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BCI Guide to Major Automotive Low Voltage and Industrial Battery Applications and Technologies

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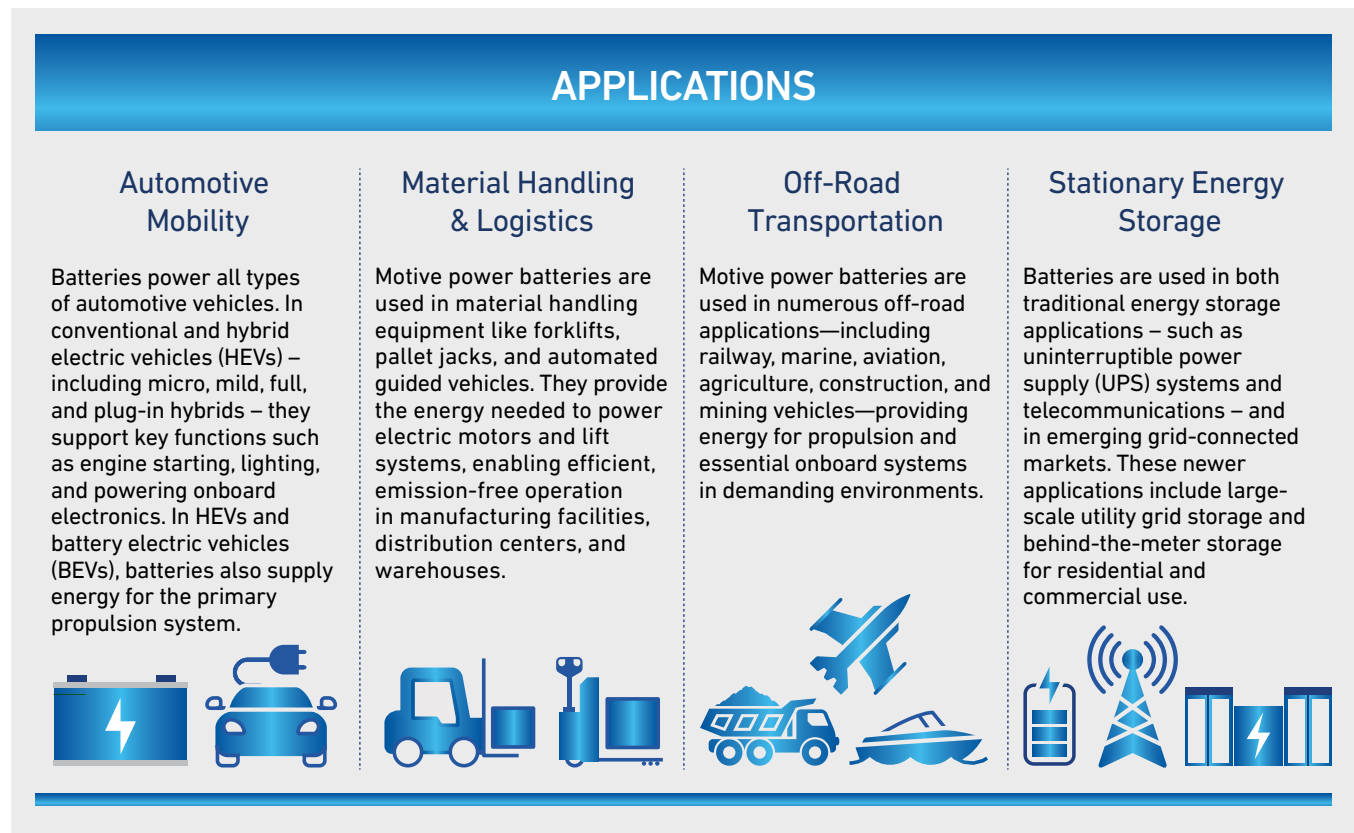
Introduction

Batteries are designed for specific applications such as automotive mobility, stationary energy storage, motive power for material handling and off-road transportation. Each application calls for unique performance requirements to meet existing and developing market needs. Through continuous investments in battery innovation and with its reliable, standardized manufacturing approach, the lead battery industry has the experience and expertise to serve both the current market and future demands.

The end-user applications that follow are to provide technical background on why different battery technologies are needed. They demonstrate how the different technologies and chemistries each have their specific role and development potential to anticipate the shifting market demands.

Regulations and battery innovation have historically driven new battery applications. This explains the very wide range of specific battery products, sizes, technologies, and chemistries that coexist in today's market.

We selected key applications grouped around four areas: **automotive mobility, material handling and logistics, off-road transportation and stationary energy storage**. The list of applications is not exhaustive, and other key markets exist where battery R&D is strongly driven by innovation. This is particularly true for military and medical applications.



