in these applications.

In 2019, CBI's previous Roadmap research areas and directions for the technology were discussed. Since then, CBI has developed more material for motive powers, focused on KPIs, detailed research areas, and technical targets for lead batteries in motive power applications. For the purposes of this chapter of the document, focused on motive power applications, the research areas are directly applicable to lead batteries for Class I, II, and III lift trucks, and small recreational vehicles, such as golf carts. Although scrubbers and sweepers are not directly addressed in this document, many of the research areas and performance goals are relevant for innovation for that application.

Across these many pieces of equipment there are commonalities:

In lift trucks there are a wide array of solutions – batteries (lead and lithium), ICE (diesel, propane, natural gas), and hydrogen.

Significant penetration from lithium-ion solutions into the market, mainly as LFP.

An evolution in warehousing, 24/7 use or multiple shifts are much more common for lift truck use.

Significant predicted growth, with total cost of ownership (TCO), driving more of the mindset for end-users of motive power batteries.

With all these factors in mind CBI has constructed KPIs focused on TCO and market driven end-user requirements.

Motive power batteries offer a range of performance in high DOD duty cycles, with products operating between **500-1500 80% DOD cycles** based on BCIS-06 testing and IEC 60254. Higher performing motive power lead batteries are much more competitive with lithium-ion in terms of TCO. Another behaviour of some lead motive power batteries is as capacity falls a corresponding drop in power, experienced as a drop in performance as the battery reaches low SOC.

Currently, most off the market offerings are flooded batteries that require maintenance and may require the customer to have watering/change out rooms for lead battery powered forklifts.

Market forecasts for motive power batteries

Lead batteries have paved the way for the electrification of the forklift fleet across North America and Europe. Over the last 15 years, the percentage of Class 1-3 lift trucks powered by batteries has steadily increased. Furthermore, the motive power market is complemented by other applications like golf carts and floor scrubbers.

In 2024, the forklift lead battery market was 7.58 billion dollars.[70] COVID caused a 10-12% retraction in the market, and since then has rebounded. The CBI commissioned Avicenne report has identified several key trends in the motive power market:

1. 24-hour warehousing and shipping centres has made a stronger case for long lasting motive power batteries – such as lithium ion. In this case the TCO makes more sense with fewer replacements necessary vs. lead batteries.
2. Lithium-ion battery penetration in the market is approximately 10%.
3. Maintenance on batteries has been identified as a negative, and developing maintenance free lead batteries for motive power is an important productization pathway to consider.

Below is current market info and predictions for the next ten years for the motive power lead battery market.

Motive battery demand CAGR15-30: 7,3%/year

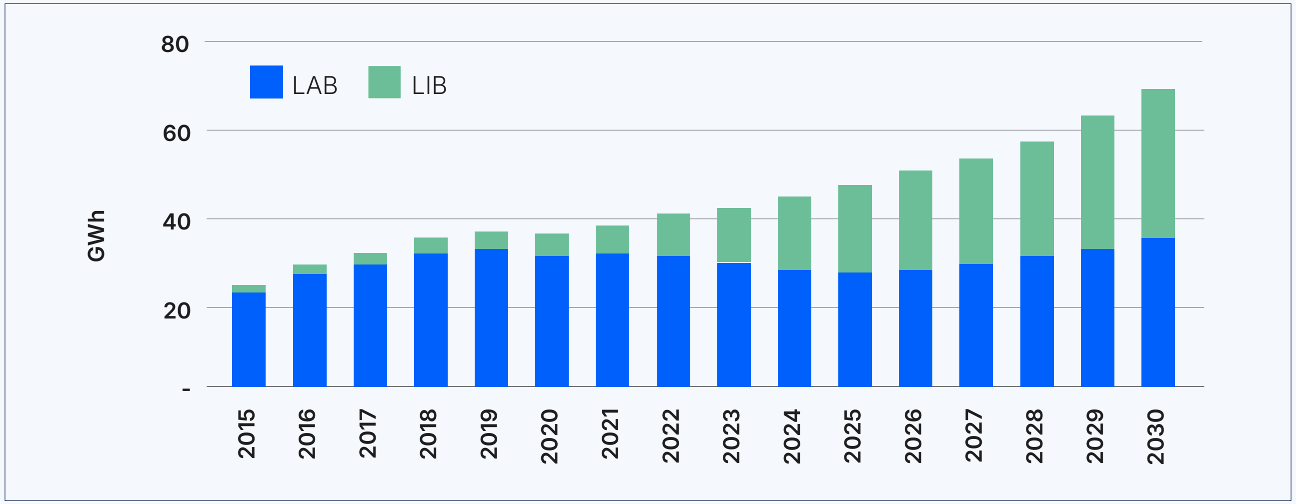
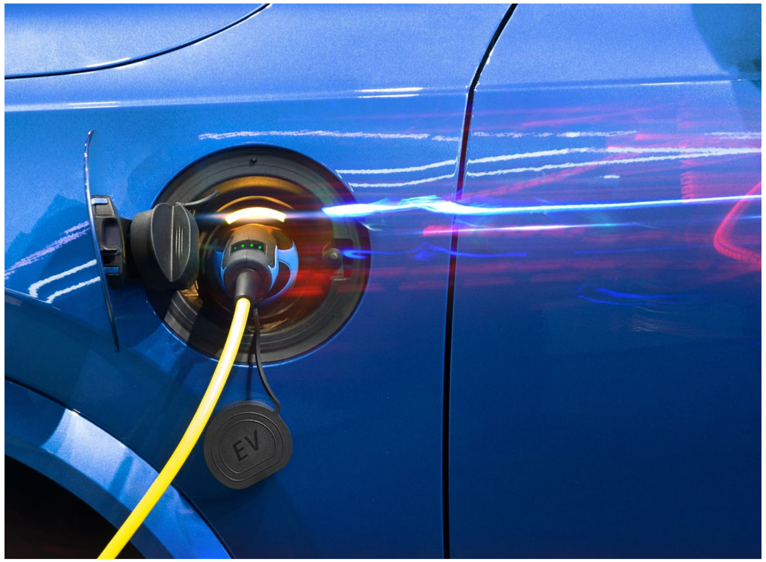


