



ASSOCIATION OF EUROPEAN AUTOMOTIVE
AND INDUSTRIAL BATTERY MANUFACTURERS



2035

Battery Innovation Roadmap

TECHNICAL ANNEX

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→ REPRESENTS ALL BATTERY TECHNOLOGIES

EUROBAT covers the main battery technologies used across automotive, industrial, and energy storage applications. These include:



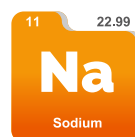
LITHIUM BASED BATTERIES

Used widely in electric vehicles, consumer electronics, industrial equipment, and stationary energy storage.



LEAD BASED BATTERIES

A mature and highly recyclable technology used in automotive starter batteries (12V SLI), backup power, industrial traction, and stationary applications.



SODIUM BASED BATTERIES

Including emerging **sodium-ion Room Temperature** and established high-temperature sodium systems, increasingly considered for stationary storage and selected mobility applications.



NICKEL BASED BATTERIES

Primarily **Nickel-Metal Hydride (NiMH)** and **Nickel-Cadmium (NiCd)** in particular, used in industrial, rail, aviation, backup, and specialised applications requiring robustness and long service life.

Beyond these mainstream chemistries, EUROBAT also monitors and supports discussion around **emerging and next-generation battery technologies**, particularly those approaching higher technology readiness levels (high-TRL), where they may contribute to Europe's future energy storage and electrification needs.

APPLICATION COVERED



AUTOMOTIVE MOBILITY

Batteries contribute to the decarbonisation of the European transport sector - reducing CO2 emissions via start/stop batteries and innovative solutions in xEVs.



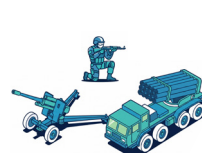
STATIONARY ENERGY

Batteries are indispensable for storing renewable stationary energy coming from solar and wind farms in on grid and off grid solutions. They also contribute to a more stable and reliable grid.



MOTIVE POWER APPLICATIONS Material handling & off-road vehicles

Batteries are a perfect fit for powering industrial vehicles, while also reducing noise and emissions. The concepts of smart charging of road vehicles to support the energy system is also relevant for off-road (rail, marine and air transportation) because their wide deployment and large energy capacities.



DEFENCE

Batteries are crucial for the defence industry because they provide reliable, mobile, and resilient energy essential for powering mission-critical systems, communications, mobility, and autonomous operations in demanding and often infrastructure-limited environments.



ROBOTICS & IOT

Batteries are crucial for robotics and IoT applications because they enable autonomous, portable, and reliable operation of connected and intelligent devices, ensuring flexibility, mobility, and continuous functionality across diverse environments.



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SCOPE & PURPOSE OF THE TECHNICAL ANNEX

This document provides an overview of the technological maturity and future development of electrochemical energy storage technologies, with a particular focus on their key application areas, sustainability and contribution to the circular economy. It examines the main drivers for battery innovation, the technological developments expected towards 2030 and 2035, and the pathways required to support Europe's transition towards climate neutrality by 2050.

The sustainability of batteries must be addressed throughout their entire life cycle, from the sourcing of raw materials and manufacturing to their use, second life, recycling and end-of-life management. Sustainable and innovative battery technologies are essential to achieving the objectives of the European Green Deal, including climate neutrality, sustainable industrial competitiveness, clean mobility, renewable energy integration and a resilient European energy system.

The Technical Annex to the EUROBAT Batteries Innovation Roadmap 2035 provides a more detailed technical assessment of mainstream and emerging battery technologies and their evolution towards 2035. It complements the cross-technology strategic roadmap by providing in-depth technical insights into:

→ Battery technologies

An assessment of the main electrochemical technologies, including lithium-, lead-, sodium- and nickel-based batteries, as well as promising high-TRL and emerging technologies such as flow batteries. The analysis considers their intrinsic performance, safety, sustainability and environmental characteristics, as well as the key areas requiring further innovation and development.

→ Applications and performance requirements

An examination of the role of battery technologies across key applications, including automotive, 12V SLI/AUX, UPS and telecommunications, railway, motive power, marine, robotics and IoT, and defence. The analysis considers the specific requirements and key performance indicators (KPIs) of each application and identifies the technology developments and innovation priorities needed to address future market and societal needs.