Area 1: Automotive Mobility

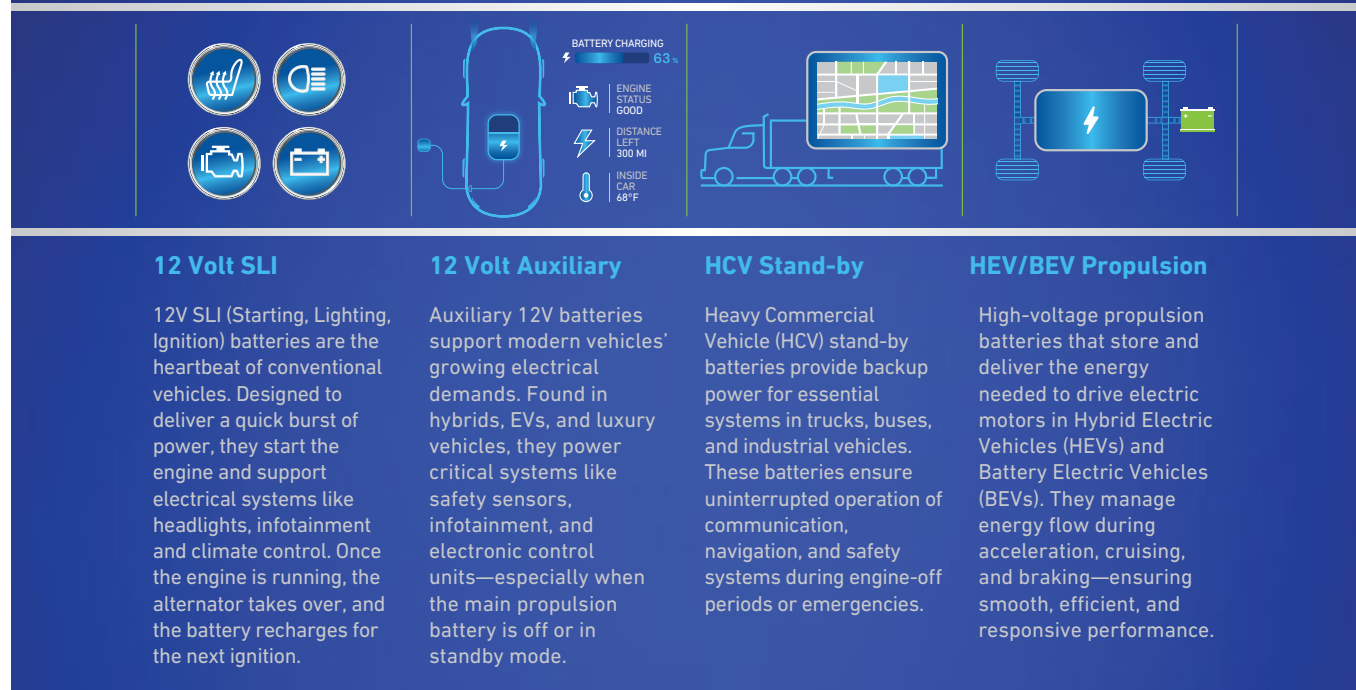
The transportation sector currently accounts for the largest portion (28%) of total U.S. direct greenhouse gas emissions¹, but has a strong potential for decarbonization, with batteries as key enablers to increase the energy efficiency of vehicles (all drive trains) and road transport infrastructure. Consumer pressure and regulatory drivers are forcing changes in vehicle technology. Today, there is a focus on electric vehicles, but there is wide potential for the role of batteries to evolve further.

In the automotive mobility area, the battery technology evolution in the four end-user applications presented is clear:

- The 12V auxiliary, 12V Starting-Lighting-Ignition (SLI) and Heavy-duty Commercial Vehicle (HCV) stand-by battery markets will remain lead-based through 2030.
- For the mild and full Hybrid Electric Vehicle (HEV) batteries, as well as for the Battery Electric Vehicle (BEV) propulsion batteries, the market will be exclusively lithium-based.
- The e-mobility-driven battery market will grow to >2,800 GWh by 2030.

Battery Functions Across Vehicle Platforms

From starting your engine to powering advanced safety features, batteries are the silent force behind modern mobility. Explore how different battery types serve distinct roles across automotive and commercial applications.



A primary task for automotive batteries in hybridized and fully electric vehicles is to capture and store the car's kinetic energy during braking or excess alternator capacity for future use to either power the wheels or start the engine, depending on the drivetrain configuration. Different battery types will continue to coexist in automotive applications, as they all have the potential to contribute considerably, but the choice of battery type will depend on the application. Low and high voltage (HV) electrification strategies drive different requirements in energy storage systems, as shown in the following applications.



12 Volt Starting-Lighting-Ignition Batteries (12V SLI)

Micro and mild-hybrid vehicles typically run with a 12V lead battery because of the advantages presented by a lead battery's cranking function. Cranking a combustion engine within a wide ambient temperature range is the main feature of the 12V SLI battery, as well as providing energy to power the lights and other accessories in the car when the engine is not running, or when the engine is running but the energy demand is higher than the alternator can supply. Cranking the combustion engine and providing energy to multiple accessories when the engine is not running has become the major challenge to meet the ever-increasing demands of the widespread start-stop micro hybrid architectures that are introduced in the original equipment market (OEM). Opportunity charging to capture the kinetic energy of the car will be key to improving energy efficiency in vehicles. With an increasing number of micro and mild hybrid vehicles on the road, this application is a key enabler to reduce CO₂ emissions, and lead-acid 12V SLI batteries will serve the replacement market for many future years.

Today, the American SLI battery market is valued at nearly \$8 billion and is predicted to increase at a growth rate of 1% through 2026². Lead batteries are expected to continue to dominate this market because of their specific features, and only a moderate penetration of lithium of 10% is predicted by 2030². In the lead battery market, flooded batteries will retain a substantial U.S. market share, although enhanced flooded (EFB) and absorbent glass mat technology (AGM) will have a growing share.

12V SLI Battery Technology by 2030 (MWh):

- Lead dominant battery technology
- Lead battery technology transitioning to AGM and EFB
- Lithium very small market penetration





12 Volt Auxiliary Batteries

Auxiliary 12V batteries are used in automotive vehicles, in internal combustion engines (ICEs) and at all levels of hybridization. From micro, mild, full and plug-in hybrids to fully electric cars, a 12V auxiliary battery's main function is to support the 12V loads and to ensure the quality of the onboard systems, as well as to ensure the safety maneuverings in case of emergency. Furthermore, start-stop functionality, cyclability and cranking are tailored to the specific vehicle architecture. The auxiliary 12V battery market is quickly growing, and expecting to increase at 12% per year in value².

The dominant transportation battery technology serving 12V auxiliary roles is lead, including the following lead battery technologies: flooded, EFB (enhanced flooded battery) and AGM (advanced glass mat). AGM style batteries will have the largest market share of lead type 12V auxiliary batteries by 2030². Together with lead, lithium (mostly LFP) will also fulfill some requirements. In the automotive sector, the role of 12V batteries will remain dominant in all vehicle architectures, with 12V Li-ion having a small market share by 2030².

For auxiliary applications, lead batteries are advantageous for their high temperature life, low temperature performance, recycling efficiency and cost, but could improve in terms of cycle life and energy density. EFB and AGM lead battery technologies will generally be preferred.

Some vehicles – particularly high-price or weight-sensitive sports cars – have seen the limited deployment of li-ion batteries for 12V auxiliary batteries recognizing advantages in weight, energy, power densities and cycle life at ambient temperatures. However, high cost, safety and recyclability, as well as extreme temperature performances, must be improved before those products can become competitive with lead batteries in mainstream vehicles.