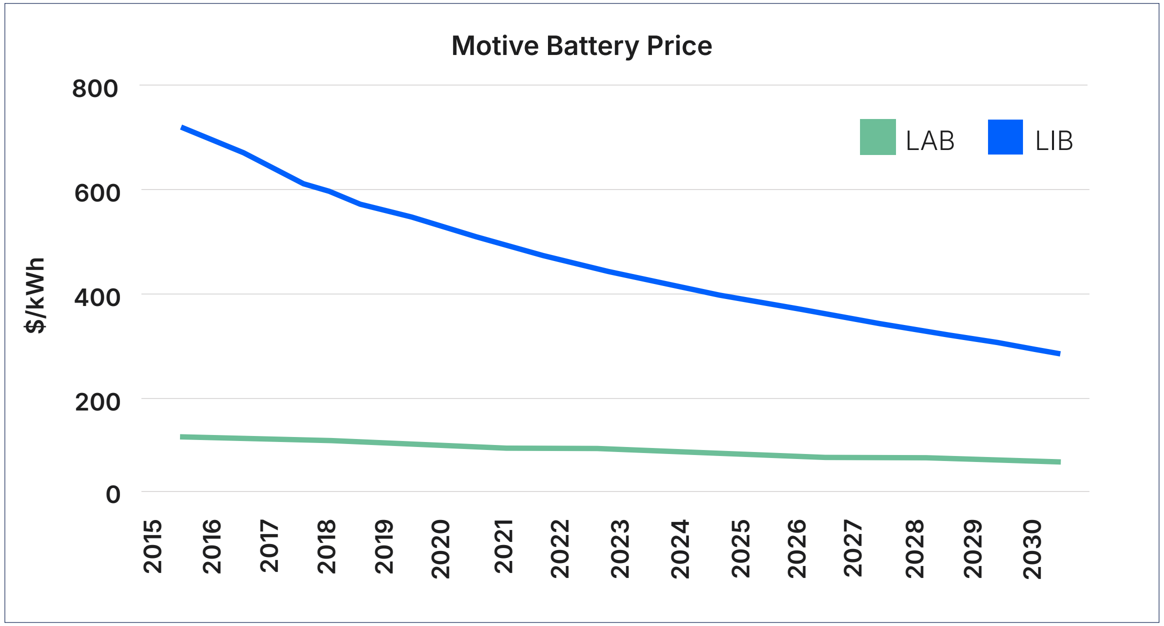
Figure 18. Market predictions for lead and lithium-ion batteries in motive power market.

Figure 19 shows the market penetrations of lithium-ion batteries (LIB) since 2015. Predicted market for lithium-ion 2030 is predicted to be 49% from the Avicenne report. However, current market info gathered through April 2024 has shown a 7.3% growth in lead battery demand. The current volatility in the motive power market, combined with efforts at the local and federal level in NA and Europe have indicated a better market for lead batteries in the coming years.

Warehousing across the world is electrifying forklift fleets, using lithium and lead batteries for continuous operations formerly carried out by ICE (propane, diesel) forklifts).

Opportunity charging has become an important part of the duty cycles for forklifts in materials handling and logistics. Uptime is a crucial piece of the TCO and increasing capacity at a given moment by charging during breaktimes and shift transitions.