→ Innovation pathways towards 2035

Identification of the principal research and development priorities across battery technologies and applications, highlighting opportunities to improve performance, safety, sustainability, resource efficiency, cost competitiveness, lifetime and circularity.

Together, the Roadmap and its Technical Annex provide a forward-looking view of battery innovation towards 2035, highlighting the technological pathways and research priorities needed to strengthen Europe's battery ecosystem and support the transition to a climate-neutral, competitive and circular economy.

PART 1

Battery Technologies and their potentials

The battery technologies considered in this White Paper have been selected based on their potential for further technological development and their significant contribution to achieving the objectives of the European Green Deal and the Batteries Regulation.

The first chapter of part 1 focuses on the mainstream battery technologies currently deployed across a wide range of applications, namely lead-, lithium-, nickel-, and sodium-based batteries. These established technologies continue to offer substantial potential for further innovation, improved performance, and enhanced sustainability.

The second chapter explores the most promising emerging battery technologies that could complement and build upon the progress achieved with existing technologies. These technologies have been identified based on their potential to address future application needs and contribute to the continued development of a competitive, sustainable, and resilient European battery ecosystem.

CHAPTER A:

Mainstream Battery Technologies



A.1. Lithium-based batteries – Established, Versatile and High Energy

State-of-the-art

Lithium-ion (Li-ion) is considered the leading lithium technology for automotive and energy storage applications where there is a cyclic demand and will remain so in 2035. For industrial applications, the Lithium-ion market progression is slower as lead acid batteries are predominant and proven for these applications. Lithium is currently deployed in mass-produced standard cell types in different applications – a strategy driven by cost and safety reasons.

The major requirement for higher energy densities to achieve increased driving range is directly linked to e-mobility. This results in a development roadmap for 2035 that mainly considers the lithium-based technologies based on modified nickel cobalt manganese oxide (NMC) materials, from NMC 111 to NMC 811, with increased nickel and reduced cobalt content in combination with high capacitive anode materials with carbon/silicon composites.

Lithium Iron Phosphate (LFP) and Sodium-ion will also be part of the market share for entry-level electric vehicles. Development of Solid-state technology is being targeted to increase the energy density and improve the safety aspect. As a first step towards this and since there are strong difficulties to overcome for an all-solid-state battery, initial approaches contain a small amount of liquid electrolyte (ex 10%) commercially presented as semi-solid-state batteries. The Li-ion technologies considered in this Roadmap consist of

Table 1: Specific capacities of anode and cathode materials of Li-ion batteries covered in the roadmap

Anode	C	350 – 360 mAh/g
	Si(SiOX)/C	400 – 900 mAh/g
	LTO	150 mAh/g
Cathode	NMC 111	160 mAh/g
	NMC 532	175 mAh/g
	NMC 622	180 mAh/g
	NMC811	200 mAh/g
	NCA	200-220 mAh/g
	LFP	150-170 mAh/g
	LMO	105 – 120 mAh/g
	NA+	135 mAh/g

a combination of the following available anode and cathode materials.

Improvement potential

The development roadmap for Li-ion, Ni-rich NMC positive electrode materials and new materials for the negative electrode (e.g. Si/C composite) considered for future development are:

- Generation 2a: NMC 111 / 100% C
- Generation 2b: NMC 523 - 622 / 100% C
- Generation 3a: NMC 622 / C + Si (5-10%)
- Generation 3b: NMC 811 / Si/C composite

Due to the variety of possible combinations of cathode and anode materials, the resulting Li-ion batteries show specific and individual performance characteristics suitable for different kinds of applications. The development of Li-ion technologies suitable for industrial and automotive applications is still a challenge in terms of material research process, production, development, recycling, safety and transportation.

By 2035, with the exponential demand of Electric Vehicles (EV), the need of Lithium batteries may increase by a factor of eight times versus 2023. With the new European battery directive for the recycling of the Lithium, battery packs for EV will be built in prevision to be re-used or re-purposed in 2nd life applications like for commercial and I ESS. These packs will have to comply with the Safety level requested for these 2nd life applications. NMC with a high nickel content is more reactive in the fire