12V Auxiliary Battery Technology by 2030 (MWh):

- Lead dominant battery technology
- AGM dominant lead battery technology
- Lithium growing market share





Heavy Commercial Vehicle Stand-by Batteries (HCV)

Like passenger vehicles, heavy commercial trucks remain primarily internal combustion-powered and therefore require a battery to perform SLI functions. The current dominant technology for these applications is lead batteries.

In addition, heavy commercial trucks also require auxiliary power. There are no federal regulations limiting truck idling. However, more than half of U.S. states and dozens of cities and counties have enacted idling laws or ordinances. Trucks operated in those states and local jurisdictions are covered by the regulations, including out-of-area vehicles that are in transit. Many of these laws set a limit on the amount of time a vehicle can idle, typically ranging from 3 to 15 minutes. These legislative changes have led to new battery requirements and resulted in a completely new market for HCV stand-by batteries.

The purpose of these batteries is to ensure a high energy supply when both the engine is not running and electric energy demand is high. This requires deep-cycle performance, which cannot be achieved with conventional starting or dual-purpose lead batteries. Advanced lead battery technologies are the most common batteries in this market due to reliability and cost effectiveness, but lithium is also gaining traction. However, the temperature window and the total cost of ownership for lithium will be a challenge for many applications, suggesting limited market penetration by 2030.

Heavy Commercial Vehicle (HCV) Stand-by Battery Technology by 2030:

- Lead to continue dominating the market
- AGM technology increasing share of the lead battery market
- Lithium technology limited market penetration



Hybrid Electric Vehicle Propulsion Batteries (HEV Batteries) and Battery Electric Vehicle Propulsion Batteries (BEV Batteries)

Automotive requirements for mild and full HEV propulsion batteries and BEV propulsion batteries vary greatly due to the large variety of vehicle sizes and applications. Current HEV and BEV markets are dominated by lithium-ion technologies. Lead battery chemistry does not have a market share in these types of applications and is not expected to enter the market.

Mild & Full HEV Propulsion Battery Technology by 2030:

- Exclusively lithium based



100%

BEV Propulsion Battery Technology by 2030:

- Exclusively lithium based



100%



Area 2: Material Handling & Logistics

Batteries in Material Handling and Logistics

The worldwide industrial motive power battery demand will increase from 41 GWh in 2023 to 68 GWh in 2030. The main drivers of this large growth is an overall increase in global forklift demand, increase in electric forklift penetration and an increase in kWh per device².

Material handling vehicles are used in warehousing and distribution for loading and unloading, handling pallets, and picking and storing inventory. There are different vehicle categories and a wide variety of forklift types with distinct applications, features, and benefits. These include order pickers, reach trucks, rider pallet trucks, narrow aisle forklifts, high-capacity forklifts, and side-loaders.

Traction and semi-traction batteries for material handling, such as in forklift applications, are an established market in which lead batteries currently have around a 90% market share. Lithium is only in the early stages of starting to penetrate this market. Nickel-based batteries are complementary and all have the potential to contribute to the innovation in these applications.

Pushed by noise and emissions legislation, battery forklifts are steadily replacing ICE-types. The high battery growth in this market will include both lead- and lithium-based technologies. BCI members' forecast U.S. motive power sales for material handling and logistics to growth at +3.1% annually through 2027³.

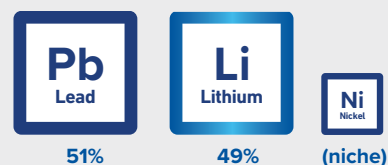
The lead battery forklift market remains stable as far as the number of units as the overall battery forklift market grows, and by 2030, the lithium share forecast shows a potential increase to a 49% market share². Lead batteries are seen as the cost-effective solution in one-shift regimes or when using battery swap infrastructures on location when there is enough charging time available. Moreover, in operations with opportunity and fast charging, newer advanced lead batteries available today and designs coming to market in the future will also offer increased flexibility and higher availability.

Lithium has an advantage in the market for smaller forklifts in multiple shift operations, which are more energy-demanding and where battery charging time is limited. The general technical requirements for energy storage systems in material handling are high charge and discharge rates, high energy content, cycle life and operating times, high recyclability, low investment cost and the need to meet strict safety requirements. Other increasingly important requirements are high capacities (increased truck dynamics), namely the power density, high temperature performance and energy efficiency.

Nickel-based batteries represent a smaller part of the market, but also have a crucial role to play as they are often used in extreme temperature conditions, such as in drive-in freezers.

Material Handling Battery Technology by 2030 (MWh):

- Lead technology will see modest unit growth
- Lithium technology increasing market share
- Nickel technology deployed in niche applications





Area 3: Off-road Transportation

Batteries in Off-road Industrial Vehicles

This segment covers a wide range of industrial applications that cannot be allocated to the previous material handling & logistics application vehicle categories which includes the following sub-segments:

- **Sweeping/Cleaning machine** used in factories, malls, and supermarkets for cleaning purposes as well as wheelchairs. Here, a different number of 6 to 12V monoblocs with different dimensions and stored energy, are typically used, connected in parallel and series.
- **Construction/Demolition machines**, such as mini-loader and scissor-lifts, used in places like production facilities and construction sites – batteries are similar to those used in the previous application.
- **Golf-carts and small carts** used for leisure or light human transportation such as in airports.
- **Automated guided vehicles and carts (AGVs and AGCs)** transport systems are characterized by the fact that they are suitable for lifting, stacking and storing loads on shelves, can pick up and unload automatically within a company's premises and generally use electric drives.
- **Other applications not included in the categories above**, such as harvesting trolleys used in greenhouses and other small machines.

Off-road Industrial Vehicles Battery Technology by 2030 (MWh):

- Lead remaining dominant in most of the off-road segments
- Lithium to replace larger ICE, ex. in building/demolition
- Nickel to serve niches for extreme environment





Batteries in Railway Applications

The U.S. rail infrastructure is widely considered the largest, safest, and most cost-efficient freight system in the world. Freight railroads account for roughly 40% of U.S. long-distance freight volume (measured by ton-miles) — more than any other mode of transportation. However, they account for just 0.5% of total U.S. greenhouse gas emissions according to EPA data, and just 1.9% of transportation-related greenhouse gas emissions⁵.

