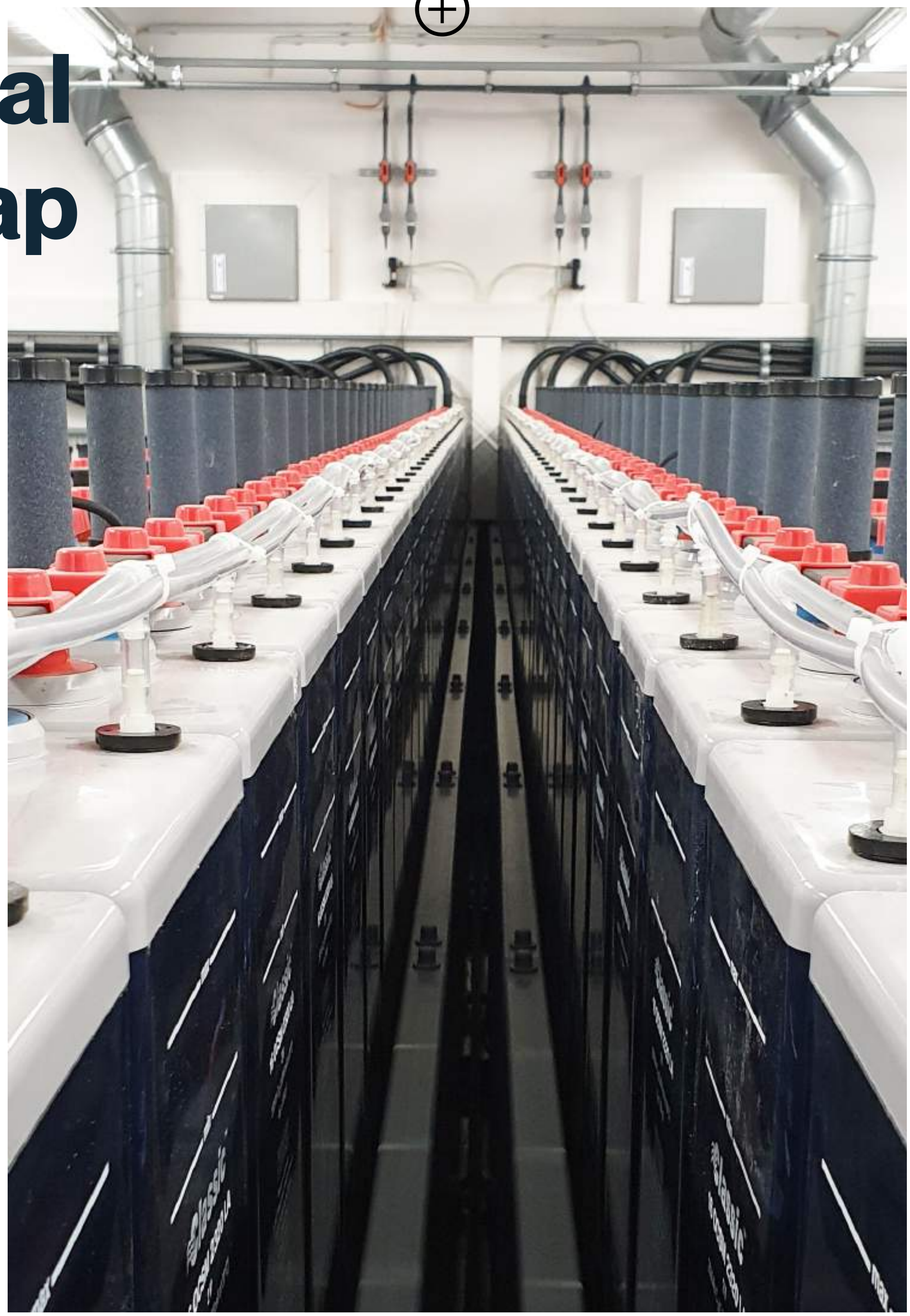
Technical Roadmap

Research and innovation pathways for next-generation advanced lead batteries



September 2021

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Foreword

A Golden Age for Battery Research

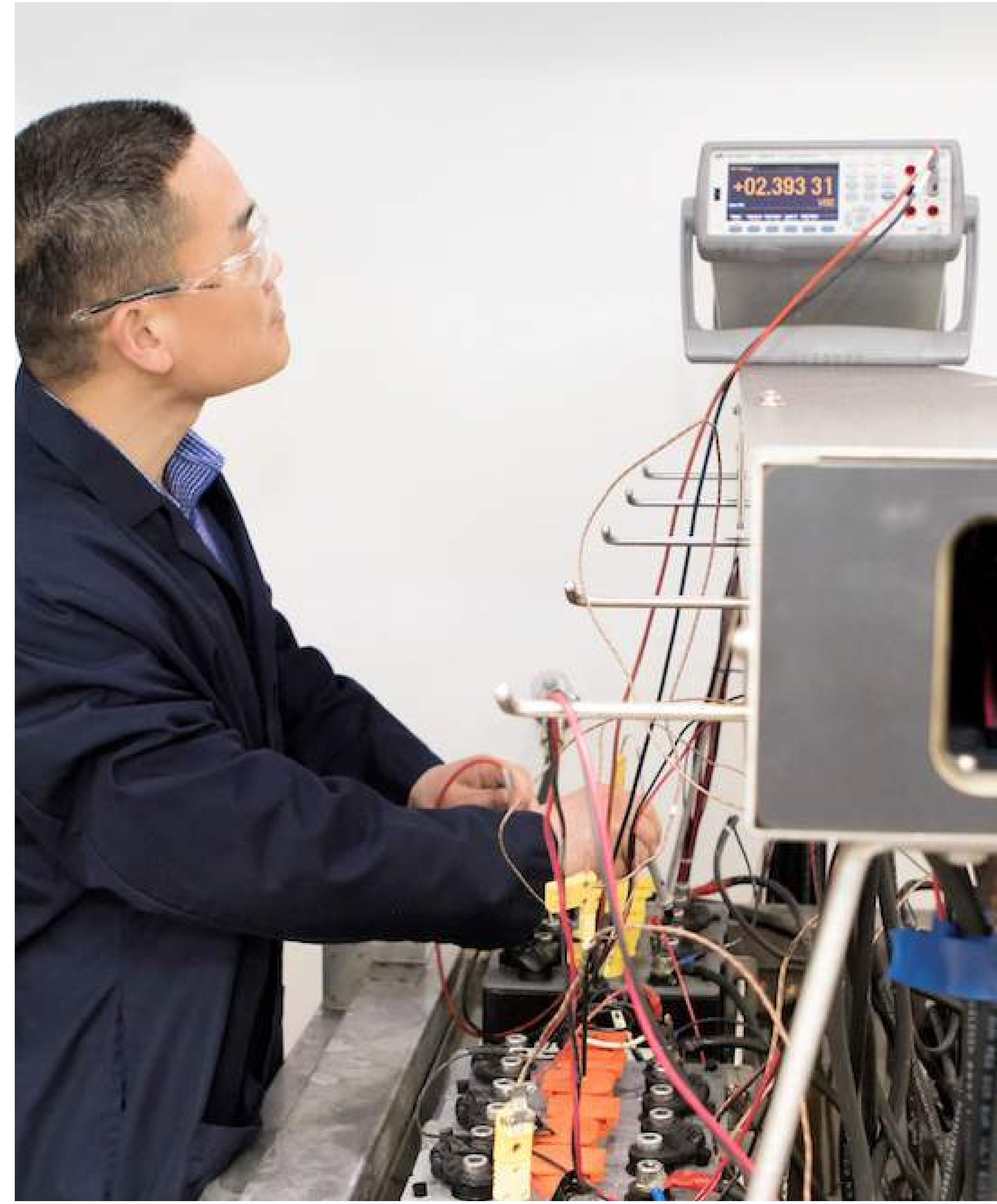
As global warming continues to have a dramatic impact on the world's climate, the imperative for decarbonization is greater than ever.

Battery energy storage is a key pillar in the move to electrification and supporting innovation and performance improvements is the highest priority. Soaring demand for battery technologies across all applications has ushered in something of a golden age for batteries From clean energy storage to hybrid and electric vehicles, demand for high-performing and sustainable batteries is driving research and development across the globe.

Analysts predict a spike in demand for a range of battery technologies, each of which display different strengths and are designed to support a range of applications. Combining pioneering research with the latest market insights, the Consortium for Battery Innovation is leading the way by ensuring advanced lead batteries continue on their innovation journey supporting ambitious climate goals set out by policy makers.

Building on the Technical Roadmap launched in 2019, the new and updated roadmap reflects the performance improvements achieved to date and sets out new goals designed to tap the unlimited potential of advanced lead battery technology. With continued performance improvement and technological advances, the opportunities for the global lead battery industry to provide cost-effective and reliable energy storage solutions remain very positive.

Economies need batteries and lots of them. It is clear through intensive market-driven analysis that end-users across the automotive, energy storage, industrial and motive power sectors want greater performance from all battery technologies.



Enqin Gao, Chief Engineer of R&D, observes the voltages of battery cells during the PSoC Cycling test in Hammond Group's state-of-the-art lead battery lab.

> **Demand for high-performing and sustainable batteries is driving research and development across the globe.**

Research pathways for next-generation advanced lead batteries

The requirements of customers are at the heart of the new research goals set out in the Consortium's updated Technical Roadmap. The automotive sector remains a significant area for lead battery innovation and one constantly adapting to new low-emission requirements. The highest priority research goal for this sector is to improve dynamic charge acceptance (DCA) to 2 A/Ah while also delivering high temperature durability and maintaining low water loss, specifically geared towards the micro-hybrid market.

This market is set to account for 80% of new cars by 2030, and the carbon emission reductions and fuel efficiency offered are directly tied to the innovative performance of advanced lead batteries. For low-voltage EV batteries (also referred to as auxiliary batteries), it is important that lead batteries can improve their DCA and charge acceptance, whilst increasing charging efficiency and lifetime.

For the motive power industry, representing the world's logistics and goods vehicles, improving the charging efficiency of lead batteries is the key priority goal. Energy storage systems continue to be a booming market for batteries, both for utility and renewable energy storage. As the world's energy grids integrate more renewable sources to meet clean energy targets and require greater flexibility and resiliency in the face of changing climate events, the lead battery industry needs to continue extending cycle life to 5000 cycles under high depth-of-discharge (DOD) and lowering total cost of ownership (TCO) of the technology.

These two priority targets also feed into the growing industrial sector, where lead batteries support data centers, hospitals and UPS back-up applications, all of which require reliable, safe and high-performing batteries.

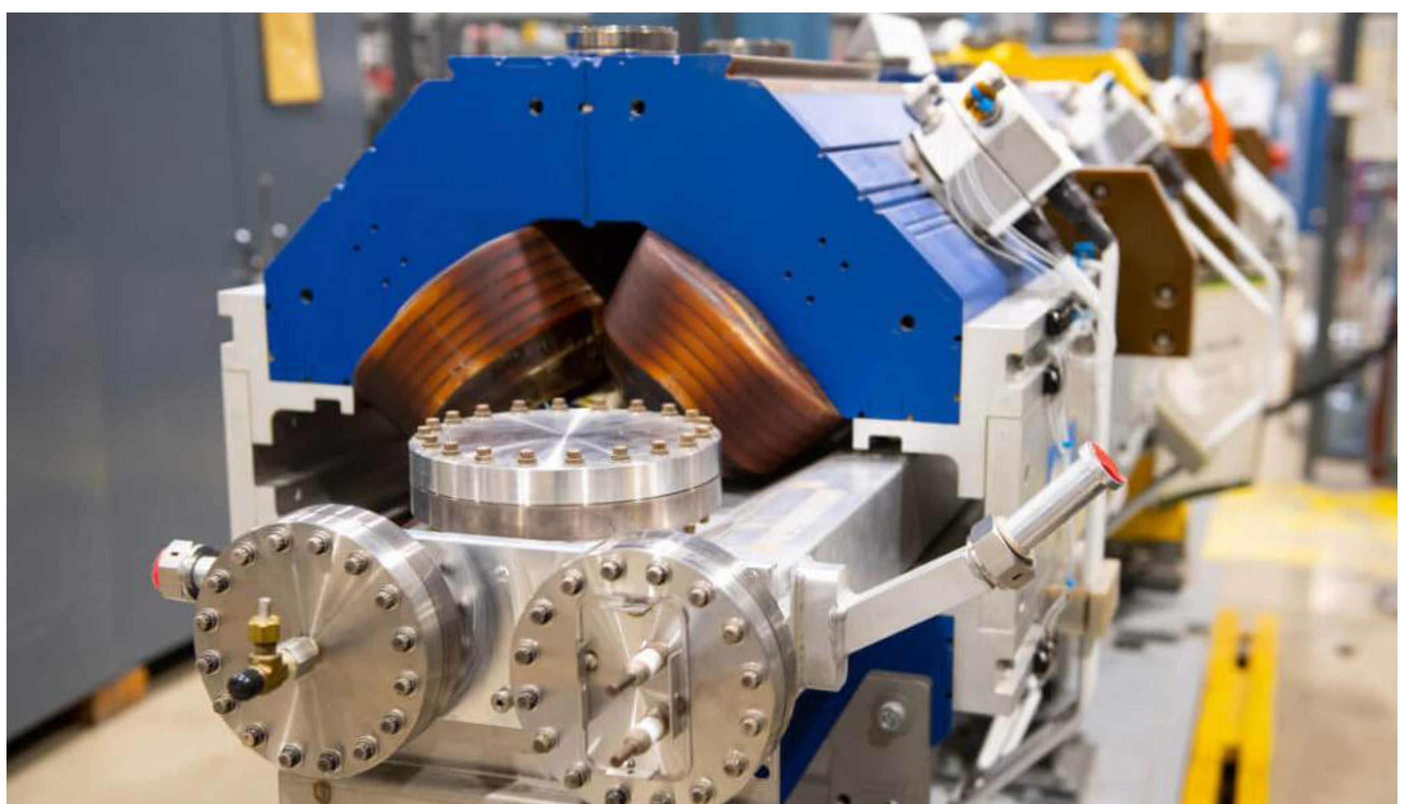
Unlocking the full potential

Driven by market analysis, current and future end-user requirements and reflecting the needs of governments as they pursue clean energy agendas, these areas have been identified by the CBI membership as the highest priority areas to target.

Working with our members, world-class research institutes, leading universities and advanced laboratories around the globe, the areas for innovation set out in this Technical Roadmap will be used to develop future technical programs and launch projects that will deliver the performance enhancements needed for advanced lead batteries.

It is a golden age for both batteries and battery research and the Consortium is ensuring the full potential of lead batteries is unlocked.

In an industry partnership with Argonne National Laboratory, scientists use the bright x-ray beams at the laboratory's Advanced Photon Source to investigate the further potential of lead batteries



Scientists conducting lead battery research at Argonne National Laboratory

Section one

About CBI

The Consortium for Battery Innovation (CBI) conducts pre-competitive research with members and partners across the globe to drive innovation in advanced lead batteries.