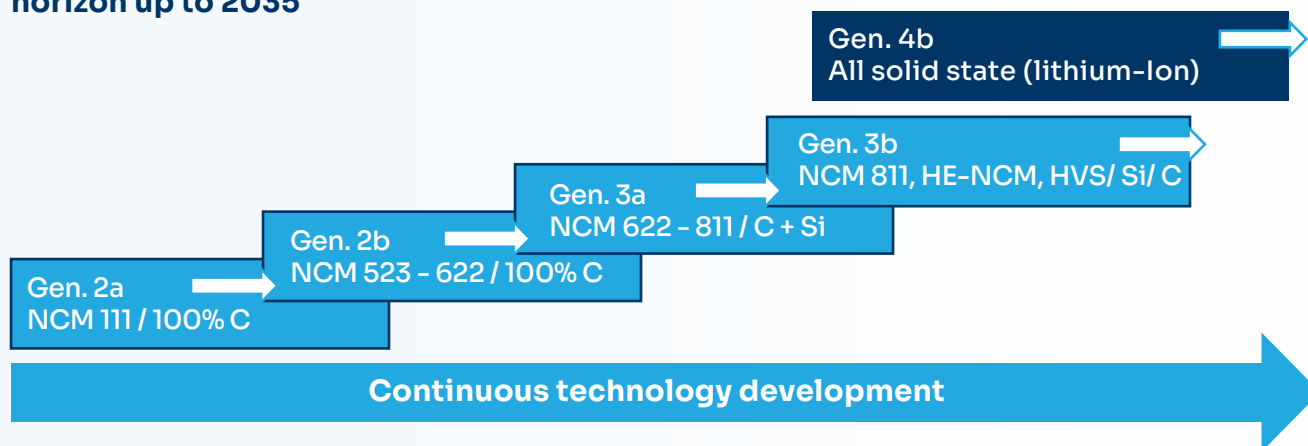
propagation tests, the cells and battery pack safety will need to be improved. For this reason, Silicone/ carbon Anode and Solid State will be significant drivers for NMC development.

As the demand for Lithium batteries will be increasing, LFP and Sodium-Ion battery will have a growing part of the market share for applications like entry level (LFP, Sodium), mid-level (LFP) and lower upper-class (LFP) EVs, delivery trucks, construction machineries, stationary storages, where weight, dimension and autonomy are not an issue but cycle life, deep temperature ability, low current charge and discharge are the advantage against NMC. Sodium-ion could become more prevalent than LFP, as the energy density improves, and the cost of material becomes lower. Also is the cycle life of LFP around factor 3 and Sodium about factor 6 better than NMC. As Sodium salts are 40 times more abundant than Lithium salt, if the lithium carbonate price increases with the demands for EVs, Sodium-Ion could be in the stationary sector very competitive alternative, it is functional to -40 degree Celsius and can be discharged to zero Volts, which is for transportation a game changer.

Requirements for safety and for the cathode materials

- High specific energy (mAh/g)
- High stability (cycle and calendric)
- High voltage, high power capabilities
 - Low polarization

Figure 1: Generation of lithium materials considered for further development with horizon up to 2035



- Low content of rare earth materials (e.g. cobalt)
- Low CO2 footprint at production, high recycling capability
- Environmental and ethically harmless
- Cost reduction

Environmental aspects

To reduce the environmental impact and improving the availability of lithium battery components, a strong push is expected in research aimed at reducing the content of rare materials (Cobalt), at researching alternative materials, activating extraction processes environmentally safe and ethically sound mining and manufacturing, and also a development of low-carbon manufacturing processes.

Lithium based battery circular economy targets

The sustainability and the circular economy targets will have a strong influence on the development of the cells and battery packs with Lithium-ion. There will be a balance between energy density improvements, safety, recyclability, neutral carbon footprint, and cost. The availability of raw materials will be key by 2035 to respond to the increased demand for Li-ion batteries, meaning security of raw material supply, sourcing more locally for minimized carbon footprint and developing recycle waste streams.

Global recycling efficiency targets for lithium-based batteries increased from 50% in the previous Battery Directive **to 65% in 2025 and then 85% by 2035**. In addition, there is an additional mandatory 'Material Recovering Target' for nickel, cobalt and lithium with specific targets by end 2027 and end 2031.

Battery second life is another important process that will contribute to the circular economy targets. After Lithium batteries end their first life in an electric vehicle, they can be subjected either to repurposing or refurbishment to create new Stationary Energy Storage applications. In this scope, new standards have emerged to reduce uncertainty across technical, safety, regulatory,

and commercial domains. With the new European battery directive for the recycling of the Lithium, battery packs for EV will be built in prevision to be recycled easily or re-used in 2nd life applications.