The U.S. rail freight market is projected to grow at a CAGR of 5.5% from 2025 to 2030⁴, reflecting strong momentum driven by strategic infrastructure investments, rising demand for efficient freight transportation, and the integration of advanced rail technologies. The shift toward sustainable and eco-friendly logistics solutions is further accelerating rail adoption, supported by government initiatives aimed at modernizing the national rail network and enhancing regional connectivity. These factors position the U.S. rail sector as a critical component in the future of domestic freight movement.

As freight demand is expected to rise 50% between 2020 and 2050⁶, it is of great importance that we develop higher performance batteries to support innovation in both vehicles and infrastructure to further increase the performance and energy efficiency of the system.

Railway batteries are located in the rolling stock and supporting infrastructure. The mainstream technologies used are nickel based, in particular NiCd, flooded and sealed lead, and lithium-based batteries. For the rolling stock, we differentiate between 'city traffic' (suburban railway and underground trains), 'regional traffic' (railway passenger carriages) and 'long-distance traffic' (railcars with ICEs), where batteries are used to serve different applications, such as for lighting and emergency power supply, delivering auxiliary services and starting diesel engines. For railway standby applications, we differentiate between batteries for 'trackside line signaling', 'street traffic control', 'signal and control boxes and enclosures' and 'wayside energy storage'.

New upcoming applications for battery systems are the hybridization and electrification of rail power traction, mainly for commuter and metro trains. The requisite high energy, power density and cyclability for such applications can be covered by lithium systems in particular, which are expected to be the fastest growing battery segment due to benefits such as being maintenance-free and having a longer lifetime. For batteries used to power auxiliary functions, as well as lights and fans in high speed and metro trains, the nickel-based chemistry is the preferred technology. Due to development trends for on-board units with smaller footprints, weight restrictions and constant reliability needs, the future requirements for energy storage systems consist mainly of improvements to volumetric energy density, lifetime and operation temperature range.

Railway Battery Technology by 2030 (MWh):

- Traction is exclusively li-ion
- Auxiliary: NiCd and lead based, lithium also penetrating



Traction 100%



Auxiliary



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Batteries in Marine Applications

The marine sector is a strong contributor to CO₂ emissions and pollution worldwide. Batteries are enablers that contribute to the transformation of maritime fleets in oceans, seas and inland waters.

We distinguish four maritime application segments, each with their specific application profiles:

- BEV smaller boat: Canal, river and lake vessels, integrated fleets with onshore charging infrastructure
- BEV and HEV ships: Off-shore, drilling, fuel cells vessels, etc.
- BEV and HEV ships: Cruise liners, ships and ferries, etc.
- Other batteries in the marine application located on-board and in the marine infrastructure

There is an urgent need to electrify all forms of boat and marine transport, which is an opportunity for both lead and lithium batteries as both technologies can contribute and have their place in these markets. Lithium batteries have higher energy densities and cycle life, while lead batteries are more suitable for on-board auxiliary services, to ensure the on-board safety and security functions and to crank the diesel engines. In all these segments, the market for electric propelled vessels is increasing to meet future demand. For BEV smaller boats, lead 48V propulsion technologies, both flooded and sealed, are dominant today. Lithium NMC and LFP are also breaking through in this market, while for the propulsion of BEV and HEV medium to large ships, the market is exclusively lithium.

For larger ships and ferries, there are different degrees of hybridization of the powertrains. Some long-distance cruise ships have thermal engines that charge the batteries via generators to power the electric propulsion engines and reduce fuel consumption and emissions when running at full power for long periods, while they can also operate on pure electric mode during short periods, for example when entering seaports. Batteries can also be used for feeding excessive loads (peak-shaving).

For the propulsion of smaller vessels, other hybrid electric systems are developing, including the integration of solar and wind energy. There are also full electric plug-in architectures developing with charging infrastructure at ports where on-board battery systems, once they are fully charged, allow vessels to run autonomously without any fuel consumption or emissions during use. Standardization is a challenge to reduce costs and meet the high safety requirements of the systems that are used on-board.

For smaller boats, 48V propulsion batteries are used. To increase the propulsion power and range, the potential for innovation is in the gravimetric/volumetric energy density.

Marine Applications Battery Technology by 2030 (MWh):

- Propulsion of large-scale ships: 100% Li
- 48V propulsion smaller vessel batteries: exclusively Li-ion
- Auxiliary: lead-based, NiCd for niche, lithium penetrating





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Batteries in Aviation Applications

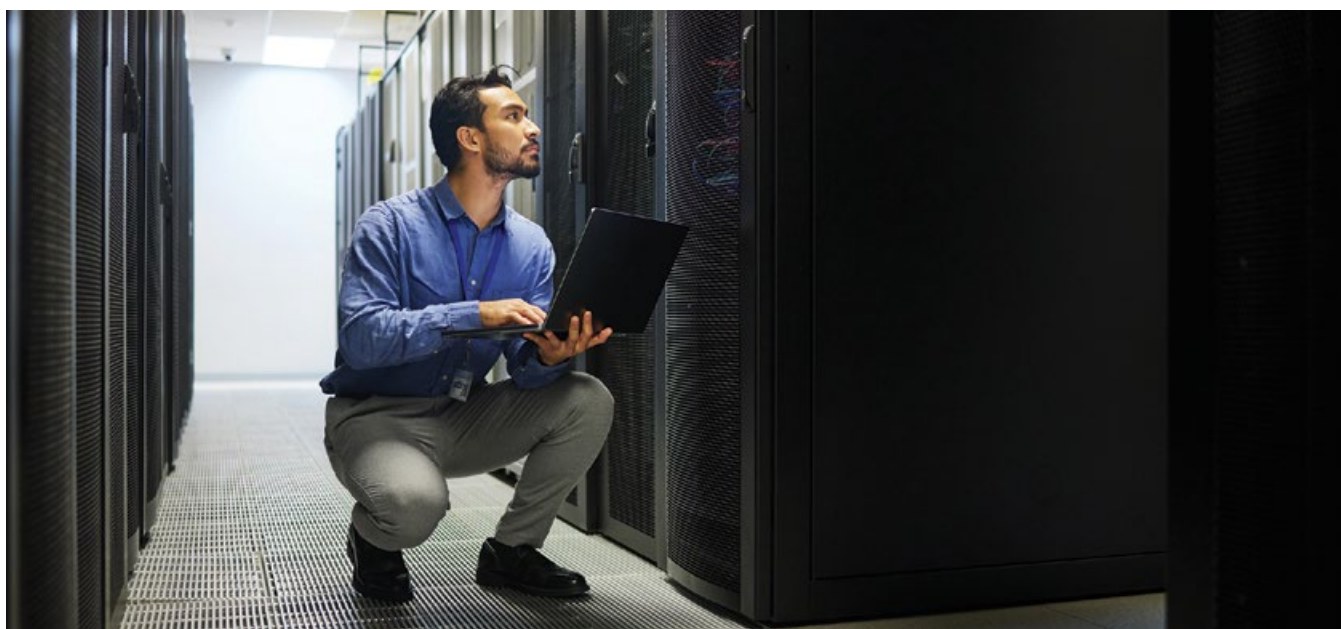
According to the International Energy Agency, the aviation industry produced nearly 950 Mt CO₂ worldwide in 2023⁸. Electric aircraft have been discussed in the last decade in the context of climate targets. However, with current battery energy densities, it is not yet possible to electrify the propulsion of commercial aircraft. Potential hybridization and the development of eVTOL (electric vertical take-off and landing) is a first step to reduce the greenhouse gas emissions of this sector.