The global membership comprises the entire value chain associated with lead batteries, from miners, lead producers and battery recyclers, to suppliers, equipment manufacturers, battery manufacturers, research and testing institutes and universities, to end-users such as car companies and utility and renewable energy storage providers.

With cutting-edge technical projects encompassing the entire application space for lead batteries, from energy storage and automotive to industrial, our research is contributing to the next generation of lead batteries.

CBI is identifying key market opportunities for the technology to meet evolving technical requirements by emerging applications and end-users. With increasing levels of vehicle electrification and the transition to a low carbon future through renewable energy storage, advanced lead batteries will play a pivotal role.

Spanning nearly three decades, the work of the Consortium has been critical for advancing the technology to provide reliable, safe and sustainable batteries for an increasingly decarbonized and electrified world.

CBI membership

Map of members

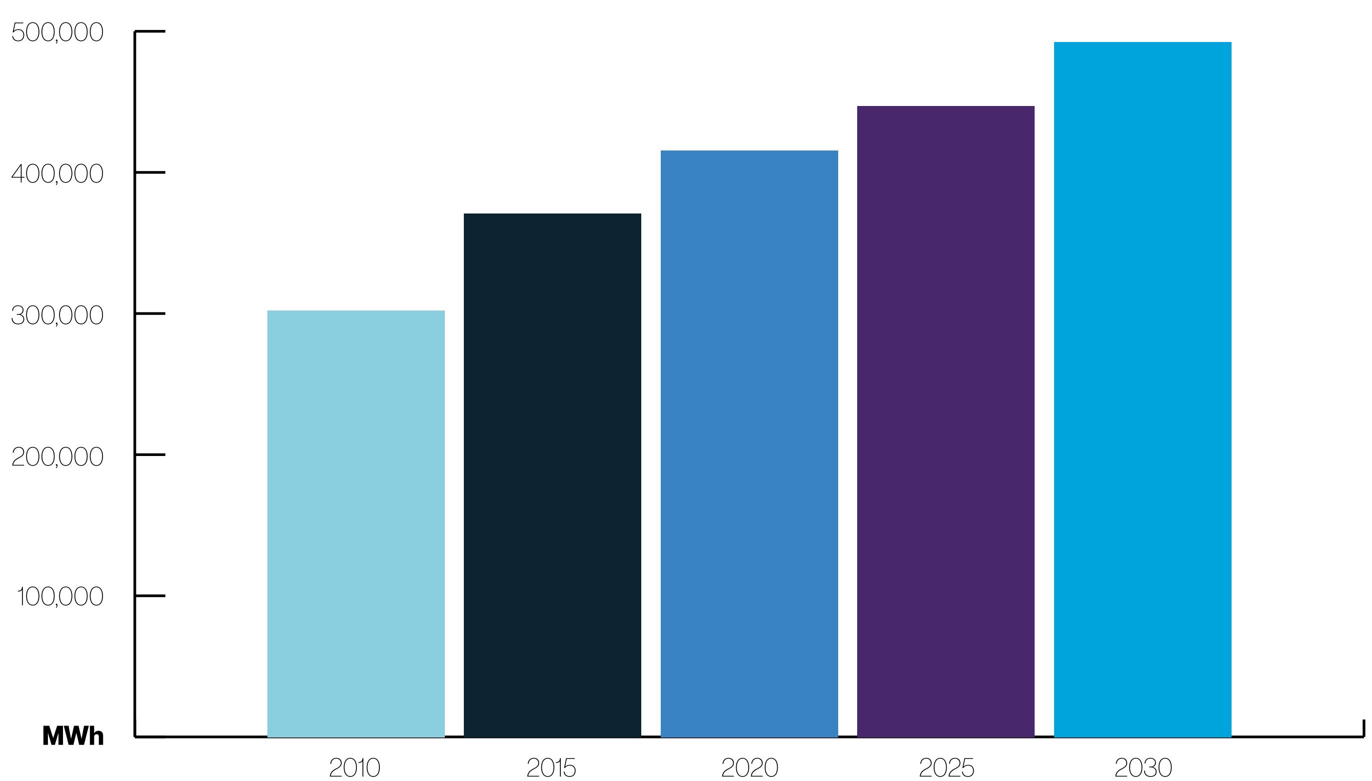
Section two

Global Changes in the Lead Battery Market

CBI market report 2021, Avicenne

Lead Battery Market

Sustained growth is predicted for lead batteries with demand of 490,000 MWh forecast by 2030.



Over the last three decades, global demand for batteries has boomed with significant growth witnessed across diverse applications.

Driven by a wide range of uses, from automotive and motive power to industrial and UPS, lead batteries have been the dominant chemistry by volume and market share. As demand reflects new technical requirements, emerging chemistries such as lithium-ion have been playing an increasingly important role in markets such as propulsion batteries for EVs, energy storage and power tools.

However, lead batteries still make up 60% of the global rechargeable battery market. Analysts expect significant growth for batteries in all markets due to the rise in battery demand to fulfil the global shift to a decarbonized and electrified future.

Soaring demand will mean battery technologies must demonstrate continuous improvement and rapid scale-up to meet the requirements of existing and new applications. As demand for battery energy storage grows, significant opportunities are presented for lead batteries as a critical technology for renewable and utility energy storage and in hybrid and electric vehicles.

There are substantial opportunities for the lead battery in all applications, if the technology continues to adapt and improve through research and innovation.

Global Lead Battery Market Value

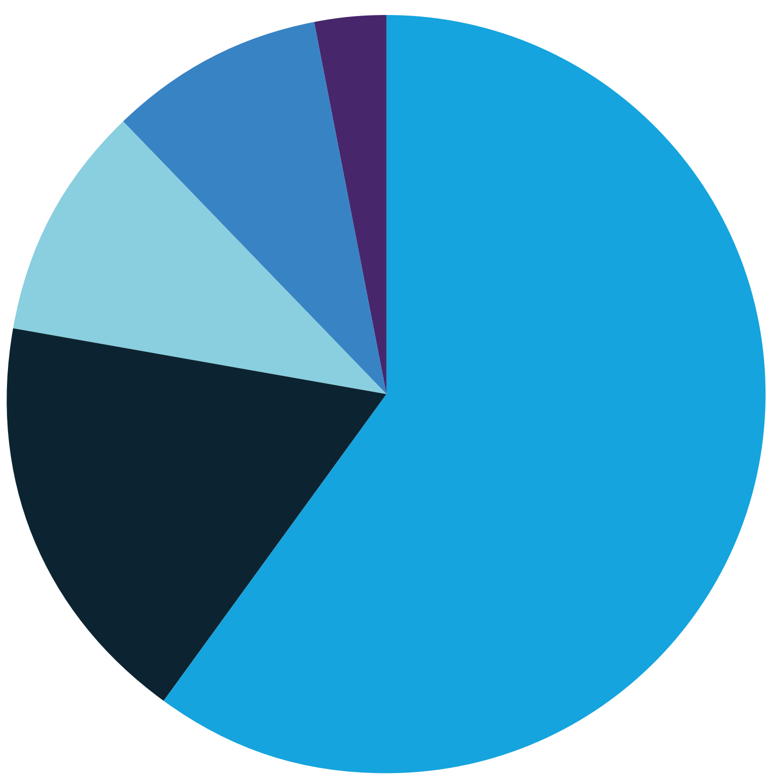
2020 witnessed a global lead battery market worth $37.5b. In the next decade, this worth is forecasted to grow to $49b, reflecting increased demand and value of the technology. With a growth of 45,000 MWh predicted between 2025 and 2030, lead battery demand is increasing across all applications.

The breakdown of the market forecasts for each lead battery application mentioned above can be found in the application-specific chapters in this technical roadmap.

CBI market report 2021, Avicenne

2020 Market forecast

US $37,5b = 415 GWh



12 V
60%

Stationary
18%

Motive
10%

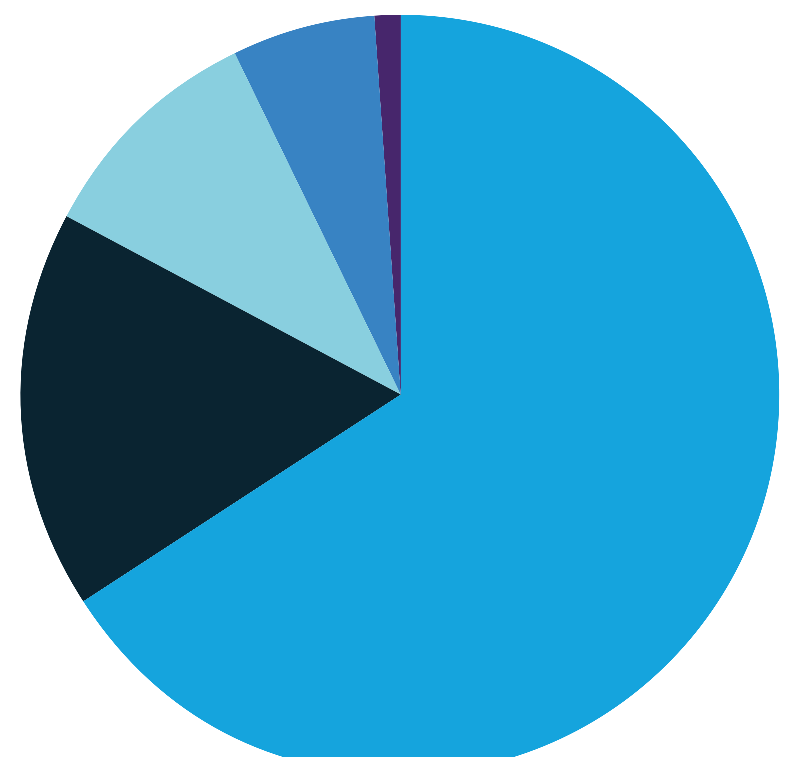
Others
9%

E-bikes
3%

CBI market report 2021, Avicenne

2030 Market forecast

US $49b = 490GWh



12 V
66%

Stationary
17%

Others
10%

Motive
6%

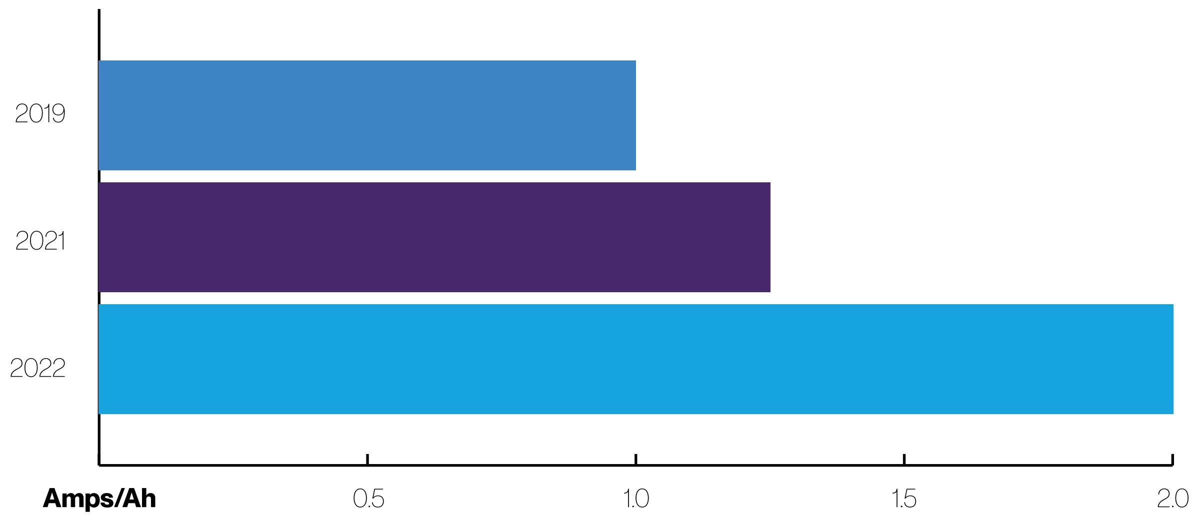
E-bikes
1%

Section three

Progress Since Last Roadmap

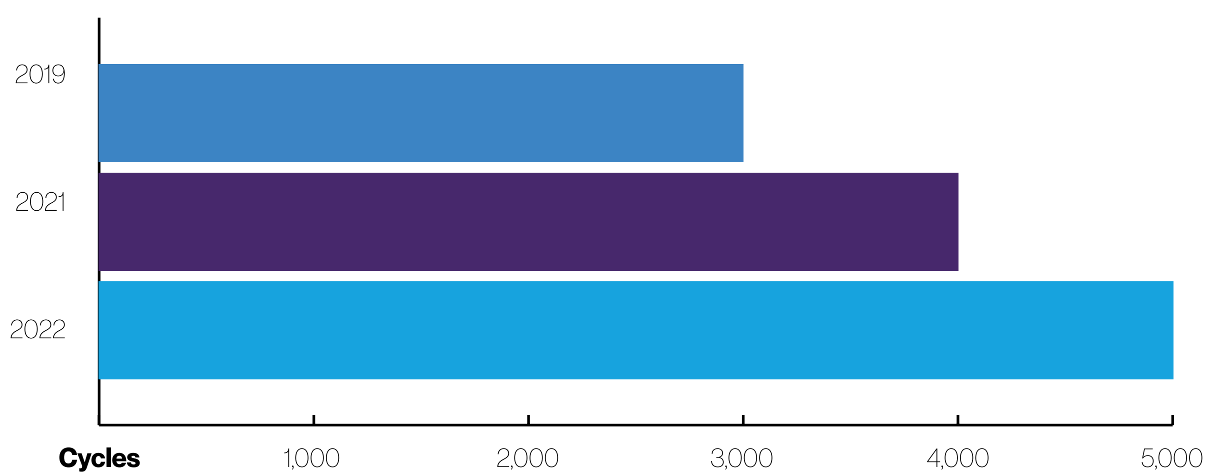
Auto

Dynamic Charge Acceptance



80% DOD

Cycle life



3.1 Major trends in lead battery improvement

Since the launch of CBI's Technical Roadmap in 2019, which acted as a rallying call for the global lead battery industry to engage in fundamental, scientific research to enhance lead batteries for a wide range of applications, there have been great strides in performance for the technology. The previous roadmap set specific high priority goals for 2022, for both automotive and ESS applications, with the aim to achieve 2A/Ah for DCA and 5,000 cycles for ESS. There has been a series of innovative new developments driven by CBI's research program that have delivered technology advancements, demonstrating that the industry is on track to meet the goals set in 2019.

3.2 Current status of automotive lead batteries

In the 2019 edition of the Technical Roadmap, clear 2022 goals for the industry were set out regarding advanced lead batteries for start-stop and micro-hybrid use, two fast-growing markets globally. These include:

a value of 2.0 A/Ah
DCA

a value of (SAE J2801) – 18 units
High-temperature durability

a value of less than 3g/Ah (EN)
Water loss

a value of 2,000 cycles EFB
PSoC (partial state-of-charge) cycle life

CBI and the industry at large are actively pursuing higher DCA 12 V automotive batteries with increased high temperature durability. In the early 2000s the average DCA for 12 V advanced lead batteries was approximately 0.2 A/Ah. Over the last 20 years that number has risen significantly, with common DCA values above 0.5 A/Ah in the most robust test sequences.