Due the lack of precious metals in LFP and Sodium cells it is foreseeable, that the interest of recyclers is lower than for NMC materials. For the NMC materials recycling is as long attractive, unless the costs for recycling per ton are below the material price per ton on the market.

Concluding remarks

Driven by the adoption of electric vehicles, the Lithium-ion technology will be challenged, the cost competition will be important on automotive market, with constraint on autonomy, performances, safety, recycling, low carbon footprint, etc... The supply chain of materials for Nickel, Copper, lithium carbonate, Cobalt, will have to improve to follow the demands, supported with recycle process more and more efficient, but also by using li-ion technologies using more common materials. Sodium-Ion will also have a market share in future due to their lower cost, cheap and available base materials and having a better expected carbon footprint.

By 2035, we can expect to have electric vehicles with ranges around >500 km on highways and that can recharge in about 5 minutes with high-voltage battery architecture. However, this is not necessary for all vehicle applications in Europe. In this regard, we expect battery packs with different chemistries and designs to satisfy the needs of different users. The Lithium battery technology landscape will be very diverse, with different chemistries and technologies to fit the multitude of applications to target costs and positive carbon footprint results. This is based on different architectures of the specific cell use case, which defines at least the cell design.



A.2. Lead-based batteries – Proven, Innovative, and Evolving

State-of-the-art

Lead batteries have been the dominant energy storage solution for industrial and automotive applications for over a century. Various designs exist, including flooded (“vented”) and valve-regulated (VRLA) batteries, which can be connected in large arrangements without complex management systems. Lead batteries stand out for their low cost per kWh installed and low cost per kWh electricity throughput.

Continuous innovation has enhanced functionality, durability, robustness, and cost efficiency. Recent advancements include tubular and Gel batteries, Absorptive Glass Mat (AGM) batteries, Enhanced Flooded Batteries (EFBs), battery monitoring sensors, and Battery Management Systems (BMS) – all demonstrating incremental improvements tailored to market needs.

Innovation Potential

To remain competitive with emerging electrochemical storage technologies, further innovation is needed.

Opportunities include:

- Higher charge acceptance and energy efficiency,
- Enhanced high-temperature durability
- Optimized system level approach with BMS embedded systems
- Improved energy and power density with extended cycle life
- Advanced materials, such as corrosion-resistant lead alloys, expanders, advanced carbon additives, and improved Thin Plate Pure Lead (TPPL)

- Bipolar and carbon-enhanced cell designs to support longer service life, Partial State of Charge (PSOC) operation, and higher power density
- Intelligent battery operation modes for optimized performance in diverse applications

These improvements are being developed with application-specific tailoring, ensuring lead-based batteries remain a cost-effective, reliable, and sustainable choice across multiple sectors.

Environmental Aspects of Lead-Based Batteries

→ Occupational Safety

Occupational exposure to lead is effectively managed, as the battery industry has proactively implemented measures to protect employees from blood lead contamination during manufacturing. Europe should continue to allow market-driven innovation, recognizing that recent advances in lead battery research contribute to safer, more efficient, and sustainable technologies.

→ Circular Economy and Resource Efficiency

Lead batteries are central to a circular economy, with recycling targets maintained at over 90% efficiency and 99% recovery of active materials. This closed-loop system reduces reliance on primary materials, strengthens Europe’s raw material independence, and benefits the entire battery value chain.

→ Future Opportunities

To meet or exceed secondary lead targets, the use of recycled lead must further expand. Continued R&D will enhance refining processes, enabling the removal of additional impurities more economically and increasing the quality and recycling efficiency of secondary lead. These efforts ensure that lead-based batteries remain a sustainable, cost-effective, and strategically important energy storage solution for Europe.



A.3. Sodium-based batteries

State-of-the-art

High-temperature sodium-based batteries use liquid electrodes and a solid ion-conducting ceramic electrolyte, typically β -alumina. They operate above $\sim 300^\circ\text{C}$, keeping the electrodes molten and the electrolyte highly conductive. Commercial types include sodium-nickel chloride (NaNiCl, ZEBRA) and sodium-sulfur (NaS) batteries.