Short-range eVTOL vehicles will bring value as personal air vehicles, air taxis and cargo carriers to replace helicopters, which are noisy, mechanically complex and expensive to maintain. Electric, multi-rotor, distributed propulsion solutions are in development. Over 100 firms worldwide have announced to work on 1–7-seat, short range urban air mobility vehicles. It is predicted that by 2050 there will be over 160,000 eVTOL-vehicles flying worldwide. Meanwhile, the development of eVTOL will further boost other battery markets. Apart from reducing fuel burn and related carbon emissions, other market drivers are noise reduction and to significantly improve competitiveness with the other existing mobility modes. In today's markets, aircraft batteries are used for many other 'non-propulsion' functions (e.g., ground power, emergency power, improving DC bus stability, and fault clearing). Small private aircraft use lead-based batteries while commercial and corporate aircraft use nickel-cadmium (NiCd) thanks to a high cycling capacity which ensures long life and reduced maintenance, and low weight and size. Lithium can also compete with such auxiliary batteries and is increasing its market share.

Aviation Application Battery Technology by 2030 (MWh):

- Propulsion batteries for eVTOL: exclusively Li-ion
- Auxiliary: Lithium to take over NiCd and lead-based





Area 4: Stationary Energy Storage Batteries

Batteries for Uninterruptible Power Supply (UPS Batteries)

When utility power fails, Uninterruptible Power Supply (UPS) ensures that critical equipment can safely shut down to protect the operation. There are various applications from small single computers to big data centers, buildings and power plants. Tendency to use energy storage devices for other purposes, for example UPS as a reserve and peak load looping. Virtual power plants and new big data centers are further driving the demand for UPS. UPS contributes to zero emission targets through longer bridging times, grid stabilization (instead of building additional power plants) and in combination with renewable energy sources.

The U.S power system is undergoing major transformations requiring more flexibility and interconnectivity to optimize energy resources. Applications are at different levels of maturity, ranking from early demonstration to very mature deployment Battery Energy Storage, which has the potential to make an effective contribution to decarbonization targets, energy security and independence. Batteries have the advantage of being tailored to specific functions and can be quickly installed on location. Innovations will focus on long service life, total cost of ownership, reliability, safety and conversion efficiency.

Because of this diversity, all battery technologies – lead, lithium, nickel and sodium – have an important role to play at each level of the grid: from generation and transmission to distribution and households, batteries will deliver important services, such as integration of renewables and grid stabilization. Batteries can deliver flexibility for a climate-friendly, safe and reliable energy supply system, enabling the decentralization of the system and integration of high proportions of renewable energies, as well as to support the charging infrastructure for high volumes of EVs. Energy storage systems are also central elements of sector coupling paths and provide the necessary flexibility to support key functions such as:

- Voltage stabilization in the medium and low voltage grid
- Ensuring energy balance and frequency
- Preventing the grid from overload
- Balancing electric generation and demand from renewable energy sources
- Surplus energy management

UPS is an established market in which lead-based batteries have been the dominant technology for decades and is expected to remain so by 2030. The global market capacity was 16.6 GWh in 2022 and will grow to 25.9 GWh by 2030². This growth is due to mobile society, increased use of big data and the associated need for new data storage centers, as well as the implementation of distributed energy resources (DER). Another driver will be the growth of emerging economies, requiring significant UPS capacity.

The dominant technologies used today are valve regulated lead batteries (VRLA) with absorbent glass mat technology (AGM) and li-ion batteries, while nickel-cadmium (NiCd) has a minor share. The expected annual growth rate for lead and lithium is 1.6% and 12.8% (in value), respectively. It is forecasted that Lithium penetration will increase from 16% in 2023 to 30% in 2030² globally (20% penetration in U.S.), depending on further lithium cost reduction, safety issues and regulatory implications.

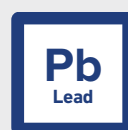
Increasing the power density is particularly necessary because of the further electrification of critical loads. As new UPS batteries should provide additional value, there is a need to work on the charge acceptance and energy throughput of the batteries. In parallel to the demand for increased power density, there is the need to reduce the operational expenditures (OPEX) of these applications by reduced climatization as one of the main cost drivers and, therefore, the heat exposure to the battery will rise and the batteries must be able to cope with it. As the typical back-up time is between 5 and 15 minutes, KPIs for the application are energy and power densities, system cost, operating temperature range and reduced cooling, as well as safety.

Other developments are the connection of UPS batteries in a single network to form a larger UPS system or virtual power plant (VPP). This will become possible thanks to 5G and artificial intelligence to allow distributed energy production, storage and consumption.

Due to its maturity, lead battery recycling processes have developed and improved over a long time and are already highly efficient and economically valuable, while recycling of lithium batteries is more complex due to thermodynamics.