Furthermore, basic carbon additives have pushed this foundational level further to mass produced products in 12 V start-stop possessing DCA values near 0.7 A/Ah. Optimization of DCA values is being studied in the current CBI research program. A project partnership between Borregard USA, Cabot, Hammond and East Penn has shown that specific ratios of carbon and lignosulfonate can increase DCA by 40%. Innovations in carbon additives have pushed the boundaries of DCA, cycle life and capacity over the last 20 years. In the past several years, Fraunhofer Institute for Silicate Research (FHISC) has developed key insights into the impact external surface area and micropore volume on the DCA enhancement offered by carbons. Ongoing research with FHISC and Wroclaw University of Science and Technology is adding to a more and more 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.

12 V automotive lead batteries

Current technical performance

The table below highlights the current situation with regards to key technical performance parameters for 12 V automotive lead batteries.

As a benchmark, there are products in low volume production lines that have achieved DCA values above 1.5 A/Ah. The aforementioned products uses carbon-based negatives to drastically increase the recuperative charge capability of lead battery technology.

High-temperature durability is important for automotive batteries and the lead battery operates from -30 – 100 °C. AGM and EFB batteries are tested routinely in SAE J2801 and HTE (high-temperature endurance) 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 18 units in the SAE J2801 and 20-25 units in preliminary testing of the HTE.

Start-stop and 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 low-voltage EV battery functions are important for all types of vehicles, and CBI is stimulating collaboration amongst OEMS and battery manufacturers to produce better understanding of low-voltage EV batteries (also referred to as auxiliary batteries).

KPI	2021/2022	Notes
DCA	1.5 A/Ah (in production)	Based on advanced carbon electrode
HTE	24+ weeks	Preliminary data from CENELEC info gathering; AGM
SAE J2801	16-20 units	EFB and AGM product
Water loss	Less than 3 g/Ah	Achievable across different products – still a drawback

3.3 Current State of the ESS Lead Battery

The need for energy storage for utility services continues to soar as energy grids require increased levels of flexibility and the integration of renewables into the grid. Similarly, the technoeconomic drivers continue to become more and more significant. The previous roadmap set specific 2022 targets for ESS applications:

5,000 cycles
Cycle life

90-95%
Charge efficiency

12-15 years
Service life

2,000 PV
PSoC

Significant advancements have been made in these areas, and there are currently multiple types, monobloc voltages, sizes, and quality to the lead battery products offered in this application space. In the below table are representative performance metrics for lead battery products currently offered.

Example Battery 2021/2022	Cycle life (80% DOD)	Energy density (Wh g^{-1})
Conventional 2 V AGM	700 – 1400	25-40
Conventional 2 V Gel	600 – 1500	25-40
Advanced Pb/C 2 V AGM	1000 – 5000	25-55
Advanced 2 V Gel	1000 – 4000	25-40
Advanced Pb/C 12 V AGM	500 – 2000	25-60
Bipolar 24, 48 V	500 – 1500	60+

Technical requirements are important drivers in ESS applications, and the economic impact of improved performance is under heavy scrutiny. Practically speaking the battery is a component of a greater system – and both the battery and system cost per kWh ($ or €/kWh) drive both product development and systems design.

Generally the $/kWh, drawn from public data on lead battery monoblocs, ranges from 135 – 400 $/kWh. Energy density directly impacts this technoeconomic driver, and advances in active material utilization, specific energy, and weight reduction in lead batteries are paramount to lowering the cost per kWh. Additives, novel electrodes, and new battery designs have proven to be a valuable pathway for improving lead battery energy density.

Another metric of concern, from both the U.S. Department of Energy (US DOE) and the European Commission (EC) is the cost per kWh per cycle (or energy throughput). Increasing cycle life directly impacts this metric, as does product cost and energy density. CBI is currently working with Electric Applications Inc (EAI) on a project using overcharge control to actively increase lead battery serial strings.

The control algorithms have resulted in a benefit to both the AGM and Gel products studied in the project. Past projects with Narada looking at a novel 2 V Pb/C AGM demonstrated not only the benefit of carbon in electrodes, but indications of both systems and failure mode issues that need to be addressed in lead battery ESS.

In both of these projects, serial string control was vital to maximizing battery capacity turnovers. The real-world impact of better control has resulted in a 100% increase in capacity turnovers.

CBI now has a range of research projects looking further into battery management, electrode additives, failure modes, and new battery design for ESS applications.

“Significant progress has been seen since the last CBI Technical roadmap, particularly in terms of cycle life and DCA.”

Section four

Current CBI 2020-21 Research Program

The previous Consortium research program concentrated on fundamental pre-competitive research to improve the dynamic charge acceptance (DCA) of lead batteries under partial state-of-charge conditions (PSoC) and increased shallow cycle lifetime for automotive batteries.

For energy storage systems (ESS), research priorities were identified to improve lifetime under PSoC cycling and to improve cycle life. The following projects were funded under the 2019-2021 program. All reports and data generated from these projects is available for members on the Consortium website www.batteryinnovation.org.

Research partners

Exide Group, Instituto de Nanociencia y Materiales de Aragón (INMA)

Neutron Scattering Analysis of the Charge/Discharge Processes inside the Battery Electrodes.

East Penn Manufacturing, Hammond Group Inc

Examination of the Effects of Surfactant Coatings & Particle Size of Barium Sulfate on the Structure Changes and Overall Performance of NAM in Energy Storage Systems (ESS) Application.

Fraunhofer ISC, Wroclaw University of Science and Technology

Electrochemical Behavior of Lead Carbon Electrodes.

University of California, Los Angeles

Visualizing the Dynamics of Carbon – Enhanced Negative Electrodes in Lead Batteries

Technical University of Berlin, Fraunhofer ISC, Ford Research, Moll Batterien

Improving Dynamic Charge Acceptance and High-Temperature Durability in Automotive Lead Batteries.

Gridtential, Electric Applications Incorporated

Bipolar Lead Batteries for Energy Storage Systems Applications

University of Warwick, Loughborough University

HALO-SMART-ESS-LAB: Health And Lifespan Optimization with Smart Management Algorithms & Recuperative Testing of ESS of Lead Acid Batteries.

Borregard USA, East Penn Manufacturing, Cabot Group, Hammond Group Inc.

Investigation into the Combined Influence of Carbon Black and Organic Expander to Improve Micro-Hybrid Service of Enhanced Flooded Batteries

Electric Applications Incorporated

Performance Improvement Using Controlled Overcharge.

measX, Ford Research, Innovation Center

Complementing CBI's core research program into investigating gassing and water loss and how it interacts with DCA is a collaborative project between CBI, measX and the Ford Research and Innovation Center based in Aachen, Germany. The project explores when and how fast gassing and water loss can occur, and any impact it has on the aging of batteries in the vehicle. An innovative portable eGAS device has been developed that allows the monitoring of gas flow in the battery, in-situ and in real time. This has direct implications for enhancing lead batteries for the growing low-voltage EV battery market.

4.1 Moving research to the next level

These programs form a balanced portfolio of work and have delivered important results which continue to drive advancements in lead battery technology.

Other projects led by the Consortium are taking our research to a completely new level. Through the first-of-its-kind Lead Battery Research Science Program (LBSRP) at Argonne National Laboratory (ANL), this program has been a key catalyst for improving understanding of lead battery technology.

For over five years, a complement of scientists from the Chemical Sciences and Engineering Division (CSE), Materials Science Division (MSD) and Advanced Photo Source (APS) have been actively studying lead battery fundamental processes governing DCA, lead sulfate mechanistics, and failure modes under representative duty cycles.

Using the U.S. Department of Energy's (DOE) laboratory, the collaborative research is using the ANL facility's ultra-bright, high-energy X-ray beams to investigate the complex interactions taking place inside lead batteries in-situ and in real time.

The Consortium is exploring new partnerships with governments, universities and laboratories around the world to push the boundaries of battery research, geared towards supporting climate change objectives and facilitating the roll-out of sustainable energy storage.

Argonne National Laboratory synchrotron

Section five

Powering the World's Vehicles: Automotive Applications

Lead batteries are vital for automotive applications, with virtually every vehicle on the road utilizing a lead battery. 12 V lead batteries dominate the market and are essential for SLI (starting, lighting and ignition), start-stop and micro-hybrid applications.

As the automotive sector has shifted to greater levels of decarbonization and electrification, this has triggered the rapid adoption of hybrid and electric vehicles worldwide. The electrification of the fleet impacts the automotive lead battery market in several ways:

1. The increasing number of hybrid vehicles on the road opens up opportunities for lead batteries as the main battery on-board (start-stop/micro-hybrid)

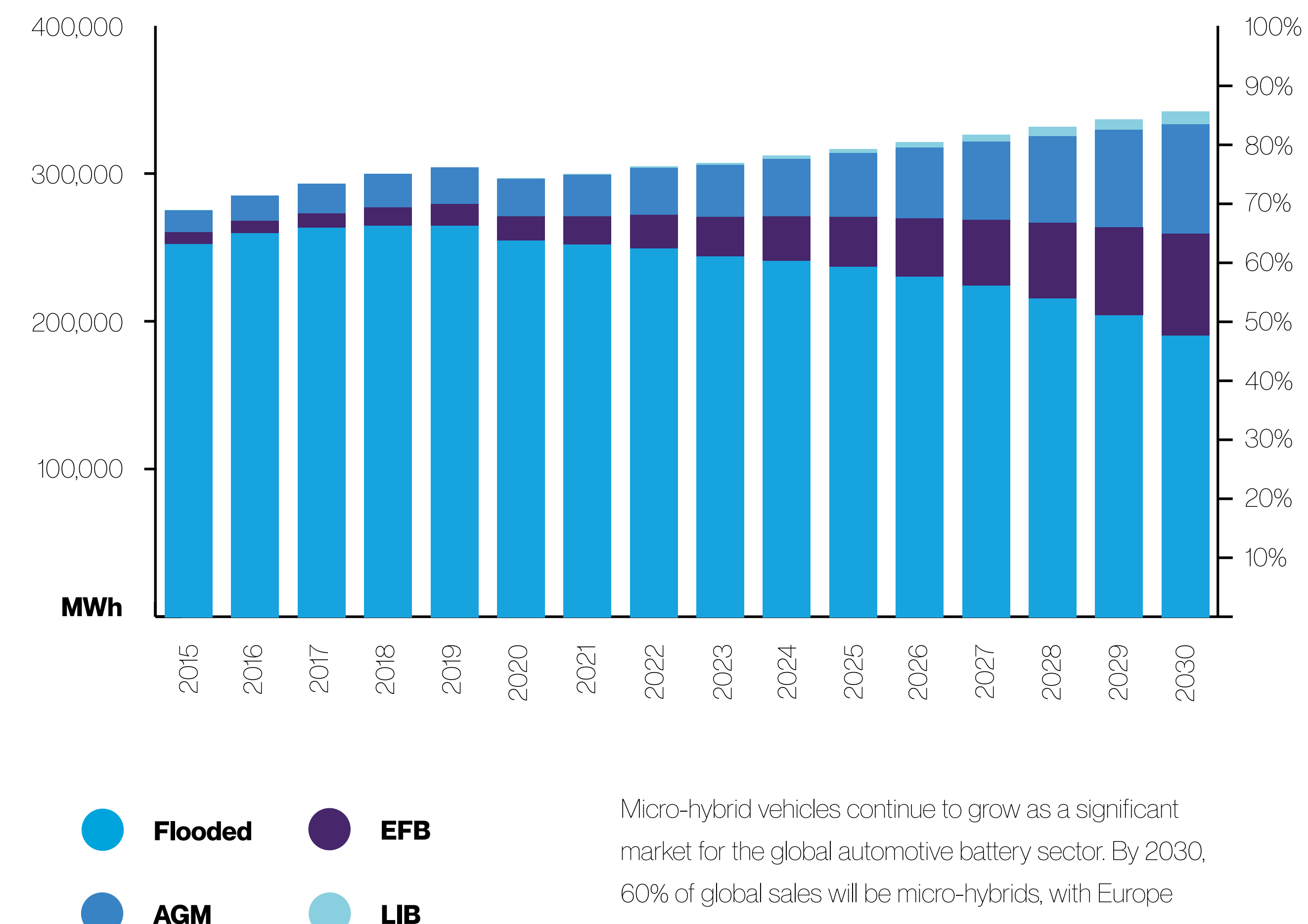
2. Vehicles with higher degrees of electrification will utilize a low-voltage EV battery (also referred to as an auxiliary battery) to power essential safety features. This provides a significant opportunity for lead batteries.

3. Increased competition from Li-ion batteries is possible in the 12 V market.

Forecasts for the automotive market are very positive, with sales for lead batteries in 12V applications predicted to grow to 333,000 MWh by 2030 in a market worth $31.9b. By 2030, it is forecast that there will be a 5-10% penetration for new cars by Li-ion 12V batteries, however since 70% of the automotive market is for replacement, only approximately 5% of the market will move to Li-ion batteries.