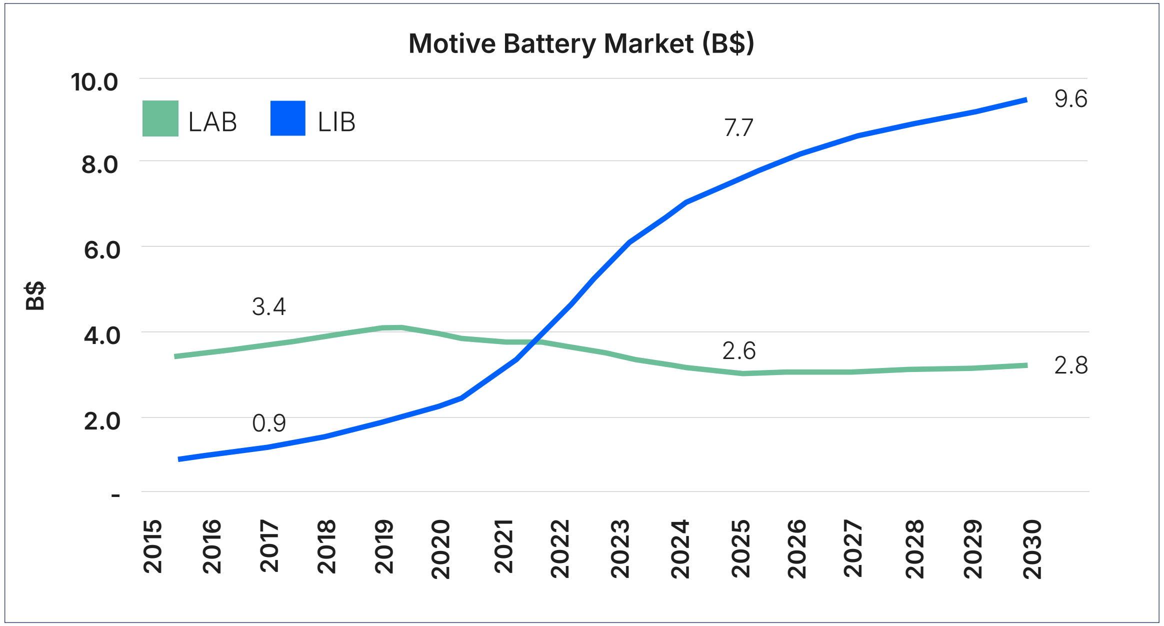


Figure 19. The pricing and motive power battery markets predicted for lead and lithium products for forklifts and other heavy industrial equipment.

Research areas for motive power batteries

Flooded lead batteries provide long service life of more than five years in forklift applications. The end-user base is familiar with the technology, the need for maintenance and the relatively slow charging times synonymous with flooded products. Despite advanced in flooded lead battery technology, mainly around lower maintenance requirements and longer service life, lithium ion (LFP) has captured approximately 10% market share in the battery power forklift market. This penetration by LFP is growing, due to several advantages that LFP offers:

1. No maintenance required. This is significant, and lead batteries must move toward lower maintenance requirement. The obvious solution is to migrate lead battery offerings toward VRLA.

2. Longer uptime/faster charging/opportunity charging. Although LFP is significantly more expensive, the total cost of ownership (TCO) for the technology is more attractive due to a higher length of uptime afforded by the product.

Research Area	Sub-Topic
Additives	Increasing service life through more uniform active material use
	Carbon addition and impact on charge time
Expanders – Lignin, organic molecules	$PbSO_4$ control and impact on reversing sulfation
Battery Management and Control	Using current systems and changing algorithms to maximize life
Tailored materials for maintenance free operation	Lowering gassing potentials, enabling VRLA architecture

Table 23. Research areas for motive power batteries.

These advantages are now drivers in the market, and lead batteries over the next six years must innovate in these broad categories. Currently there are no-maintenance VRLA products offered for forklifts, but flooded products are most of the lead battery technologies used today. KPIs are listed in Table 22, and research areas are as follows:

1. Service life – flooded lead batteries offer strong performance in this category; innovation would be focused on maintaining service life of five years or more with a maintenance free lead battery.

2. Energy density - Lead batteries serve not only as the motive power source for forklifts, but as the counterweight for lift operations. However, energy density improvements allow for better Peukert behavior.

3. Charge time/opportunity charging – increasing uptime by enabling opportunity charging and faster charge time for lead batteries is an important motivator for lowering TCO.

4. Management and Charging Equipment – battery management solutions are offered for lead batteries, but can be improved to benefit both service life and charge time.

Opportunity Charging Research

The 2023-2024 CBI Technical Program included projects focused on characterizing opportunity charging for motive power batteries. Figure 20 shows an example of the charging sequences developed to study opportunity charging of motive power forklift batteries.