Uninterruptible Power Supply (UPS) Battery Technology by 2030 (MWh):

- Lead is dominant battery technology
- Lithium increasing market share
- NiCd serves Niche applications



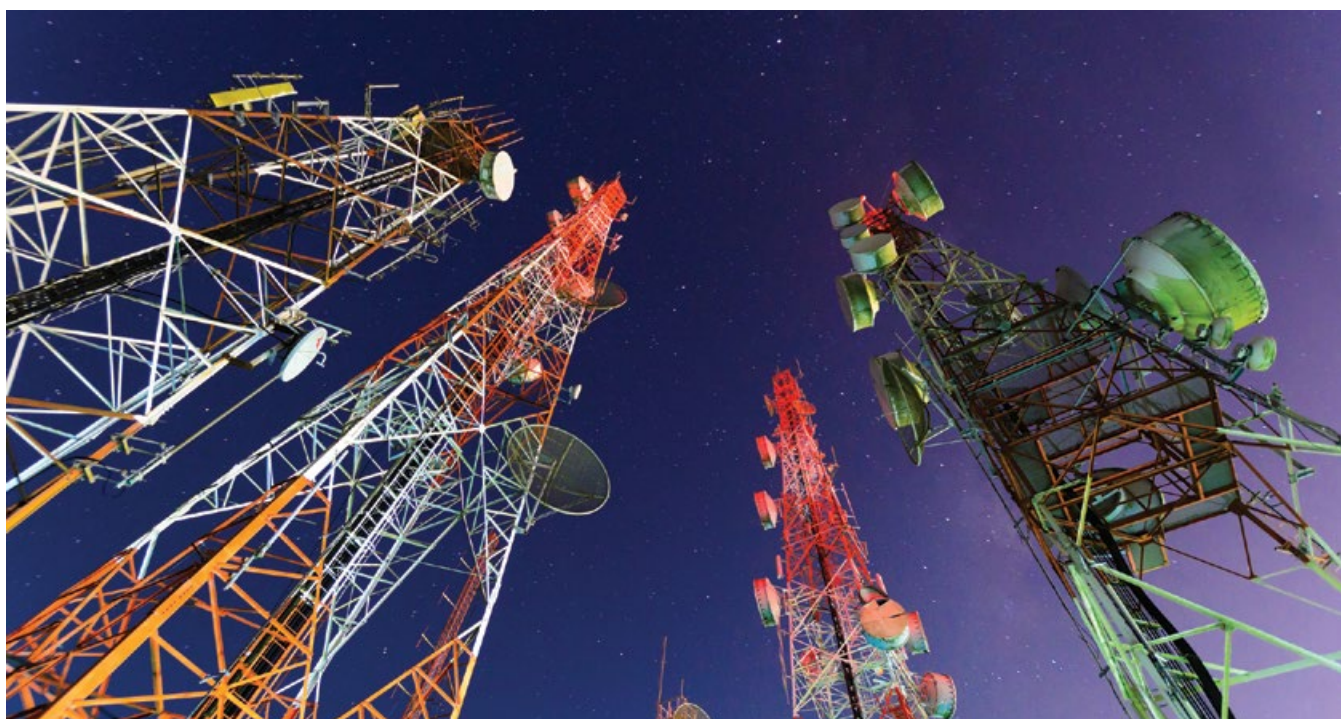
70%



30%



(niche)



Batteries for Telecommunication (TLC Batteries)

A telecom unit is an information and communication technology or telecom site with critical loads. In case of unavailability or insufficiency of the main power source, telecom batteries provide instant and continued power to all redundant equipment to ensure that the telecom application continues to function until a diesel generator or, in future, a fuel cell can take over or power is restored. In contrast to UPS batteries, telecom batteries serve only telecom applications, connected to the 48V DC electricity supply net.

There are also off-grid telecom towers combined with renewable energy sources or other hybrid systems, such as in emerging countries with a lack of power grids or in remote areas. In these cases, the batteries provide electricity when the energy from renewable sources is insufficient or unavailable. The transfer to virtual power plants (VPP) also demands a higher energy throughput from the batteries involved and the profile is changing from floating to a cycling application, very often at partial state of charge (PSOC).

The global market demand in 2022 was 21 GWh, which is expected to grow to 32 GWh in 2030 (7% annual growth in volume). The annual growth rate for lead batteries is expected to be 2.7% and for Li-ion batteries it is expected to be 10.6%. In this scenario, lead will remain the dominant technology but the lithium market share will grow to 27% by 2030². This is because lithium is often more expensive than lead, but with a lower total cost of ownership (TCO) than lead in hot climates because of a higher expected lifetime, especially in high temperatures. The main drivers for this application are the extension of Wi-Fi, strong network growth in China, India, Eastern Europe and South America, as well as the transition from 4G to 5G. Other drivers are the further actions to reduce diesel consumption and emissions, especially in countries and areas with unstable grids, which will necessitate higher energy throughputs for the battery.

Key features of batteries for telecom applications are energy and power density, energy throughput, and hot temperature robustness. These criteria are prioritized based on end use type, namely, whether the battery is used for standby or heavily cycled applications. In addition, safety, cost and end-of-life management are key aspects. For the end-of-life management, product collection, recycling and circularity are key. With respect to recycling, lead-based batteries are

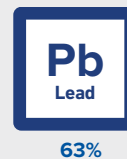
among the products with the highest recycling efficiency worldwide. Recycling processes are established and recycling plants well distributed. Recycling of lithium batteries is not yet established at commercial-scale and the recycling efficiency and economy needs to be further developed.

The main targets for lead-based batteries are an increase in the gravimetric energy density at system level while increasing the cycle life performance at different Depth of Discharge (DoD) and extending the battery lifetime to 10 years at higher temperatures to improve the TCO. The calendar life in off-grid and VPP applications might be significantly shorter and would require further improvements in endurance. These new features are expected to be reached working on increased mass utilization, the use of corrosion resistant alloys, improved cycle life, more maintenance free or reduced maintenance solutions and further cost reduction initiatives, like increased content from secondary raw materials and a higher level of production automation.