CBI market report 2021, Avicenne

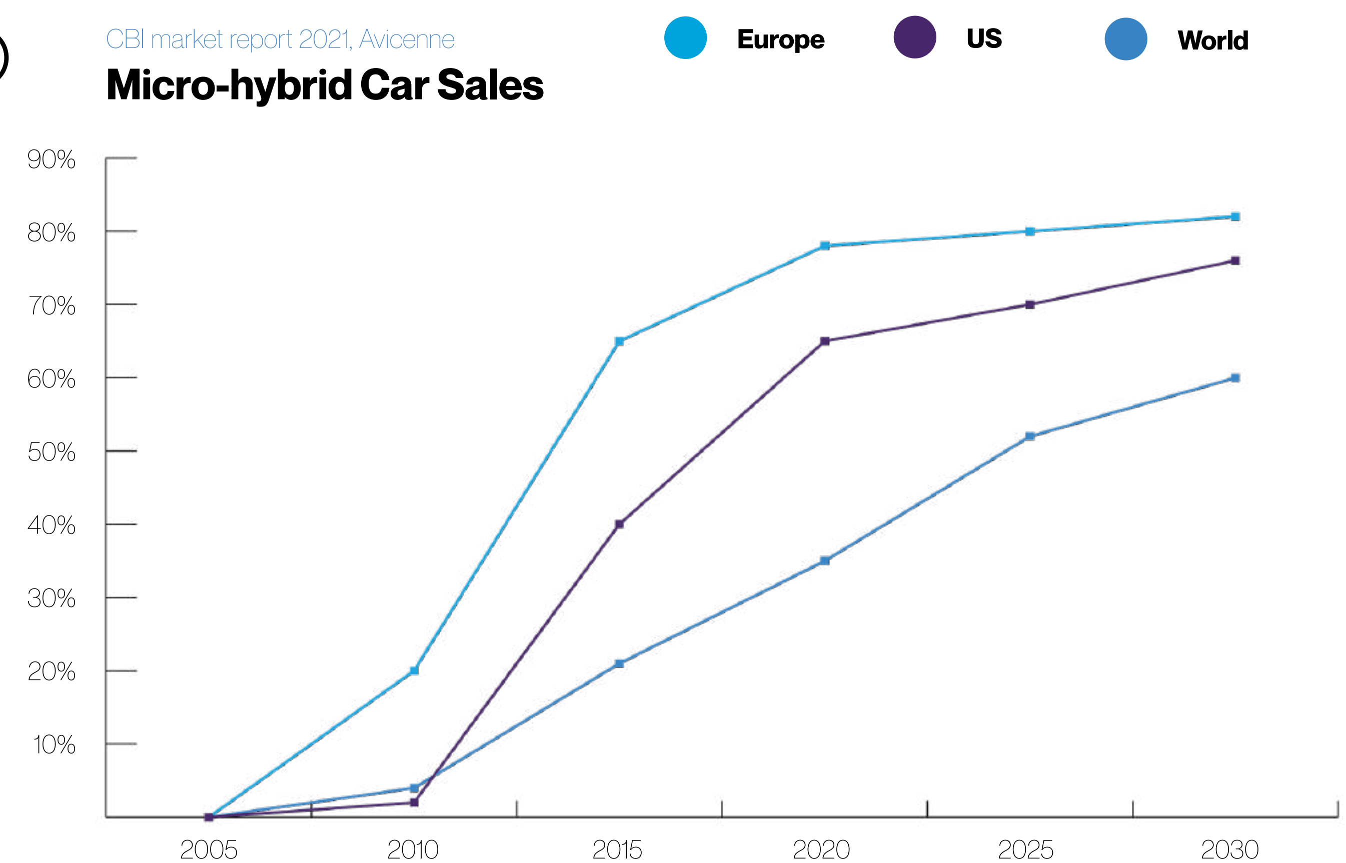
Battery Market for SLI



Micro-hybrid vehicles continue to grow as a significant market for the global automotive battery sector. By 2030, 60% of global sales will be micro-hybrids, with Europe leading the way with an expected 82% of sales by 2030, and the US close behind with 75%.

CBI market report 2021, Avicenne

Micro-hybrid Car Sales

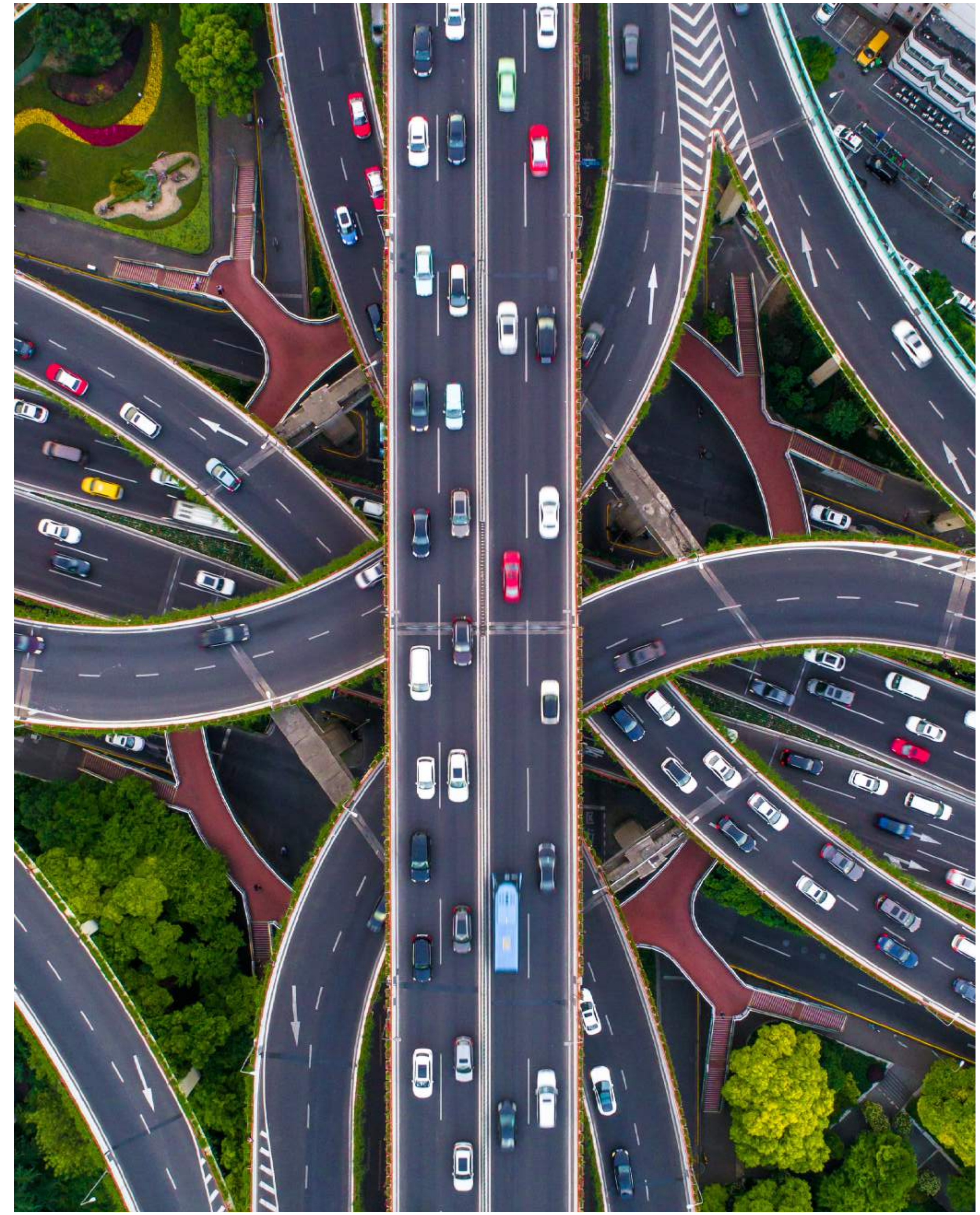


These trends will result in the original equipment manufacturer (OEM) market continuing to use two advanced lead battery technologies - enhanced flooded batteries (EFB) and absorptive glass mat (AGM) - in increasing numbers and there will be a growing market for these types in the replacement market.

With the global shift to e-mobility, low-voltage EV batteries are gaining in importance for the market. A critical part of the electric vehicle revolution is the lead battery, with almost all electric vehicles on the road using lead batteries in low-voltage EV applications. As more functions within internal combustion engine vehicles are electrified, low-voltage EV batteries will also be utilized as secondary batteries for vehicle safety and security. For example, if a high voltage propulsion battery were to fail, the 12V lead battery takes over and powers safety features such as power steering and breaking so the vehicle can safely pull over.

In order to take advantage of these opportunities and defend against competition from other technologies, the lead battery must continue to adapt and improve. Significant performance enhancements have been demonstrated over the past few years but lead battery performance must increase in several key metrics to ensure current and future end-user requirements are met for both the 12 V start-stop, micro-hybrid and low-voltage EV market.

The CBI Technical Roadmap describes the key performance indicators (KPIs) that need to be met to take these future opportunities. The roadmap also contains research pathways which will ensure KPIs will be met and provides technical notes to assist CBI membership in delivering on the KPIs. CBI's long record of research excellence and collaboration has been leveraged through multiple avenues to form a research program that directly supports these goals.



5.1 Start-stop and Micro-hybrid Application: Key Performance Indicators

The below table summarizes the KPIs for start-stop and micro-hybrid batteries. The KPIs encapsulate the battery-based metrics that must be improved. The focus of this work is to ensure that recent improvements in DCA are maintained, whilst improving high-temperature performances and ensuring no trade-offs in key parameters such as CCA and water loss.

The table the current status of these metrics and encapsulates the short-term and medium-term improvements that are important for lead batteries in automotive start-stop/micro-hybrid applications.

The table below showcases the KPIs for 12 V automotive applications for start-stop and micro-hybrid batteries – covering durability, charge acceptance, and other metrics.

Start-stop and micro-hybrid batteries

KPIs for 12 V automotive applications

Indicator (start-stop, micro/hybrid)	**2021/2022**	**2025**	**2030**
DCA (EN 50342-6, A/Ah)[a]	1.25	2.0	2.0
Ford Run-In Test B (A/Ah)	1.0	1.5	2.0
Durability: HTE (IEC/CENELEC draft)	16	20	20
Water Loss – EN/HTE (g/Ah)	<3	<3	<3
CCA, RC (comment)	Must not be compromised	Must not be compromised	Must not be compromised

EN 50342-6:2015 (M1, M2, M3 classification) should be used for cycle life requirements
Maintain 15 weeks of SAE J2801

[a] DCA testing from EN 50342 – 6 : 2015 theoretically only allows a DCA value up to 1.67 A/Ah (33*120). DCRss discharge rate may be too low. An adjustment of the EN DCA protocol would be necessary.

3.3 Current State of the ESS Lead Battery

The low-voltage EV battery market is a relatively new application, with no widely accepted testing standards. CBI, with its membership, is working with OEMs to develop international testing standards, and will use these to set future KPIs, with the below topics considered very important in this field:

1

DCA and CA (charge acceptance)

are important metrics to consider in low-voltage EV batteries. The performance expectation for these batteries is to have as much capacity available as possible, necessitating quick recharge of low voltage EV batteries. This would mean developing DCA toward 1.5 A/Ah in the short-term and 2.0 A/Ah in the long-term.

2

Service Life Determination

has been loosely predicted by using MHT protocols, DOD 17.5% cycling, and DOD 50% test sequence described in EN 50342-6. The actual use of low-voltage EVs by OEMs and the consumer alike is unpredictable, and further test development is likely needed. The expectation is to maximize service life (actual use, self-discharge at rest, float charging). Service life of approximately 5 years across multiple use cases is the desired performance – more information on typical use cases and best practices needs to be generated.

3

Float Charging

may be a concern – accurate testing of this use case is underway within the International Electrotechnical Commission (IEC). CBI plans to monitor and provide feedback, as well as gather information on what is necessary of low-voltage EV batteries for float life.

4

Low voltage EV battery diagnostics

SOF (state-of-function) and SOH (state-of-health) is well established in micro-hybrids for over a decade, but now needs to undergo new verification against safety requirements. Automotive OEMs, sensor producers and lead battery manufacturers must work collaboratively to establish generic verification methods for 12 V battery diagnostics that support ISO 26262 vehicle functions, which should be based on archived test datasets based on scenarios (highway driving, urban, mixture of both). Sudden hardware faults like ruptures of intercell connectors are extremely rare events in state-of-the-art automotive lead batteries. Where safety-relevant vehicle functions are to be supported, design and process controls as well as quantitative estimates for elementary failure-in-time (FIT) rates should be compiled in a reference document. Lastly, the current low-voltage EV battery technology is immature from a product development standpoint. Recent products for the market were adapted from the UPS or motorcycle markets. Developing a 12 V lead battery that is both responsive (high DCA) to the DC/DC output with a long service life is key. It does not have to provide high pulse discharge power or a number of the standard SLI performance parameters.

5.3 Research pathways

To the right is an overview of the suggested research pathways to ensure lead batteries can deliver on the KPIs outlined in the Technical Roadmap. Further information regarding specific research is discussed in the full roadmap document reserved for CBI members.

- Optimization of the beneficial effect of carbon in the positive and negative plates. In particular, further study of function of carbon in following areas:
  - Carbons coated with other materials by chemical or physical methods.
  - Carbons with different functional groups bonded to the surface.
  - Carbons in concert with selected trace elements.
- Studies of water loss and gassing behavior.
- Studies of alternative additive materials (ionic salts, fibers, novel carbons) and their interactions.
- Understanding the effect of rest periods on DCA by examination of the active mass and electrical performance.
- Further work on how to optimize behavior for different duty cycles, specifically using the HTE and WLTP (Worldwide harmonized Light-duty vehicles Test Procedure).
- Studies of how the following measurement techniques improve charging and battery life:
  - BMS (battery management systems)
  - SoC (state-of-charge)
  - SoH (state-of-health)
- Harmonized interfaces and verification methods for SoF state-of-health)/SoH diagnostics in safety-relevant applications as an enabler for cost-efficient commodity solutions that reliably support driver-assistance and autonomous-driving functions.

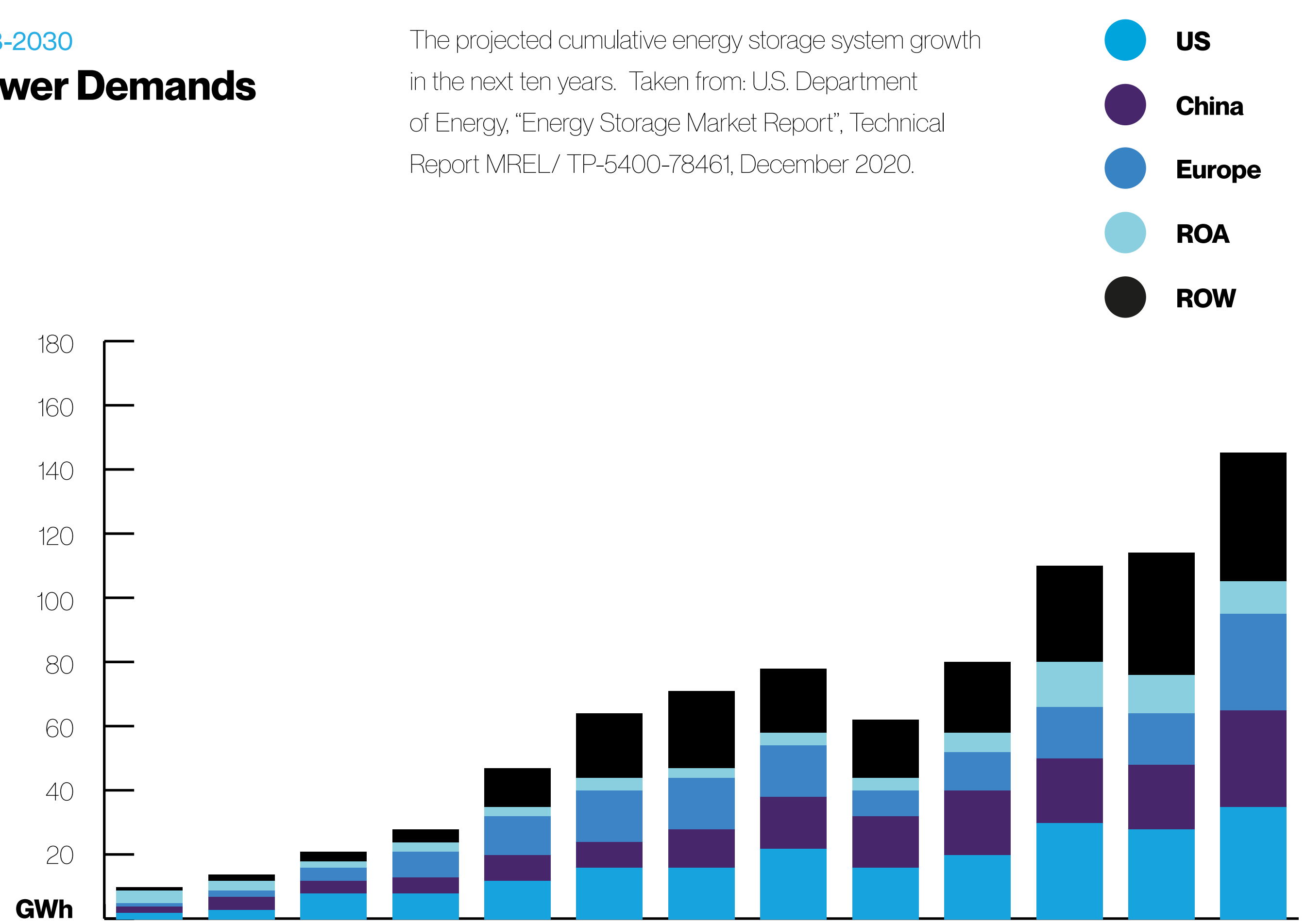
Section six

Delivering Reliable, Sustainable and Renewable Power: Energy Storage Applications

2018-2030

Power Demands

The projected cumulative energy storage system growth in the next ten years. Taken from: U.S. Department of Energy, "Energy Storage Market Report", Technical Report MREL/ TP-5400-78461, December 2020.