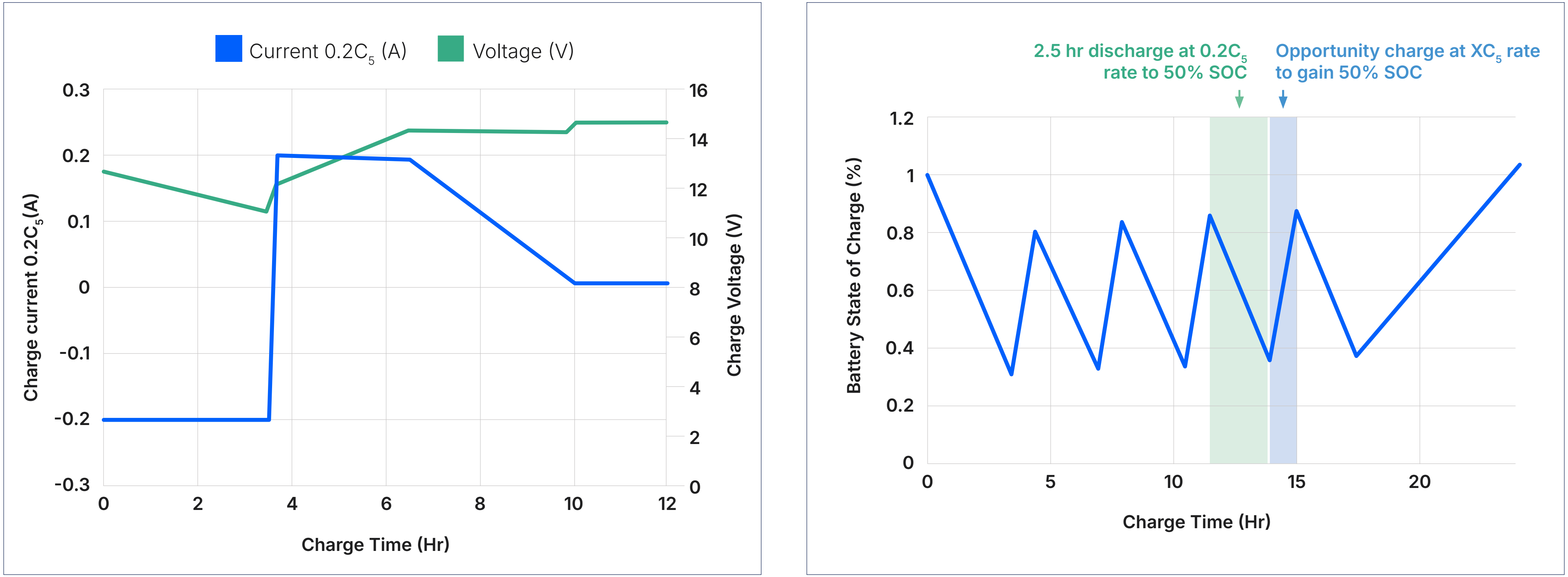


Figure 20. Comparison of standard motive power testing sequences from IEC 60254-1 to a new opportunity charging regime for lead batteries developed by CBI.

Advanced charging algorithms have been developed, allowing for 50% SOC recovery in AGM batteries in under 1 hour and less than 15 minutes for LFP without suffering measurable damage. BCI-22 opportunity charging test sequences are also a suitable method for measuring opportunity charging in forklift batteries.

Summary of motive power battery research objectives

This document outlines the suggested research pathways and areas to ensure lead batteries can deliver on the KPIs set out:

- Improve total energy throughput via additives and materials – lowering operational costs.
- Increase energy density by using new electrode designs – lower acquisition costs in well-established manufacturing.
- Advanced battery management and monitoring are increasingly more important as motive power batteries are continuously used and opportunity charged.
- Optimize new battery designs, such as bipolar, to motive power applications.
- Productize lead battery solutions with properly controlled charge algorithms and configured controls.

Concluding Remarks

CBI works with our member companies to increase battery performance, especially in lead battery applications, with a focus on improving and promoting sustainable, robust, and safe energy storage solutions. The CBI Battery Roadmap is important, as it provides a clear picture on the needs for batteries in the global energy storage applications, as shown in Table 24.

CBI believes the market will move in the directions outlined above, and in order to meet these requirements, we believe the research goals set out in this roadmap must be met. This document also highlights the research areas we believe will deliver on these goals. These goals will be used to develop a new RFP to select new CBI technical projects.