Sodium-Nickel Chloride (NaNiCl) Batteries:

- *Positive electrode*: porous nickel with NiCl_2 impregnated in NaAlCl_4 .
- *Negative electrode*: molten sodium.
- Solid β -alumina ceramic separates electrodes and conducts Na^+ ions.
- *Operating temperature*: $270\text{--}350^\circ\text{C}$; cell voltage: $2.3\text{--}2.6\text{ V}$; specific energy: $\sim 120\text{ Wh/kg}$.
- *Advantages*: Inverse structure with sodium outside allows inexpensive steel housings; easy assembly using uncharged materials.
- *Applications*: small-series electric vehicles and stationary storage.

Sodium-Sulfur (NaS) Batteries:

- *Positive electrode*: graphite fabric soaked with molten sulfur.
- *Negative electrode*: molten sodium; β -alumina electrolyte conducts Na^+ ions above $\sim 300^\circ\text{C}$.
- *Operating temperature*: $300\text{--}340^\circ\text{C}$; cell voltage: 2 V .
- *Advantages*: high cycle stability ($>4,500$ cycles), long calendar life (>15 years), internal resistance nearly independent of state of charge.
- *Applications*: grid storage ($>1\text{ MWh}$) and niche markets.

- *Performance*: Both NaNiCl and NaS offer long service life ($>4,500$ cycles) and efficiencies of $75\text{--}86\%$, limited by thermal losses. Improved insulation can reduce energy losses during idle periods.

Key Features of High-Temperature Sodium Batteries

Feature	NaS	NaNiCl
Operating Temperature	$300\text{--}350^\circ\text{C}$	$270\text{--}300^\circ\text{C}$
Typical Applications	Grid storage, load shifting, frequency regulation	Industrial, grid support, niche high-temp storage
Energy Density	$\sim 150\text{--}240\text{ Wh/kg}$	$\sim 120\text{--}140\text{ Wh/kg}$
Cycle Life	$2,500\text{--}4,500$ cycles	$2,000\text{--}4,000$ cycles
Global Deployment	$\sim 4.9\text{ GWh}$	$\sim 130\text{ MWh}$

Room-temperature Sodium-Ion Batteries (SIBs)

operate on the "rocking-chair" principle, shuttling sodium ions (Na^+) between the positive and negative electrodes, similar to lithium-ion batteries. Research on sodium-based active materials dates back to the late 1960s, but commercialization interest only began around 2010 and accelerated in the early 2020s.

SIB development is often categorized into three generations:

- *Gen I*: Prussian Blue analogues (PBA) as cathodes and simple carbon-based anodes, early prototypes.
- *Gen II*: Layered oxide cathodes and hard carbon anodes, offering improved capacity and stability.
- *Gen III*: Polyanion cathodes with optimized electrolytes and advanced anodes, targeting high-performance commercial applications.

Compared to the state-of-the-art high temperature sodium batteries, the new sodium-ion battery technology is operating at room temperature.

The sodium-ion battery has a similar working principle to the Li-ion battery. Sodium ions also shuttle between the cathode and the anode to store and release energy. As sodium resources are cheap and widely distributed and considering the technological similarities with existing Li-ion batteries, the industrialisation process of sodium-ion batteries will be accelerated.

Based on potential application scenarios, higher energy density, longer cycle life and better low temperature performance are the most critical indicators. In total, the cost and safety advantages of sodium batteries will gradually gain in prominence. Therefore, it is likely that sodium-ion batteries will be used as traction batteries in two-wheeled vehicles, such as e-scooters, 12V starter applications, A0 and A00 passenger vehicles for A-level EV charging, and electrical energy storage (EES), as an effective supplement to Li-ion batteries.

Environmental and circular economy target

NaNiCl battery production is relatively energy-intensive and therefore has the highest share of environmental impact (depending on the heat supply source). Other factors are the high demand for nickel and the complex modular construction (insulation). The nickel content in the battery can be recovered, which can be used in the steel industry. The ceramic content in the cells, as well as the salt collected in the resulting slag, can be used in road construction.

Regarding the manufacturing process, the production of the β -aluminum oxide solid electrolyte is also energy-intensive. NaS batteries contain large proportions of steel and aluminum, which can be recycled accordingly, leading to a reduction in the environmental impact.