The needs of the world's energy storage systems (ESS) are diverse. With ambitious climate targets being implemented across the globe, from regional commitments such as Europe's climate-neutral aims by 2050 and the U.S. pledge to reduce emissions by 50% by 2030, to smaller-scale installations in communities and homes to combine solar with storage, batteries are one of the big facilitators of this global shift to clean energy.

As shown in graph to the left, large growth is projected in every region in the world over the next ten years. This will result in a significant increase in demand for batteries, a demand that will be so large it cannot be met by one battery technology alone. This means a range of technologies will be required in the future and this provides significant opportunities for growth for the advanced lead battery market, as a technology that can meet all the technical requirements and on a mass market scale.

These sectors provide significant opportunities for lead batteries:

1

Renewable energy integration

A wide range of systems will be needed to support smart grids and remote area power supplies for which lead batteries are ideally suited. The Consortium has identified case studies across the world where lead battery installations are demonstrating their value and effectiveness.

2

Transmission and distribution reserves and investment deferral

There are potential options in this sector with smaller systems (<5 MW, <10 MWh). Vital to deferment is distribution of solutions, and lead battery energy storage is best suited for this purpose due to high safety and reliability.

3

ESS for residential applications

This market is shared with Li-ion and lead batteries can expect to develop a significant share of the market going forward based on cost and performance. Lead batteries are currently used more widely in these applications in India, China and Africa.

4

ESS for commercial and industrial applications

There are excellent opportunities for lead batteries to expand in this sector, especially for residential applications in India, China and Africa.

5

Long Duration Storage

Lead batteries are well suited for long duration projects. The characteristic slow charge/discharge rates in this application are amenable to the technology, resulting in incredibly long life (+20 years) of lead batteries in these applications.

As a conservative estimate, analysts suggest ESS has the potential for new business with a value in the range from $600M to $1.2BN for lead batteries between now and 2025 . However, this could be significantly higher with greater levels of uptake of renewable generation, which governments and administrations are supporting through new climate change targets and policies. Further growth opportunities are possible and broadly available in several different applications:

1

EV fast-charging ESS

The use of lead batteries as a sustainable, reliable and safe battery technology for charging stations is being trialed in a feasibility study in Missouri, U.S. to explore the economic viability of the technology for this application

2

5G cell tower expansion

The ongoing deployment of both small installations throughout cities and neighborhoods and the infrastructure that ties these distributed resources together require UPS backup.

US DOE targets

ESS battery performance

An example of the type of battery (target) performance for lead batteries to fulfill the needs of US DOE and the European Energy Commission. This specific example was given in the Lead Battery Grand Challenge Roadmap document developed by CBI/BCI.

Performance Category	Current Maximum	*Target
Cycle life (80% DOD)	4000	5000
Round Trip Efficiency (%)	82	88
Acquisition Cost ($/kWh)	~135	35
Operating cost ($/kWh/cycle)	0.09	0.025

*The target is reflective of comments from Venkat Srinivasan, the director of the DOE JCESR program, and input from stakeholders in the DOE, including Sue Babinec, Program Lead for ESS at ANL.

The industry must move toward a longer lasting and more energy dense lead battery for utility, commercial, residential, and industrial ESS applications. Both EU and U.S. performance targets are aggressive and require batteries with long lifetimes to meet the proposed technoeconomic needs. Only lead batteries offer the reliability, sustainability and infrastructure to meet this need.

Research and productization of lead battery technology should focus on optimizing active material utilization/energy density and total energy throughput (commonly measured through various cycle life tests). The table to the left is an example of the improvements the U.S. DOE believe are needed to meet current requirements.

Exide's lead batteries used at the M5BAT energy storage project in Aachen, Germany

6.1 ESS: Key Performance Indicators

The key focus for the energy storage sector is to improve cycle life, calendar life and round-trip efficiency whilst reducing acquisition and operating costs.

An update of the KPIs necessary for lead batteries to be competitive in the ESS market is summarized in Table 4 below. Equally important is the need to develop lead battery technology into a systems approach, productizing energy storage solutions. The CBI Technical Roadmap covers the impact of productization on the cost metrics set out by government and utility stakeholders. The customization and configuration costs are significant and developing functional well-developed interfaces can be introduced into other systems at a significantly lower cost.

For ESS applications KPIs are reported as 2021/2022 (state-of-the-art), 2025 (medium-term goal), 2028 (long-term goal), and stretch targets loosely timed for 2030. The stretch target category is unique to ESS applications in this roadmap and demonstrate the potential of lead batteries to meet the highly aggressive targets set out by federal stakeholders in US DOE and EU energy commission.

These targets are listed to show the comparison to predicted advancement in 2025 and 2028, demonstrating disruptive innovation is necessary to push lead battery technology to the stretch targets in the 8-year period. The 2030 targets align with the many opportunities from various governments for battery energy storage.

These targets are ambitious, based on:

- Current scientific understanding of lead battery technology potential
- Offerings from within the lead battery industry.
- Future end-user/market requirements.
- Offerings from other competing technologies.

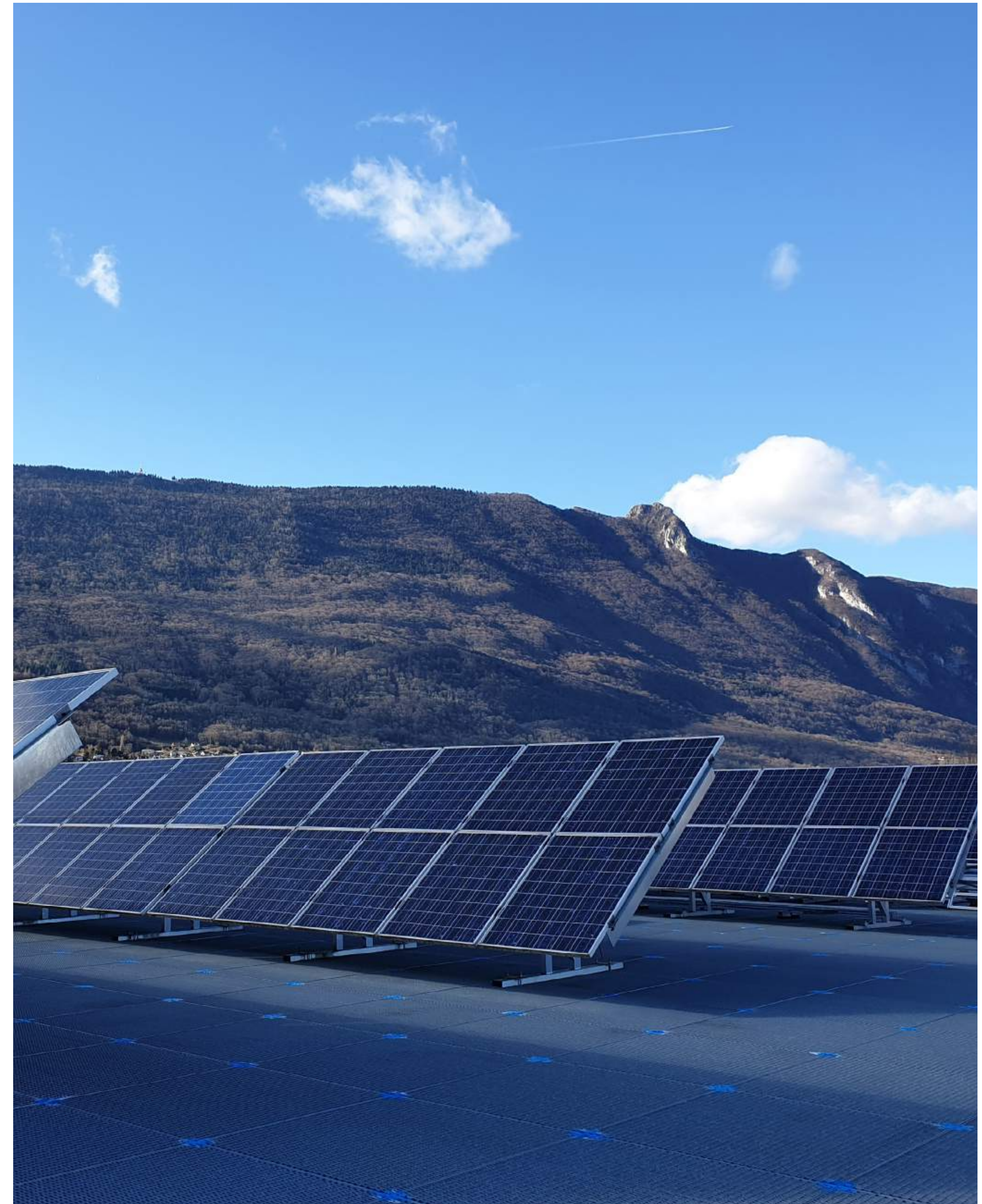
Indicator	2021/2022	2025	2028	Stretch Target 2030
Service life (years)	12-15	15-20	15-20	15-20
Cycle life (80% DOD) as an estimate for C10 or higher rates	4000	4500	5000	6000
Operational cost for low charge rate applications (above C10) – Grid scale, long duration	0.12 $/kWh/energy throughput	0.09 $/kWh/energy throughput	0.06 $/kWh/energy throughput	0.04 $/kWh/energy throughput
Operational cost for high charge rate applications (C10 or faster) - BTMS	0.25 $/kWh/energy throughput	0.20 $/kWh/energy throughput	0.15 $/kWh/energy throughput	0.10 $/kWh/energy throughput
Energy Storage efficiency (Wh in vs Wh out)(%)	75-90	80-90	85-90	88-92
Round Trip Efficiency (%)	85	88	90	92
Acquisition Cost (cell level) ($/kWh – 10 MW assumption)	175	140	100	75
Energy Density (Wh/l)	80-100	110	120	140
Acquisition cost, ESS level ($/kWh)	350	325	300	275
Safety	Maintain safety – deploy charging algorithms to control gassing			

6.2 Research pathways

To the right is an overview of the suggested research pathways to ensure lead batteries can deliver on the KPIs outlined in the roadmap. Further information regarding specific research is discussed in the full roadmap document reserved for CBI members..

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

Narada's 16 MW frequency regulation project in Bennewitz, Germany uses lead-carbon batteries for energy storage



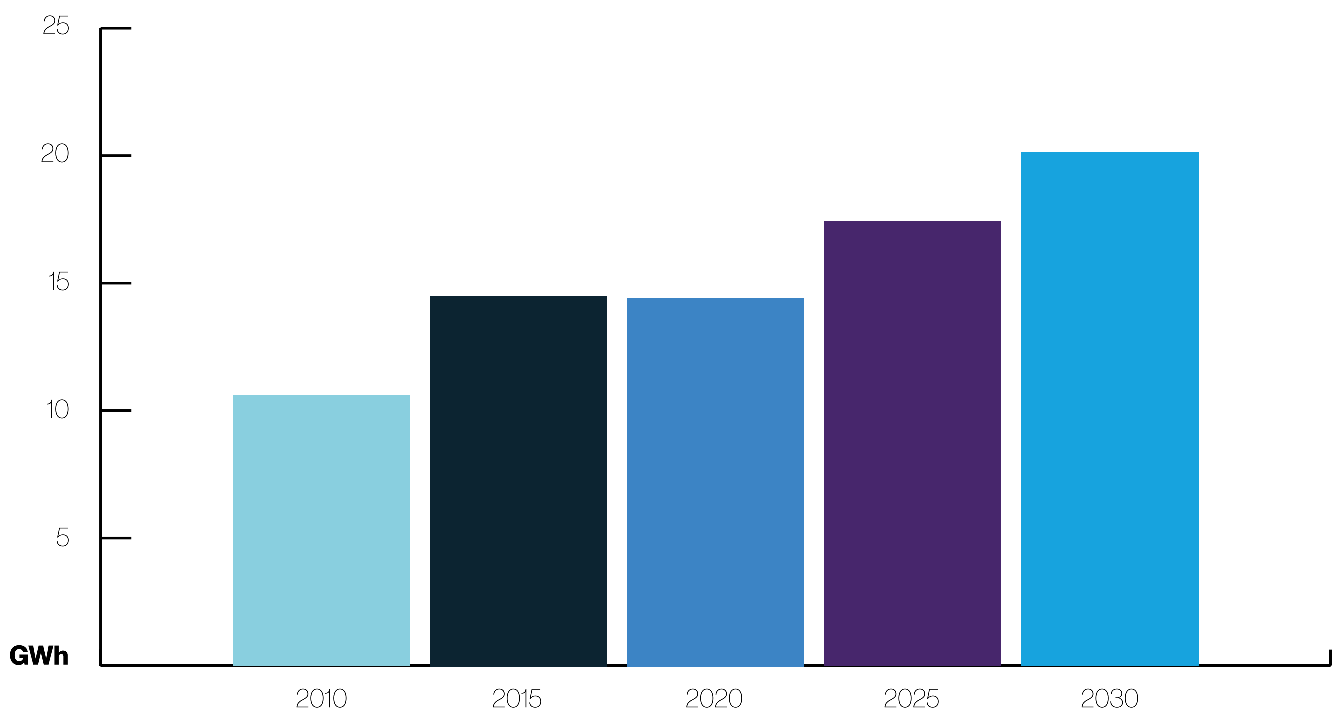
Section seven

Keeping the World Connected and Online: UPS and Telecoms Applications

CBI market report 2021, Avicenne

Telecom Market

Lead batteries remain the dominant technology for telecom, back-up and UPS applications. For telecoms and back-up they provide an invaluable resource in keeping the power on in blackout events, with a growth of 5.6 GWh predicted between 2015 and 2030.