SLI	ISS / Micro-hybrid	Auxiliary batteries
▪ CCA ▪ 20 h capacity ▪ 5 – 7 year life ▪ Low cost ▪ Recyclable	▪ Maintaining DCA ▪ Maintaining HT durability ▪ Low cost ▪ Recyclable ▪ CCA	▪ PPC ▪ Charge Recovery ▪ 5+ year life ▪ Low cost ▪ Recyclable

Telecom	UPS	Motive Power/LSEV	ESS
▪ Calendar life ▪ 8 – 10 h capacity ▪ Low cost ▪ Recyclable	▪ Calendar life ▪ 15 m performance ▪ Footprint ▪ Low cost ▪ Recyclable	▪ Cycle life ▪ 5 h capacity ▪ Low cost (TCO) ▪ Recyclable ▪ Weight	▪ Calendar life ▪ Cycle life + PSOC operation ▪ Footprint ▪ Low cost ▪ Recyclable

Table 24. Summary of the requirements for batteries in major applications.

In low voltage automotive applications, lead batteries dominate the market providing a low cost, sustainable, robust energy storage technology. SLI and micro-hybrid/SS battery markets are mature and the requirements from end-users have not changed. Improving DCA and high temperature durability is no longer as important, and lowering cost is the main need now in these markets.

In the Auxiliary battery market, PPC and charge recovery are the most important concerns, especially at low temperatures. Lead batteries excel in low temperatures vs. lithium and sodium-based alternatives. Charge recovery must improve for lead batteries to stay competitive.

In stationary applications, energy throughput is key across all the applications, with service life at float or from cycling being the most important requirement. In BTM applications, footprint and safety are important, as these systems will be found at residences and within population centers.

In motive power and LSEV, opportunity charging and lifetime are most important, and creating long life (+5 years in forklift, +2 years in LSEV) batteries is key in these markets. Safety is a major concern as these batteries are used in densely populated areas and near large capital assets.

CBI Member Only Roadmap

For CBI members, a more detailed version of this Roadmap is available. In the member only document there is more info on:

1. Specific research pathways for each technology
2. Examples of how CBI research helps either understanding or the performance of KPIs
3. Details on research progress to date
4. Examples of performance testing
5. Appendices covering testing protocols

Interested in membership? Reach out to info@batteryinnovation.org and find out how to become a member of CBI.

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References

1 CBI, KPMG Battery Market Report 2025.

2 Lead acid & global battery market report from Avicenne Energy, May 2025.

3 Battery market report: 2030 Outlook from KPMG Strategy, June 2025.

4 Avicenne Energy, 2024.

5 EU Regulation 2019/631 on CO2 Emission Standards for Cars and Vans.

6 Amara Raja integrated annual report 2024-2025 and Exide integrated annual report 2024-2025, presentation by M. Shariff in ALBA Asia, Kota Kinabalu, September 2025.

7 Overview of the Asean-6 automotive market report, February 2025.

8 Yu Ping, ALBA Asia Workshop, September 2025, Kota Kinabalu.

9) May, G.J.; Davidson, A.; Monahov, B. Journal of Energy Storage 2018, 15, 145-157.

10 Myrvold, B.O.; J. Power Sources 2003, 117, 187-202.

11 Mavredaki, E.; Neville, A.; Sorbie, K.S. Cryst. Growth Des. 2011, 11, 4751–4758.

12 Stack, A.G.; J. Phys. Chem. C 2009, 113, 6, 2104–2110.

13 Myrvold, B.O; "The relationship between lignin expander structure and performance in lead-acid batteries" Conference: Battery Conference on Applications and Advances, 2000. The Fifteenth Annual, February, 2000.

14 https://www.gs-yuasa.com/en/newsrelease/article.php?ucode=gs160310154418_236

15 (1) Giess, H.K.; Ding, F. B. "Charge acceptance issues when a VRLA/AGM cell is operated with the IEC 61427-2 clause 6.2 and Sandia PNNL 5.3.2 profiles simulating frequency-regulation duty in power grids" LABAT' 2021 Lead Acid Batteries Conference, Virtual, June 2021. (2) For full report: http://batteryinnovation.org/?secfile=7915

16 (1) Lannellongue, J.; Cugnét, M.; Guillet, N.; Kirchev, A. J. Power Sources 2017, 365, 194-207. (2) Kirchev, A.; Serra, L.; Dumenil, S.; Brichard, G.; Alias, M.; Jammet, B.; Vinit, L. J. Power Sources 2015, 299, 324-333. (3) Lannellongue, J.; Cugnét, M.; Guillet, N.; De Vito, E.; Boulineau, A.; Kirchev, A. Journal of Energy Storage 2018, 20, 230-243.

17 Department of Energy, U. (2023). Technology Strategy Assessment Findings from Storage Innovations 2030 Flow Batteries. https://www.energy.gov/oe/storage-innovations-2030.