Room temperature SIB are touted as a sustainable technology. R&D should be carried out to prove evidence and the actual carbon footprint and other sustainability indicators. While in principle bio-derived materials have potential to be more sustainable, their scalability, as well as carbon footprint, need to be correctly assessed. For example, it is important for bio-derived materials

feedstocks for the production of hard carbons to be an easily scalable waste material. Evidence should be further collected on the recycling potential of SIB.



A.4. Nickel-based batteries

Overview

Nickel-based batteries are available using several mechanical architectures for the positive, Ni-rich, electrode (pocket, sintered, plastic-bonded, nickel foam and fiber). These may be arranged in prismatic grids or as a wound spiral, and the cells can be designed as flooded (or 'vented') or valve regulated. The latter arrangement is practically maintenance free, and all Nickel-based batteries offer a long lifespan thanks to their ability to operate in a wide range of temperatures. There are two major types:

→ Nickel-Cadmium batteries (Ni-Cd):

are renowned for their very long life (typically in excess of 17 years) and unmatched sturdiness, as well as their progressive aging which can be monitored, hence allowing preventive maintenance (They do not suffer from a "sudden death syndrome").

→ Nickel-metal hydride batteries (Ni-MH):

offer a higher energy density and are generally well suited for high-current-drain applications, thus being found in some consumer devices as well. The Ni-MH technology however requires a BMS for its proper operation, hence introducing an element of vulnerability.

The market for Ni-Cd batteries

The industrial Ni-Cd technology is today the technology of choice for several highly demanding industrial applications. Due to their superior resistance to mechanical and electrical stress as well as to extreme temperatures and frequent temperature changes, Ni-Cd batteries are the best solution in challenging conditions for mission critical applications such as off-shore oil and gas production, the supply of back-up power in nuclear

power plants, as well as for telecommunication base stations and transportation infrastructure when located in harsh climate conditions.

Ni-Cd batteries are widely used as back-up power where human life is at stake and unflinching reliability must be ensured. This is the case in the railway rolling stock (with over 50% market share) as well as in civilian and military aircraft (with over 70% market share) in which they supply emergency power in case of failure of the main energy supply. Other critical applications include backup power systems in energy generation and distribution facilities, large data centres, hospitals, lighting and ventilation in road tunnels, coastal lighthouse systems, as well as many installations in harsh climate or remote locations.

In conclusion, industrial Ni-Cd batteries constitute a highly specialized market which grows along with a country infrastructure. The market is currently growing modestly in the EU (1 to 2% pa), but at a faster rate in Asia and in the Americas, which make the EU industrial Ni-Cd manufacturing base a significant exporter.

Improvement potential

For industrial applications, Nickel-based batteries will most likely remain relevant even in a decade or more. Manufacturers are further improving the already superior characteristics of these batteries such as low maintenance requirements and tolerance to extreme temperatures. Current and possible future innovations include optimized cell design, different electrolyte additives, electrolyte level monitoring and improving reducing the maintenance.

Environmental aspects and circular economy targets

Used industrial Ni-Cd batteries are extremely well collected in the EU. Fully permitted specialized recyclers extract the embedded metals (nickel, cadmium and steel) with very high efficiency. Pyro-metallurgical methods of recycling are well proven and highly effective.

In the course of the previous decade, the recycling efficiency of Ni-Cd batteries in the European Union had to be improved to reach the 75% level mandated by directive 2006/66/EC, and industry is currently working to reach the 80% recycling efficiency goal set by the new European Battery regulation 2023/1542, a level which will be mandatory by 2025.

Furthermore, an additional requirement has been introduced in this new European Battery regulation to especially recover 90% by 2027 (and 95% by 2031) of the embedded nickel.

CHAPTER B:

Most Promising Future and Emerging Battery Technologies

The promising future technologies identified in this chapter are based on the following criteria:

Sustainability Aspects: Emphasis is placed on technologies that reduce the carbon footprint and offer sustainable alternatives to raw and secondary materials, particularly those identified as Critical Raw Materials (CRMs). By reducing dependency on these materials, these technologies contribute to enhancing sustainability and resilience within the supply chain of raw materials.