For the UPS battery market, lead batteries provide 90% of global demand and an expected increase of 5.5 GWh is forecast in the period between 2015 and 2030. This critical application ensures the world's hospitals and data centers remain online when the power is out.

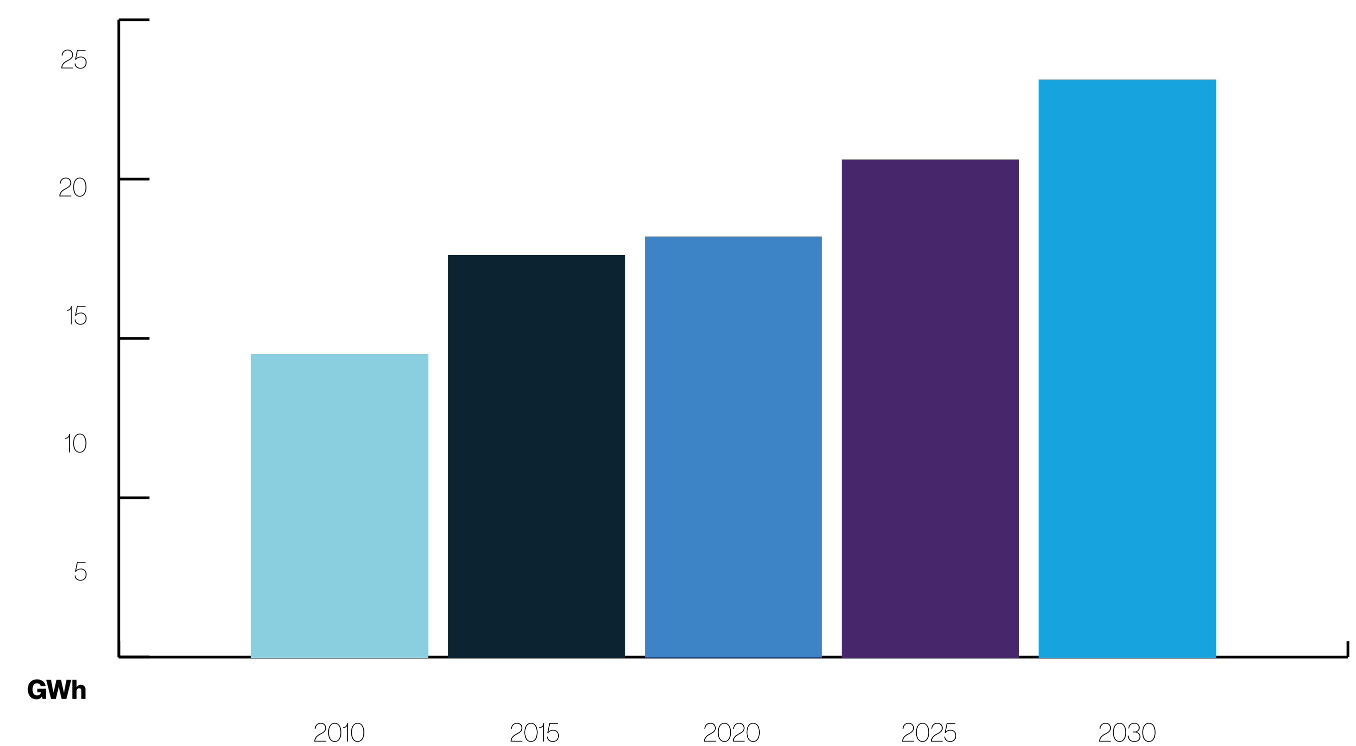
As a technology providing inherent safety, small footprint and long lifetime, lead batteries are a premium product for both the telecom and UPS sectors.

Furthermore, significant further market growth is expected in areas such as IoT (Internet-of-Things) expansion and 5G infrastructure buildout. Energy storage is vital for the ever-growing importance of data centers, and the increased need for energy resiliency for fundamental institutions like banks and hospitals.

CBI market report 2021, Avicenne

UPS Battery Demand

By enhancing the cycle life and charging efficiency of lead batteries, whilst lowering total cost of ownership (TCO) future opportunities for lead battery technology in this market are substantial.



7.1 UPS and Telecoms: Key Performance Indicators

The current status and targets for 2028 for telecom and UPS standby batteries are set out below. The key focus of this work is to improve cycle and calendar life, whilst reducing battery costs. There is no interim 2025 target set due to the long development cycles for telecom and UPS batteries. Table 5 describes the KPIs for telecom batteries and Table 6 describes the KPIs for UPS batteries.

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 product. Cycle 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 plants tend to have a shorter life because of high ambient temperatures.

Research targets

KPIs for lead batteries in telecom applications

Indicator	2021/2022	2028
Calendar Life on float	15 y at 20°C	7-10 y at 40°C 20 y at 20°C
Cycle life (Testing should follow IEC 60896-21/22)	300 at 80% DoD	500 at 80% DoD
Cost	$175/kWh	$150/kWh

Maintain Safety and Recyclability, Maintain Shelf life

For UPS, the calendar life on float is shorter than for telecoms for an equivalent product because if short, 15-minute, autonomy times are required, the ability of the battery to sustain a high-rate discharge is compromised earlier in life as a result of positive grid corrosion.

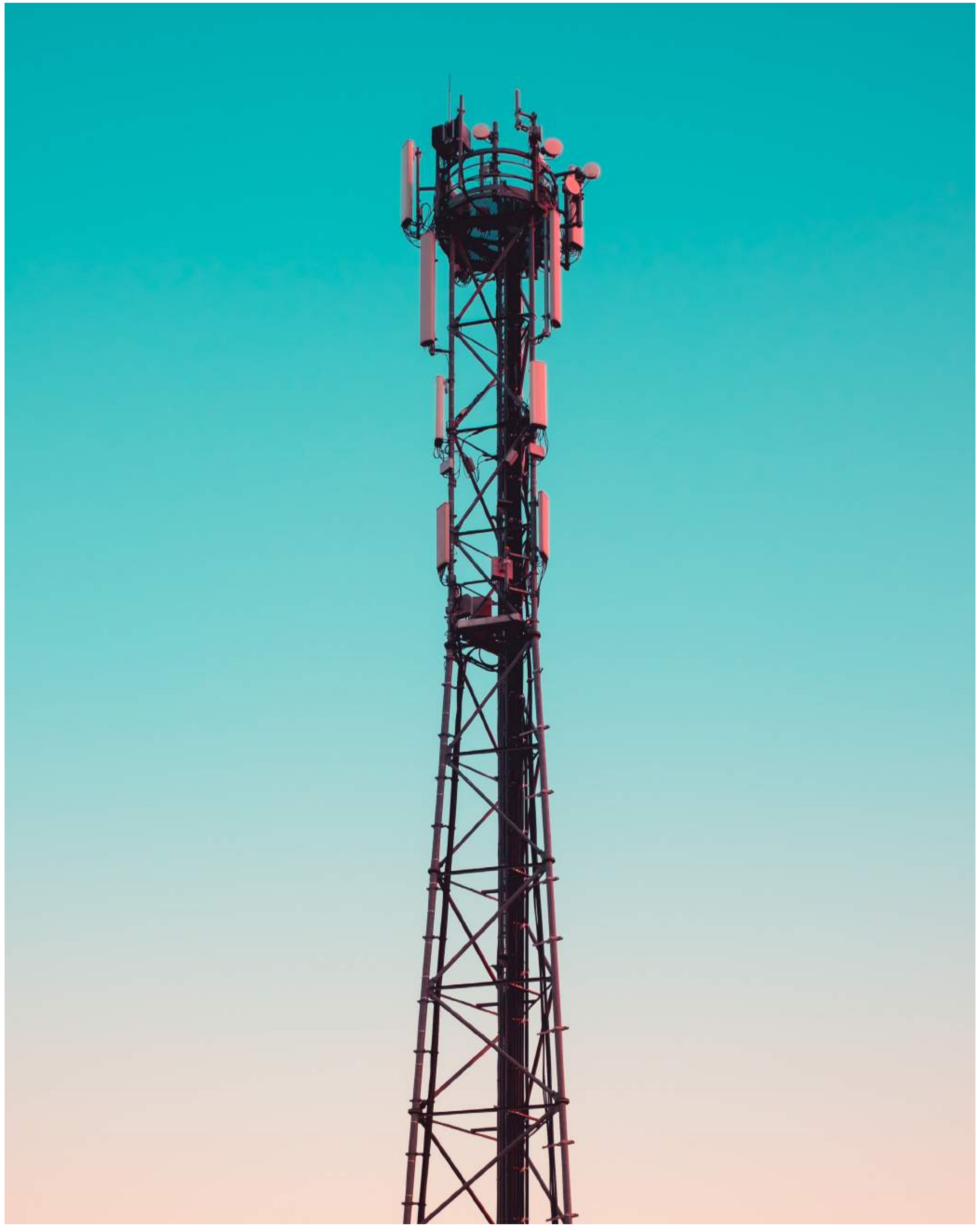
Cycle life for normal UPS service is, as for most standby battery applications, not critically important but a new class of hybrid UPS is offered by a number of suppliers where the critical load is protected but services are provided to a utility or to a behind-the-meter application to provide an additional revenue stream. This is discussed in further detail in the full roadmap document, but it results in a requirement for PSoC operation in a similar manner to ESS.

Research targets

KPIs for lead batteries in UPS applications

Indicator	2021/2022	2028
Calendar Life on float	10 y at 20°C	15 y at 20°C
Peukert Capacity (15-minute vs. 10-hour capacity)	65-80%	85-90%
Cycle life Testing should follow IEC 60896-21/22	1000 at 50% DoD 6000 at 10% DoD	5000 at 50% DoD 12000 at 10% DoD
Cost	$175/kWh	$150/kWh

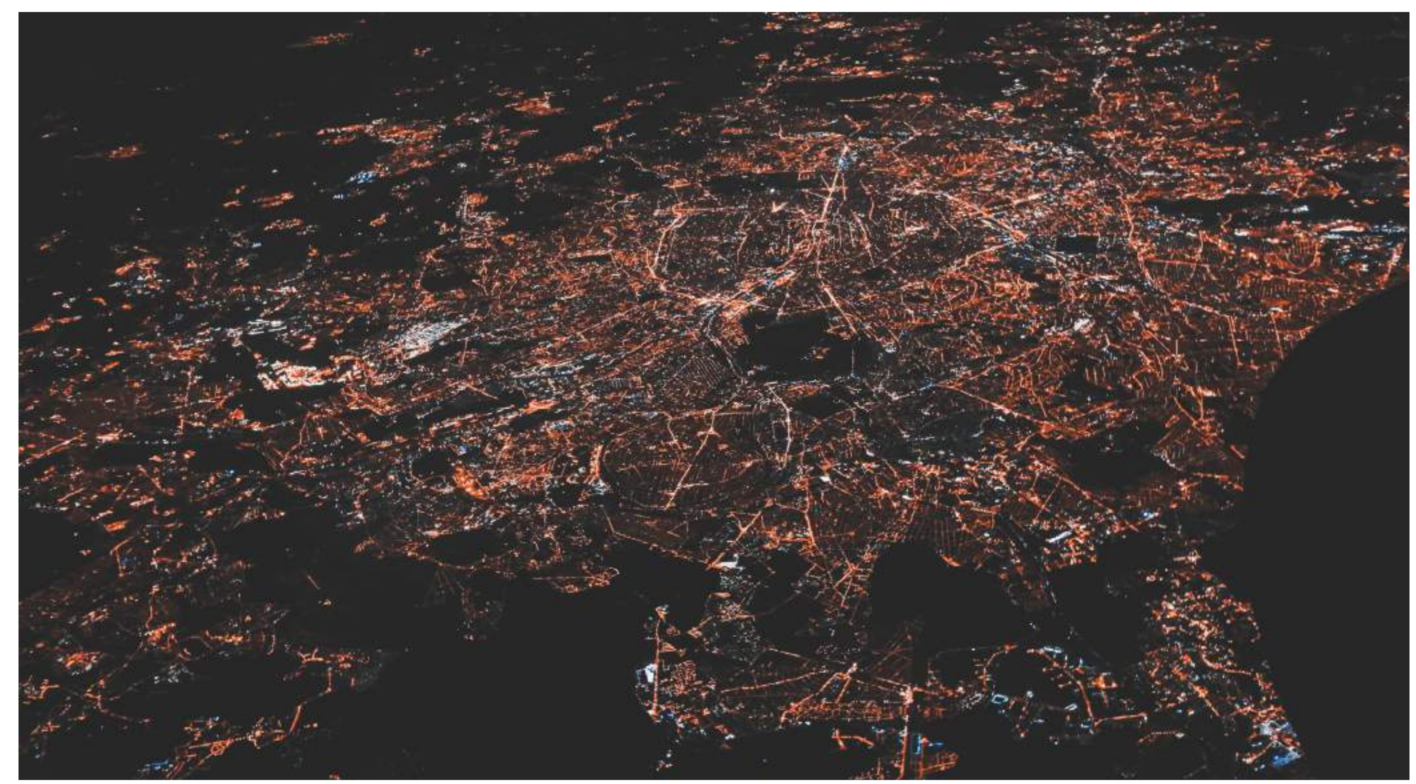
Maintain Safety and Recyclability, Maintain Shelf life



7.2 Research pathways

To the right is an overview of the suggested research pathways o ensure lead batteries can deliver on the KPIs outlined in the roadmap. Further information regarding specific research will be discussed in the full roadmap document reserved for CBI members.

- Improve the corrosion resistance of positive grids to extend life at higher temperatures.
- Increase cycle life in all duty cycles using additives tailored to shallow cycling and float life:
  - Optimize expander and carbon composition.
  - Control crystallization and dissolution of $PbSO_4$ over long periods of service life.
- Maximize life at float for UPS using highly pure lead (99.99%) for active material.
- Improve shallow cycle life for UPS batteries for hybrid applications through battery management and monitoring methodology.