For Li-ion battery technologies, an increase in the gravimetric energy density at system level, together with an increase in cycle life at different DoD, will be needed to improve the TCO significantly. The main area of action for Li-ion technologies will involve the development of new anode and cathode materials, cost reduction actions and an improvement in the safety of products.

Telecommunications (TCL) Battery Technology by 2030 (MWh):

- Lead is dominant battery technology
- Lithium increasing market share
- NiCd serves Niche applications





Batteries for Residential and Commercial Storage Behind the Meter

As of 2022, the residential and commercial sectors were responsible for 13% of the U.S. total CO₂ emissions¹. Additional capacity is predicted from an increased number of units sold and the rising demand for larger storage systems, which will enhance self-consumption. The use of different electro-chemistries provides an overall benefit to the decarbonization of the residential sector, and batteries are key enablers for making this happen.

Stationary batteries for storing energy from renewable sources behind the meter are used both in residential and commercial buildings (offices, SMEs, etc.), where they can also fulfill additional roles such as peak-shaving or uninterruptible power supply (UPS). Their primary task is to supply the load when electricity costs are high or renewable power output is low, offering consumers a level of independence from grid-supplied energy. For example, residential solar power presents an opportunity for stationary battery storage when there is energy demand after the sun sets. In addition to cost benefits, other drivers for residential and commercial storage include increased self-consumption, reduced reliance on grid-based power, and reserve capacity to ensure power continuity. Residential storage batteries should be designed and sized according to the location and local power needs.

The forecast for this market is strong, with 33% total growth predicted by 2030. Both lead and lithium-ion technologies compete in this space, each offering distinct advantages. Lithium currently dominates the commercial (grid-scale) market, driven by its compact form factor and scalability. Although lead batteries represent only 3–4% of the grid market today, they still accounted for over 7 GWh in 2023, with expectations to exceed 12 GWh by 2030. This translates to a market value of US\$1 billion in 2023, projected to grow to US\$1.7 billion by 2030².

In the residential sector, lead technology leads with 89% market share, largely due to its strong safety profile and recyclability. While growth is more modest at 3%, lead is expected to see 8% overall market growth by 2030², supported by innovations such as bipolar technology, which aim to improve energy density and charge efficiency.

Lead is already fully recyclable and benefits from established economies of scale that operate without subsidies. In contrast, lithium-ion still requires further improvements to become economically viable at scale. Lifecycle advancements for both technologies will be essential to reduce total cost of ownership (TCO). Enhancements in partial state-of-charge (PSOC) cycling and energy throughput will also be critical. With continued progress in energy density and cycle performance, lead-based solutions could become increasingly attractive, especially in applications where safety, cost, and recyclability are key considerations.

Residential & Commercial Storage Behind the Meter (BTM) Battery Technology by 2030 (MWh):

- Lithium dominant technology for combined residential and commercial sector (97%)
- Lead dominant technology in residential market (89%)



Batteries for Utility Grid-scale Energy Storage

Utility grid-scale energy storage systems are large storage facilities that can provide grid stability in multiple ways. Depending on the grid function, a large variety of operating profiles are considered, in which, depending on the requirements, all mainstream battery technologies can have a role to play.

Grid functions, such as voltage/frequency regulation, arbitrage, black-start, back-up, investment deferral and grid independent power supply (GIPS) are typically suitable for batteries. Below is a table of application profiles per grid function.

Battery Profiles Per Grid Function

Application	Description	Duration of Service	Typically Valued in U.S. Electricity Markets?
Arbitrage	Purchasing low-cost off-peak energy and selling it during periods of high prices.	Hours	Yes
Firm Capacity	Provide reliable capacity to meet peak system demand.	4+ hours	Yes, via scarcity pricing and capacity markets, or through resource adequacy payments.
Operating Reserves			
• Primary Frequency Response	Very fast response to unpredictable variations in demand and generation.	Seconds	Yes, but only in a limited number of markets.
• Regulation	Fast response to random, unpredictable variations in demand and generation.	15 minutes to 1 hour	Yes
• Contingency Spinning	Fast response to a contingency such as a generator failure.	30 minutes to 2 hours	Yes
• Replacement/ Supplemental	Units brought online to replace spinning units.	Hours	Yes, but only values are very low.
• Ramping/Load Following	Follow longer-term (hourly) changes in electricity demand.	30 minutes to hours	Yes, but only in a limited number of markets.
Transmission and Distribution Replacement and Deferral	Reduce loading on T&D system during peak times.	Hours	Only partially, via congestion prices.
Black-Start	Units brought online to start system after a system-wide failure (blackout).	Hours	No, typically compensated through cost-of-service mechanisms.

Source: [NREL Grid-Scale Energy Storage Grid Integration Toolkit](#)

Utility grid-scale energy storage for grid-functionalities is a market where batteries compete with other storage technologies, such as hydro-power and fuel cells. However, batteries have considerable advantages as they are easy to install at location and scalable to the power and capacity needs of the application.

For large storage systems, lithium and lead technologies are considered the reference technologies. Nickel-based batteries were previously preferred for large system storage in low temperature applications. Lithium is relevant for high-current applications, such as optimizing self-consumption through the integration of renewables, and for peak-shaving.

Drivers and trends for grid support applications are the major infrastructure changes in the power supply industry, the integration of renewables, emerging electro-mobility and demand for higher power quality.

A distinction must be made between energy and power applications. General technical requirements are PSOC cyclability, high power density and wide operating temperature ranges. General technical requirements are high reliability, scalable power supply and low maintenance/service cost. A particular feature for this market is also the projected service life of 20 years, which can be met both with lithium and lead. A potential way of reducing costs for Li-ion systems is the deployment of second-life EV batteries.

The development of the multi-use aspect of ESS will also increase the profitability. Due to their multifunctional capabilities, storage systems are often efficiently used in the form of mixed operating models in which several areas of application are combined ("multi-use storage systems").

Research priorities for lead are, in particular, the cycle life, PSOC cycles and the charge efficiency. Lead carbon batteries can match the PSOC cycle life of lithium batteries for voltage stabilization in solar power plants.

Research priorities for lithium are safety, capacity, retention of the negative graphite electrodes and material cost reduction of the positive electrode, e.g. through reduced cobalt and higher nickel content.