18 Ding, C., Zhang, H., Li, X., Liu, T., & Xing, F. (2013). Vanadium flow battery for energy storage: prospects and challenges. J. Phys. Chem. Lett., 4(8), 1281–1294. https://doi.org/10.1021/jz4001032

19 Liu, W., Lu, W., Zhang, H., & Li, X. (2019). Aqueous flow batteries: research and development. Chem. Eur. J., 25(7), 1649–1664. https://doi.org/10.1002/chem.201802798

20 Zhang, H., Lu, W., & Li, X. (2019). Progress and Perspectives of Flow Battery Technologies. Electrochemical Energy Reviews, 2(3), 492–506. https://doi.org/10.1007/S41918-019-00047-1/FIGURES/13

21 C. Doetsch and J. Burfeind, "17 - Vanadium redox flow batteries," in Storing Energy (Second Edition), T. M. Letcher, Ed., Elsevier, 2022, pp. 363–381. doi: 10.1016/B978-0-12-824510-1.00030-1.

22 S. C. Caroline, S. P. Madhusudanan, G. K. Dalapati, and S. K. Batabyal, "Chapter 22 - Energy storage technologies for sustainable development," in Sulfide and Selenide Based Materials for Emerging Applications, G. Dalapati, T. Shun Wong, S. Kundu, A. Chakraborty, and S. Zhuk, Eds., Elsevier, 2022, pp. 583–606. doi: 10.1016/B978-0-323-99860-4.00004-6.

23 https://storion.com/about-us/

24 "Innovative Iron-Chromium Redox Flow Battery Technology." Accessed: Oct. 07, 2025. [Online]. Available: https://redoxone.com/technology; C. Sun and H. Zhang, "Review of the Development of First-Generation Redox Flow Batteries: Iron-Chromium System," ChemSusChem, vol. 15, no. 1, p. e202101798, Jan. 2022; M. FANG et al., "Research progress of iron-chromium flow batteries technology," Energy Storage Sci. Technol., vol. 11, no. 5, p. 1358, 2022; Y. K. Zeng, T. S. Zhao, L. An, X. L. Zhou, and L. Wei, "A comparative study of all-vanadium and iron-chromium redox flow batteries for large-scale energy storage," J. Power Sources, vol. 300, pp. 438–443, 2015.

25 H. Vafiadis and M. Skyllas-Kazacos, "Evaluation of membranes for the novel vanadium bromine redox flow cell," J. Membr. Sci., vol. 279, no. 1, pp. 394–402, Aug. 2006, doi: 10.1016/j.memsci.2005.12.028.

26 P. Symons, "Quinones for redox flow batteries," Curr. Opin. Electrochem., vol. 29, p. 100759, Oct. 2021, doi: 10.1016/j.coelec.2021.100759; B. Huskinson et al., "A metal-free organic–inorganic aqueous flow battery," Nature, vol. 505, no. 7482, pp. 195–198, Jan. 2014, doi: 10.1038/nature12909; E. Sánchez-Díez et al., "Redox flow batteries: Status and perspective towards sustainable stationary energy storage," J. Power Sources, vol. 481, p. 228804, Jan. 2021, doi: 10.1016/j.jpowsour.2020.228804; J. Cao, J. Tian, J. Xu, and Y. Wang, "Organic Flow Batteries: Recent Progress and Perspectives," Energy Fuels, vol. 34, no. 11, pp. 13384–13411, Nov. 2020, doi: 10.1021/acs.energyfuels.0c02855.

27 Technology," Quino Energy. Accessed: Oct. 09, 2025. [Online]. Available: https://quinoenergy.com/technology

28 Department of Energy, U. (2023). Technology Strategy Assessment Findings from Storage Innovations 2030 Flow Batteries. https://www.energy.gov/oe/storage-innovations-2030

29 "Technology," Eos Energy Enterprises. Accessed: Oct. 09, 2025. [Online].

30 J. Purtill, "Redflow was the great hope of Australian manufacturing. Its collapse left customers with broken batteries," ABC News, Dec. 04, 2024. Accessed: Oct. 09, 2025. [Online].; A. Colthorpe, "Zinc-bromine flow battery maker Redflow 'unable to continue as going concern,'" Energy-Storage.News. Accessed: Oct. 09, 2025. [Online].

31 X. Liu, T. Li, Z. Yuan, and X. Li, "Low-cost all-iron flow battery with high performance towards long-duration energy storage," J. Energy Chem., vol. 73, pp. 445–451, 2022; K. L. Hawthorne, J. S. Wainright, and R. F. Savinell, "Studies of iron-ligand complexes for an all-iron flow battery application," J. Electrochem. Soc., vol. 161, no. 10, p. A1662, 2014; S. Belongia, X. Wang, and X. Zhang, "Progresses and Perspectives of All-Iron Aqueous Redox Flow Batteries," Adv. Funct. Mater., vol. 34, no. 5, p. 2302077, Jan. 2024.