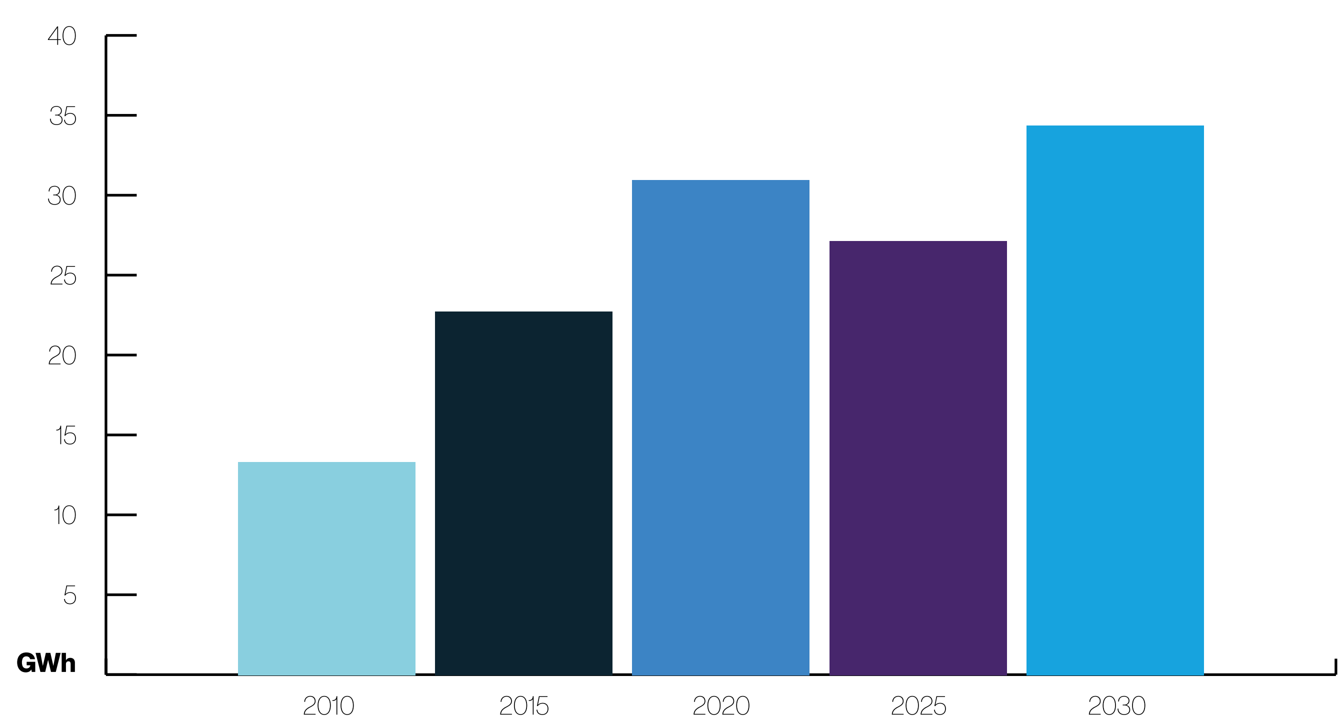
Section eight

Facilitating the Global Movement of Goods: Motive Power Applications

CBI market report 2021, Avicenne

Motive Battery Demand

With the market predicted to grow to 34.3 GWh by 2030, this is a significant sector for lead batteries.



The motive power lead battery has been key to the electrification of forklift trucks, providing a cost-effective, reliable solution. Lead batteries have been the dominant chemistry in this market for many years and 89% of the current motive power market is fulfilled by lead batteries, in applications such as forklift trucks, mining vehicles and other warehousing vehicles.

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.

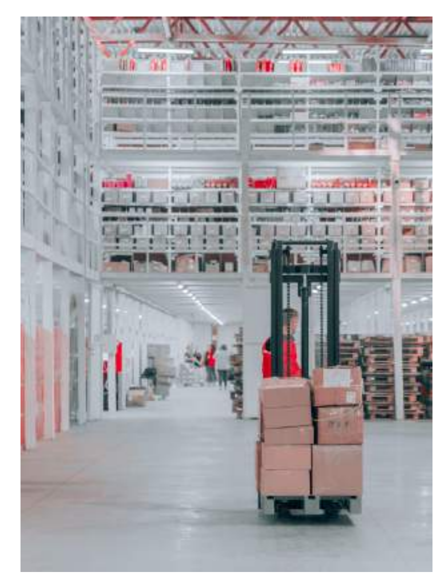
In 2019, CBI's previous roadmap provided research areas and directions for the technology. Since then, CBI has developed more material for motive power batteries including KPIs, detailed research areas and technical targets for motive power applications.

The research areas covered by this Technical 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 and e-rikshaw markets particularly in India, China and Southeast Asia but the market drivers and performance needs differ and batteries for these applications will be covered in the e-bike chapter.

Across the many types of equipment that may use lead batteries, forklift trucks and golf carts for instance, there are commonalities:



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

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

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

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

8.1 Motive Power: Key Performance Indicators

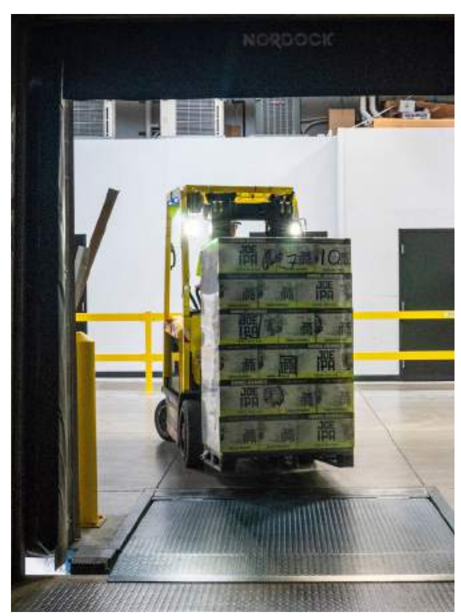
Taking all of these factors into consideration, CBI has constructed KPIs focused on TCO and market driven end-user requirements. The key focus of future work in this area is too lower TCO by increasing cycle life, recharge time, and producing maintenance-free batteries.

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 behaviour 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.

CBI has developed KPIs focused on keeping motive power lead batteries the dominant battery for electric forklift trucks and small recreational vehicles like golf carts. The KPIs in table to the right are based on market-driven requirements forming in these applications.

Cycle life for traction (motive power) batteries is tested currently using BCIS-06 and IEC 60254. The KPIs for 2025 - 2000 (80% DOD) and 1500 at (100% 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.



Research targets

KPIs for lead batteries in motive power applications

Indicator	2021/2022	2025	2028
Service life	5	5-6	6-7
Energy throughput	1200 equivalent cycles	1400 equivalent cycles	1600 equivalent cycles
Cycle life IEC 60254	2400 (50% DOD)	2800 (50% DOD) 1750 (80% DOD)	3000 (50% DOD) 2000 (80% DOD)
Energy density (specific to charge efficiency)	35 Wh/kg	40 Wh/ kg [c]	42-45 Wh/kg [c]
Charge time to 30 – 80% Opportunity Charging (Highly dependent on charger/charge current)	Less than 2 hrs	1 – 1.5 hrs	1 hr or less
Technology requirements	- Maintenance free present - Management of the battery [a] - Harmonization with Chargers [b] - Few products capable of opportunity charging	- Maintenance free more common - Management and monitoring of the battery [a] - Harmonization with Chargers - Capable of opportunity charging	- Maintenance free typical. - Management and monitoring of the battery [a] - Harmonization with Chargers - Capable of opportunity charging

[a] Use of smart management systems and sensors to maximize ease-of-use, provide reliable interim charging SOC, and prolong battery life.
[b] Migration away from watering and charging rooms, work area-based chargers with programming specific to lead batteries.
[c] Will likely mean VRLA or some design other than flooded.

Similar to 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, 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.

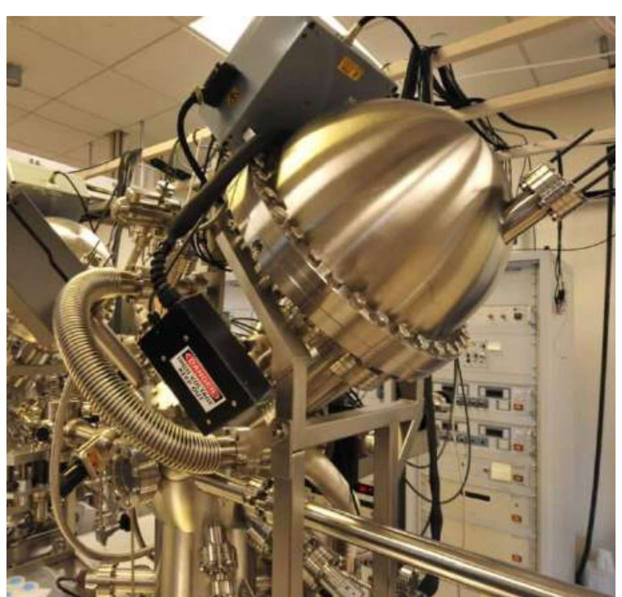
2

Charging time to a "fast" charge (80% SOC) is an important consideration when choosing a product for electric forklifts. Similar to 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.

Electrochemical Discovery Laboratory equipment, Argonne

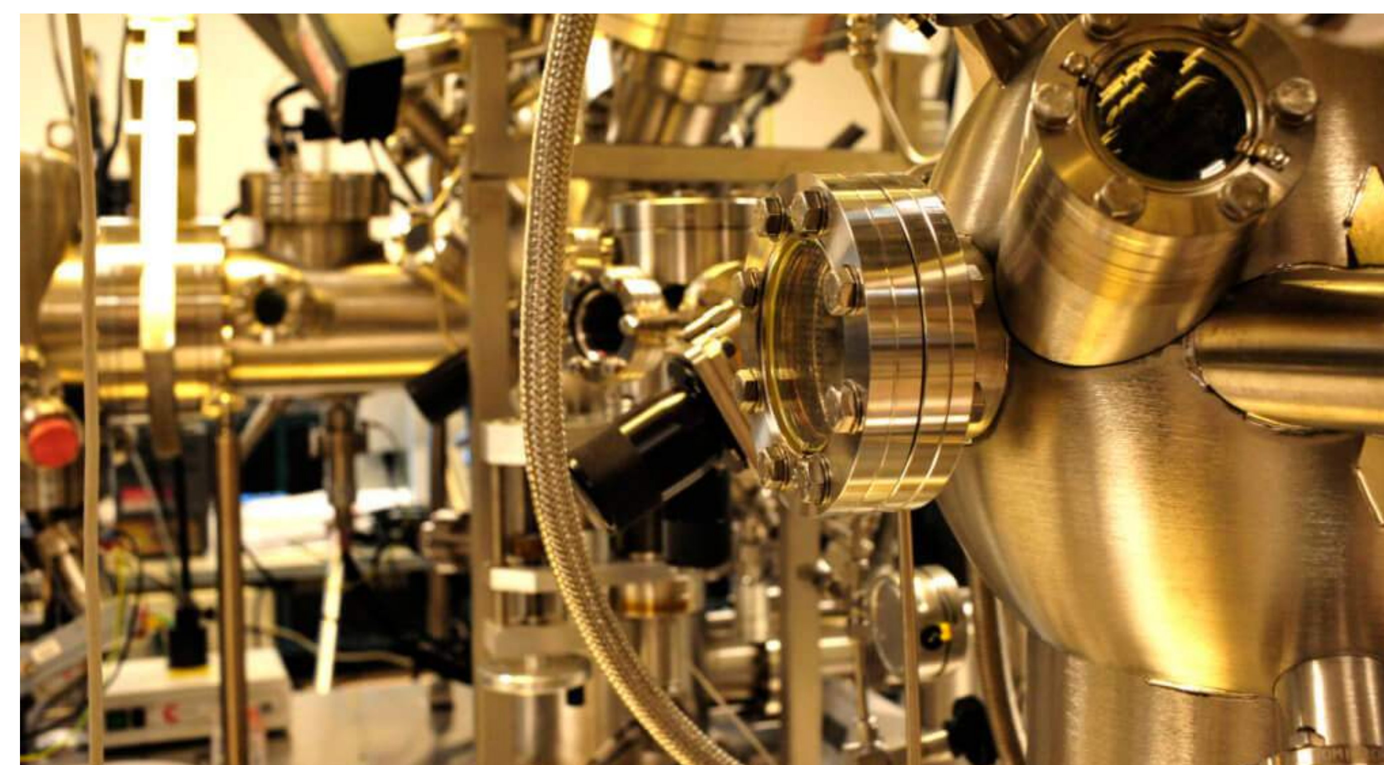


8.2 Research pathways

To the right is an overview of the suggested research pathways to ensure lead batteries can deliver on the KPIs outlined in the roadmap. Further information regarding specific research is discussed in the full roadmap document reserved for CBI members.

- Improve cycle life and energy throughput via carbon additives and new expander materials – lowering TCO.
- Optimize lead batteries toward antimony-free grids to introduce more maintenance-free lead battery options.
- Increase energy density by using new types of electrodes.
- Battery management tuned to lead batteries specifically to maximize cycle life.
- Develop and incorporate additives into the negative active material to improve recharge time.
- Pursue other battery designs to maximize energy density and provide maintenance free operation at the same time – tubular, gel, and bipolar designs.

Innovative research into improving lead battery technology is being undertaken at Argonne National Laboratory



Section nine

Driving Demand for Low-speed Electric Bikes: E-bike, E-Trike and E-Rickshaw Applications

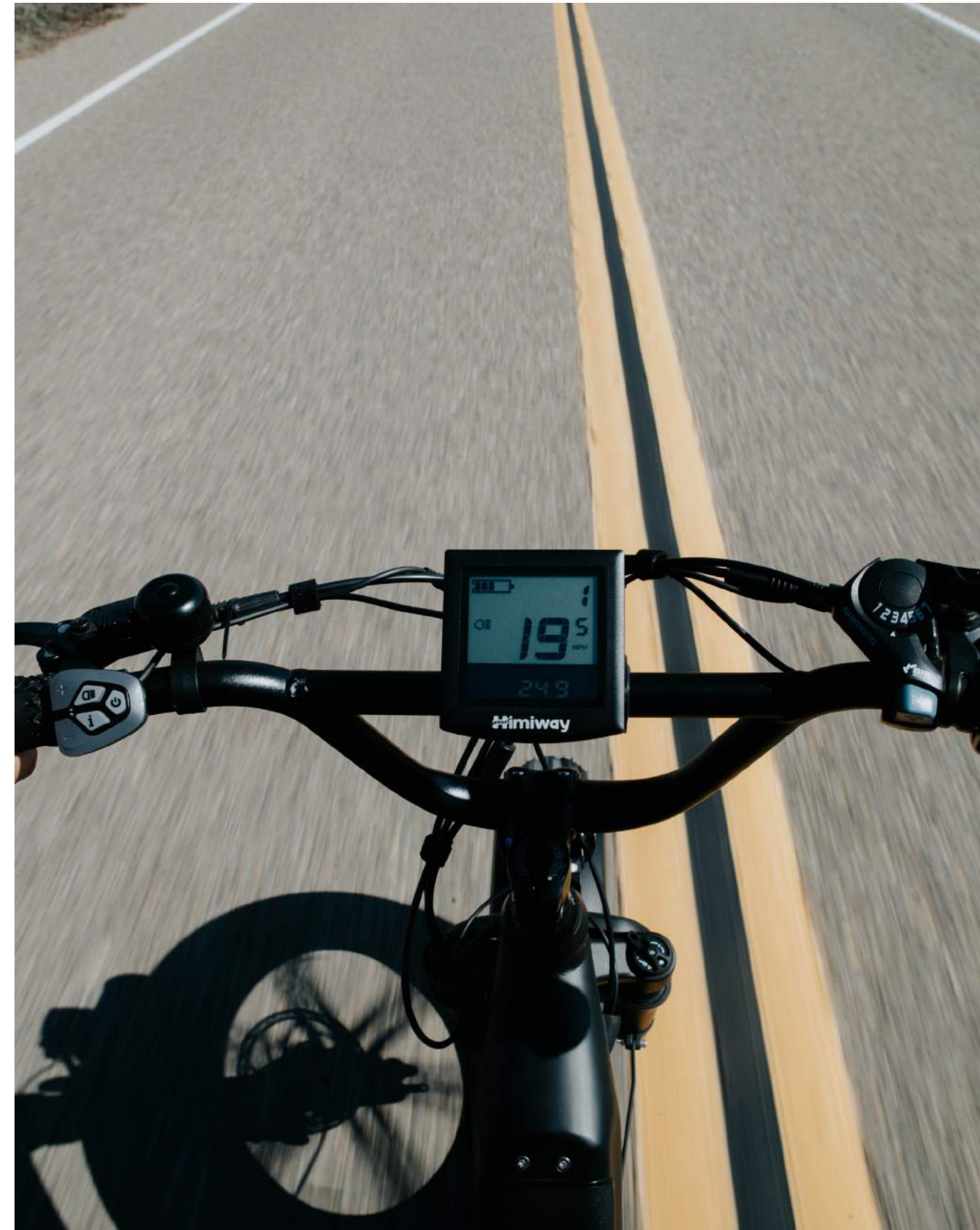
Decarbonization of the world grid and mobility sector is happening due to the increased adoption of batteries across multiple levels of our society. A primary case of this shift to electrification and decarbonization is the relatively new e-bike, e-trike, e-rikshaw market in India, China, and Southeast Asia. The market is estimated to currently be at US$2 billion.