Intelligently combining lead- and lithium-based batteries could also increase the market significantly for lead as it would offer considerable benefits in terms of lower energy reserve costs.

Utility Grid-scale Energy Storage (ESS) Battery Technology by 2030 (MWh):

- Mainly grid functions suitable for batteries
- Mainly li-ion but also niches for lead and sodium HT based technologies
- Nickel-based as niche for harsh environments





Batteries in Off-grid Configuration

This application segment covers batteries for stand-alone use or in 'hybrid' (combined with diesel generators or renewable energy production), off-grid or remote mini-grid systems to provide rural electrification at locations where electrical power can be provided most cost-effectively and sustainably with batteries rather than through grid extension. This can include:

- Isolated rural areas in developing countries
- Peri-urban areas with weak grids in developing or emerging countries
- Small islands separated from the national grid (e.g. mini-grids)

Utility Grid-scale Energy Storage (ESS) Battery Technology by 2030 (MWh):

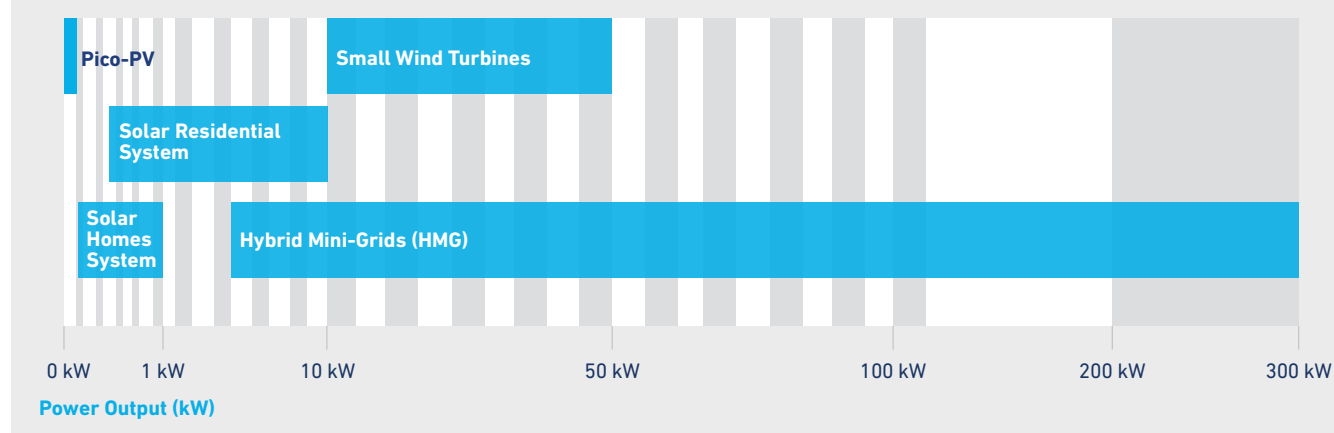


Figure: Power ranges for different off-grid Rural Electrification segments⁸

The main applications are battery energy storage systems (BESS) in a range from pico-PV and domestic solar homes systems over small wind turbines, industrial/commercial hybrid mini-grids, up to community scale usages and back-up power for telecom towers.

Lead, lithium, nickel and sodium-based batteries are complementary technologies to serve the combination of functions in this off-grid segment as depending on the system's technical, environmental and situational requirements.

Recent studies from the International Energy Agency (IEA) have quantified that off-grid and mini-grid configurations using Battery Energy Storage (BES) are often the most efficient and sustainable way to electrify isolated rural areas or remote commercial and industrial sites (C&I sites). In order to achieve universal energy access by 2030, the IEA estimates that a further 379 TWh of on-grid electricity generation will be needed, along with 399 TWh from mini-grid systems and 171 TWh from off-grid systems.

Another market is on small islands without mainland interconnections where peak production relies on fossil fuel. Nowadays, there is a clear tendency towards the installation of off-grid and mini-grid renewable energy sources instead. Market drivers are the worldwide expansion of fluctuating renewable energy sources like PV and wind. National and multinational funding programs support these developments. With an increasing global population and despite the growing electrification worldwide, in 2023 there were still 750 million people worldwide without direct access to electricity⁹.

The main KPIs for the majority of off-grid applications are high performance in rugged atmospheric conditions, low maintenance and affordability.

For lead-based batteries, increased energy throughput and the development of operation strategies by integration of BMS (battery management system) are important. For lithium-based batteries, improving the design life, safety aspects like high temperature operation, cost and recyclability are paramount.

Circularity and recycling are key parameters for further development. Cycle or lifetime performances are measured differently depending on the battery chemistry and the depth and rate of discharge. Cycling profiles are different in each IEC cell chemistry-specific standard, so it is not meaningful to compare results across technologies. Instead, the application-specific standard IEC 61 427-1 is the reference to benchmark.

Off-grid- Configuration (ESS) Battery Technology by 2030 (MWh):

- Lead and Lithium are the dominant battery technologies
- Nickel services niche applications



About Us

Battery Council International (BCI) is the leading trade association representing the global battery industry and is the premier authority on energy storage solutions. Founded in 1924, BCI advocates and educates on behalf of battery manufacturers and recyclers, marketers and retailers, suppliers of raw materials and equipment, and battery distributors. With a unified voice, BCI conveys an industry-wide commitment to sustainability, safety and science. The organization unites its 140+ members to successfully communicate and protect through education, science and advocacy efforts the most successful circular economy on the planet. For more information, visit www.batterycouncil.org.

Sources:

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² Lead Acid & Global Battery Market Report, Avicenne Energy, May 15, 2025

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⁷ [IEA Aviation Tracking](#)

⁸ BEPA Strategic Research Agenda (BEPA SRIA)

⁹ [IEA \(2024\), SDG7: Data and Projections, IEA, Paris](#)

Note:

Some content in this document is adapted from the EUROBAT Innovation Roadmap, Version V2.0, published June 2022. EUROBAT. (2022). <https://www.eurobat.org/campaigns-and-initiatives/battery-innovation-roadmap-2035/>

Contact Us

info@battery council.org
277 S Washington St
Suite 210 #1018
Alexandria, VA 22314

Learn more at BatteryCouncil.org

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