32 Ref 32 - 32 S. Prakash Yadav, M. K. Ravikumar, S. Patil, and A. Shukla, "Soluble Lead Redox Flow Batteries: Status and Challenges," ChemElectroChem, vol. 11, no. 18, p. e202400267, Sept. 2024, doi: 10.1002/celc.202400267.

33 M. Lanfranconi and H.-J. Lilienhof, "All-Lead-Flow-Batteries as Promising Candidates for Energy Storage Solutions," J. Sustain. Dev. Energy Water Environ. Syst., vol. 7, no. 2, pp. 343–354, June 2019, doi: 10.13044/j.sdewes.d6.0256.

34 D. Yu, W. Xu, C. Yuan, Z. Yuan, and X. Li, "Lead-Based Flow Battery Based on New Pb-Based Anolyte Chemistry," Ind. Eng. Chem. Res., June 2024, doi: 10.1021/acs.iecr.4c01530.

35 W. Wang, W. Xu, L. Cosimbescu, D. Choi, L. Li, and Z. Yang, "Anthraquinone with tailored structure for a nonaqueous metal-organic redox flow battery," Chem. Commun. Camb. Engl., vol. 48, no. 53, pp. 6669–6671, July 2012, doi: 10.1039/c2cc32466k.

36 Y. Chen et al., "A Stable and High-Capacity Redox Targeting-Based Electrolyte for Aqueous Flow Batteries," Joule, vol. 3, no. 9, pp. 2255–2267, Sept. 2019, doi: 10.1016/j.joule.2019.06.007; R. Yan and Q. Wang, "Redox-Targeting-Based Flow Batteries for Large-Scale Energy Storage," Adv. Mater., vol. 30, no. 47, p. 1802406, 2018, doi: 10.1002/adma.201802406.

37 https://invinity.com/vanadium-flow-batteries/

38 https://sumitomoelectric.com/products/flow-batteries/product-variations

39 https://rkpstorage.com/upower-series/

40 https://rkpstorage.com/products/spower-series/

41 V. Viswanathan, K. Mongird, R. Franks, X. Li, V. Sprenkle, and R. Baxter, “2022 Grid Energy Storage Technology Cost and Performance Assessment,” Pacific Northwest National Laboratories, Richland, WA, Technical Report PNNL-33283, Aug. 2022. [Online]. Available: https://www.energy.gov/sites/default/files/2022-09/2022%20Grid%20Energy%20Storage%20Technology%20Cost%20and%20Performance%20Assessment.pdf

42 S. Childers and M. Raiford, “Discussion of Flow Battery Technology,” Aug. 22, 2025.

43 “UPower Series - Rongke Power,” RKP Storage. Accessed: Sep. 22, 2025. [Online]. Available: https://rkpstorage.com/upower-series/

44 Sumitomo Electric, “Sumitomo Electric Initiates Project for Redox Flow Battery System in the Oki Islands —Contributing to Carbon Neutrality and Electricity Resilience on Remote Islands— | Sumitomo Electric.” Accessed: Sept. 23, 2025. [Online]. Available: https://sumitomoelectric.com/press/2025/02/prs013

45 V. Viswanathan, K. Mongird, R. Franks, X. Li, and V. Sprenkle, “2022 Grid Energy Storage Technology Cost and Performance Assessment,” Department of Energy, Office of Electricity, Washington, D.C., Technical Report PNNL-33283, 2022 com/press/2025/02/prs013

46 M. B. Lim and T. N. Lambert, “CHAPTER 5 RECHARGEABLE ZINC BATTERIES FOR GRID STORAGE,” 2021.

47 J. F. Parker et al., “Rechargeable nickel–3D zinc batteries: An energy-dense, safer alternative to lithium-ion,” Science, vol. 356, no. 6336, pp. 415–418, Apr. 2017, doi: 10.1126/science.aak9991.

48 “ZincFive Nickel-zinc Battery Chemistry.” Accessed: Nov. 22, 2025. [Online]. Available: https://zincfive.com/our-chemistry/

49 Enzinc, “Enzinc Joint Development Agreement.” [Online]. Available: https://www.linkedin.com/posts/enzinc_innovation-cleanenergy-energystorage-activity-7386770601836920833-KrzR

50 N. Zhang et al., “Rechargeable aqueous zinc-manganese dioxide batteries with high energy and power densities,” Nat. Commun., vol. 8, no. 1, p. 405, Sept. 2017, doi: 10.1038/s41467-017-00467-x

51 “Urban Electric Power | Rechargeable Zinc Alkaline Batteries,” Urban Electric Power. Accessed: Nov. 22, 2025. [Online]. Available: https://www.urbanelectricpower.com

52 N. Borchers, S. Clark, B. Horstmann, K. Jayasayee, M. Juel, and P. Stevens, “Innovative zinc-based batteries,” J. Power Sources, vol. 484, p. 229309, Feb. 2021, doi: 10.1016/j.jpowsour.2020.229309.