Over the last 15 years, this market has grown from niche to a multibillion-dollar market for lead batteries. Lead batteries are dominant in these applications and help power over 300 million bikes, trikes and rikshaws.

Over the last three years there have been concerns on federal regulation related to battery weight limits in the e-mobility sector, suggesting a gradual decline and replacement of lead batteries by li-ion analogs.

However, monitoring of the markets and new trends have been observed in China, a key market for e-bikes. Importantly, ongoing improvements in gravimetric energy density have allowed lead batteries to persist in these applications. Along those lines, CBI aims to focus on innovation in this sector, providing insights in how to ensure the continued use of lead batteries in this application.

Future KPIs will developed with the CBI membership.



9.2 Research pathways

To the right is an overview of the suggested research pathways to ensure lead batteries can deliver advancements in E-bike performance. Further information regarding specific research is discussed in the full roadmap document reserved for CBI members.

Improve gravimetric energy density

The use of new battery designs and electrode materials to maximize performance and minimize weight. This is Important for e-bike batteries under current the regulatory climate.

Increased recharge capability

Lowering the internal resistance within the battery using new designs, pure lead materials, and other innovations will enable faster charge times, an important metric in this application.

Improving service life

Use stronger Pb alloys for better high temperature durability, study additives that improve active material cohesion, and focus on battery management techniques that maximize service life. This is an important metric to improve, aiming to have equitable performance when compared to other battery chemistries.

Section ten

Conclusion

To deliver on the sustainable targets set by governments across the globe, high-performing, innovative, next-generation batteries will be needed.

This is the golden age for lead battery technologies. CBI's Technical Roadmap is setting out the research pathways, guided by market assessment for the upcoming decade, to put the global lead battery industry on the path to delivering the advanced lead batteries needed.

The applications for lead batteries are vast, as are the opportunities for the technology to accelerate its innovation journey. By assessing future market trends and through discussion with end-users regarding future technical requirements for lead batteries, CBI has set specific research goals and key performance indicators to grasp these opportunities in key markets:

Automotive (start-stop/micro-hybrid)

Ensure that recent improvements in Dynamic Charge Acceptance (DCA) are maintained, whilst improving high-temperature performance and ensuring no trade-offs in key parameters such as Cold Crank Amps (CCA) and water loss.

Automotive (low-voltage EV)

Improve DCA and charge acceptance, whilst increasing charging efficiency and lifetime.

Energy Storage Systems

Improving cycle life, calendar life and round-trip efficiency whilst reducing acquisition and operating costs.

Industrial applications

Improving cycle and calendar life, whilst reducing battery costs.

Motive Power

Lowering TCO by increasing cycle life, recharge time, and producing maintenance-free batteries.

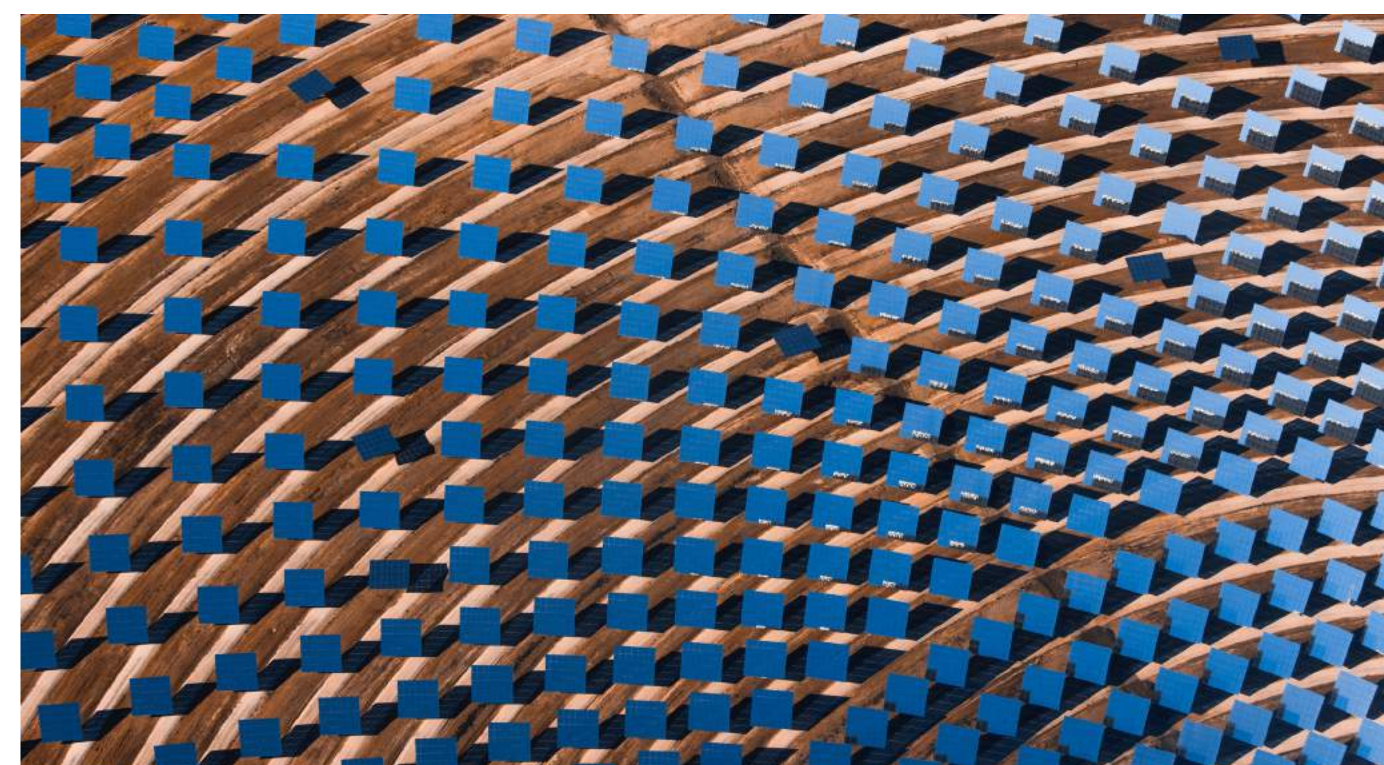
Other applications (including e-bikes)

Improving gravimetric energy density, recharge capability and service life.

Using the technical roadmap and the KPIs identified, CBI will develop research programs dedicated to improving lead battery performance and driving innovation to increase product development and decrease adoption for products in the lead battery industry. With specific standards developed for each application, this ensures technical progress can be demonstrated.

As technical demand for lead batteries evolves, so too will the roadmap to adapt to the changing requirements of research and innovation within the industry to ensure the continued criticality of the technology for global electrification and decarbonization goals.

A full Technical Roadmap, including detailed research pathways and current research underway led by the Consortium with its members, research institutes and governments around the world, is available for CBI members.



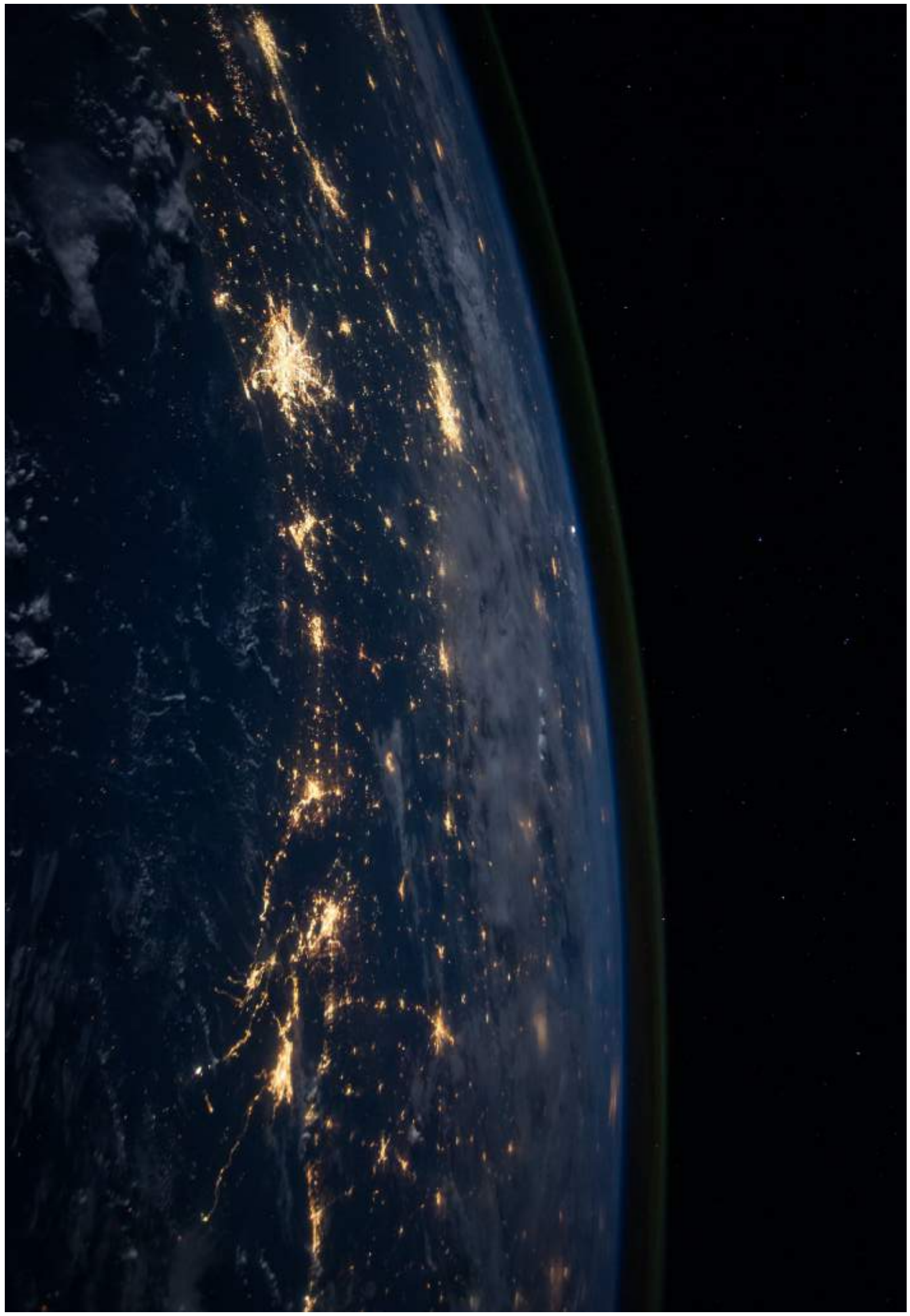
Glossary of Terms

AGM: Absorptive Glass Mat
BMS: Battery Management System
CA: Charge Acceptance
CCA: Cold Cranking Amps: the battery's ability to start an engine in cold temperatures
Charge efficiency: ratio of charge and discharge capacity (Coulombs)
Cycle life: The number of charge and discharge cycles that a battery can complete before losing performance.
DCA: Dynamic Charge Acceptance – the ability of a battery to capture instantaneous energy such as through regenerative braking.
DCR: Dynamic Charge Rate
DOD: Depth-of-Discharge – associated with cycle life, this is the percentage of rated capacity that has been removed from a charged battery. Sometimes referred to as % utilization.
EFB: Enhanced Flooded Batteries
ESS: Energy Storage Systems
EV: Electric Vehicle
Float life: The life expectancy of a battery under continuous charge
High-temperature durability: HTE test sequence used to determine the durability. For automotive applications, this commonly refers to the life of the battery above 60°C, for other applications 40°C.
HTE: High-Temperature Endurance
ICE: Internal Combustion Engine
IoT: Internet-of-Things
KPIs: Key Performance Indicators
LFP: Lithium Iron Phosphate Battery
LIB: Lithium-ion Battery
Low-voltage EV Batteries: also known as auxiliary batteries
MW: Mega-Watt
MWh: Mega-Watt hour
OEM: Original Equipment Manufacturers
Pb/C: Lead-carbon battery
PSoC: Partial State-of-Charge - operating in a SOC range (typically 20-80% SOC) as the duty of the application. Normal for MHT and some ESS applications.
Service life: The total life in years of the battery before failure – covers many duties and applications. A major OEM requirement across every application.
SLI: Starting, Lighting, Ignition
SoC: State-of-Charge
SoF: State-of-Function
SoH: State-of-Health
Start-stop: also know as Idle start-stop (ISS)
TCO: Total cost of ownership
UPS: Uninterruptible Power Supply
VRLA: Valve-regulated Lead-Acid Battery
Wh: Watt-hour
WLTP: Worldwide harmonized Light-duty vehicles Test Procedure

Organizations
ANL: Argonne National Laboratory
APS: Advanced Photon Source
CSE: Chemical Sciences and Engineering Division
FHISC: Fraunhofer Institute of Silicate Research
IEC: International Electrotechnical Commission
LBRSP: Lead Battery Research Science Program
MSD: Materials Science Division
U.S. DOD: Department of Defense
U.S. DOE: Department of Energy

CONSORTIUM FOR
BATTERY
INNOVATION

Technical Roadmap
Research and Innovation



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