53 G. Nazir et al., “A Review of Rechargeable Zinc–Air Batteries: Recent Progress and Future Perspectives,” Nano-Micro Lett., vol. 16, no. 1, p. 138, Feb. 2024, doi: 10.1007/s40820-024-01328-1

54 “Technology,” Eos Energy Enterprises. Accessed: Nov. 23, 2025. [Online]. Available: https://www.eose.com/technology/

55 Company Overview,” Eos Energy Enterprises. Accessed: Nov. 23, 2025. [Online]. Available: https://www.eose.com/company/

56 J. Daniel-Ivad, “Zinc Battery Discussion,” Oct. 28, 2025.

57 M. Rana et al., “Scientific issues of zinc-bromine flow batteries and mitigation strategies,” Exploration, vol. 3, no. 6, p. 20220073, July 2023, doi: 10.1002/EXP.20220073.

58 A. Colthorpe, “Flow battery maker Redflow out of business with administrators unable to find buyer,” Energy-Storage. News. Accessed: Nov. 23, 2025. [Online]. Available: https://www.energy-storage.news/flow-battery-maker-redflow-out-of-business-with-administrators-unable-to-find-buyer/

59 J. Purtill, “Redflow was the great hope of Australian manufacturing. Its collapse left customers with broken batteries,” ABC News, Dec. 04, 2024. Accessed: Oct. 09, 2025. [Online]. Available: https://www.abc.net.au/news/science/2024-12-05/redflow-australian-battery-manufacturer-collapse-defects/104650074

60 “Primus Power.” Accessed: Nov. 23, 2025. [Online] Available: https://primuspower.com/

61 Y. Gong, M. Jia, Q. Yuan, and B. Yang, “Advancements and Prospects in Cathode Materials for Aqueous Zinc-Ion Batteries: Mechanisms, Challenges and Modification Strategies,” Mol. Basel Switz., vol. 30, no. 20, p. 4143, Oct. 2025, doi: 10.3390/molecules30204143.; H. Xu et al., “Advances in Aqueous Zinc Ion Batteries based on Conversion Mechanism: Challenges, Strategies, and Prospects,” Nano-Micro Lett., vol. 20, no. 27, 2024, Accessed: Nov. 23, 2025. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/smll.202310972; Y. Hu, P. Wang, M. Li, Z. Liu, S. Liang, and G. Fang, “Challenges and industrial considerations towards stable and high-energy-density aqueous zinc-ion batteries,” Energy Environ. Sci., vol. 17, no. 21, pp. 8078–8093, Oct. 2024, doi: 10.1039/D4EE03628J.; J. Wei et al., “Advanced electrolytes for high-performance aqueous zinc-ion batteries,” Chem. Soc. Rev., vol. 53, no. 20, pp. 10335–10369, Oct. 2024, doi: 10.1039/D4CS00584H

62 S. Lawrence-Geschwindt, “Enerpoly goes bust in latest jolt to Europe’s battery sector | Impact Loop.” Accessed: Nov. 23, 2025. [Online]. Available: https://www.impactloop.com/artikel/swedish-startup-enerpoly-goes-bust-in-latest-blow-to-europe-s-battery-ambition

63 Zinc Battery Initiative, “Case Studies - Zinc Battery Initiative.” Accessed: Nov. 23, 2025. [Online]. Available: https://www.zincbatteryinitiative.com/case-studies/

64 International Zinc Association, “International Zinc Association explains zinc’s use in energy storage.” Accessed: Nov. 23, 2025. [Online]. Available: https://www.zinc.org/energy-storage/

65 E. D. Spoerke, E. Takeuchi, J. Connell, and S. Tepavcevic, “Technology Strategy Assessment - Zinc Batteries,” Department of Energy, Washington, D.C., Technical Report, July 2023. Accessed: Oct. 17, 2025. [Online]. Available: https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Zinc%20Batteries.pdf

66 V. Viswanathan, K. Mongird, R. Franks, X. Li, and V. Sprenkle, “2022 Grid Energy Storage Technology Cost and Performance Assessment,” Department of Energy, Office of Electricity, Washington, D.C., Technical Report PNNL-33283, 2022

67 Burz, M., Macher, M., & Baker, P. (2021). Communication between Michael Burz, Meinrad Macher, Philip Baker of Enzinc and PNNL; Eguchi, T. (2021). Correspondence between Tak Eguchi of NGK and PNNL; Plautz, K. (2021). Communication between Kirk Plautz and PNNL.

68 NFPA 855 2026, IFC

69 Garche, J.; Moseley, P. T.; Karden, E. Advances in Battery Technologies for Electric Vehicles 2015, 75-101.

70 Avicenne Battery Market Report.

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