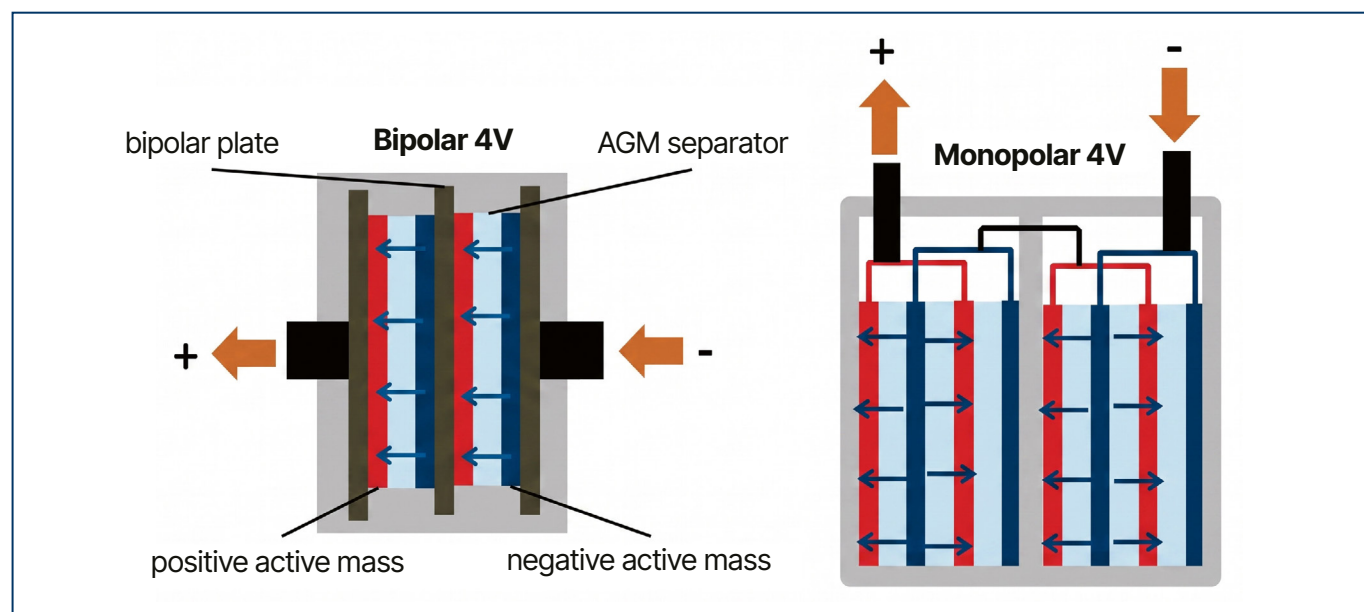
Technology Readiness Level (TRL): Given the urgency to mitigate CO₂ emissions, the TRL level of a technology is crucial. Technologies with higher TRL levels are prioritized as they are closer to market deployment and can facilitate more immediate impact in reducing carbon emissions

In pursuit of enhancing battery performance across real-life applications, and driven by imperatives of durability, safety, sustainability, and affordability, industry experts have converged on promising future technologies for inclusion in the current roadmap. Sustainability stands as a paramount driver, aiming to produce batteries with minimal environmental impact, obtained in adherence to social and ecological standards, ensuring longevity, safety, and the potential for repair, reuse, or repurposing.

B.1. Advanced Lead battery technologies

While bipolar and monopolar designs share the same lead-based chemistry, they differ in that in

Figure 2: Bipolar design – the cells are stacked in a sandwich construction



bipolar batteries, the cells are stacked in a sandwich construction so that the negative plate of one cell becomes the positive plate of the next cell. The cells are separated from each other by the bipolar plate, which allows each cell to operate in isolation from its neighbours.

Stacking these cells next to one another (figure hereunder) allows the potential of the battery to be built up in 2V increments. Since the cell wall becomes the connection element between cells, bipolar plates have a shorter current path and a larger surface area compared to connections in conventional cells. This construction reduces the power loss that is normally caused by the internal resistance of the cells. At each end of the stack, single plates act as the final anode and cathode.

This simpler construction leads to reduced weight since there are fewer plates and bus bars are not needed to join cells together. The net result is a battery design with higher power than conventional monopolar lead-based batteries.

The focus of R&D focus is on the availability of a lightweight, inexpensive and corrosion resistant material for the bipolar plate, and the technology to properly seal each cell against electrolyte leakage.

Architectural advantages are:

- Direct current path = low impedance
- Uniform current density = high material utilization
- Thin active material and separator = high power
- Pb-Bipolar technology = increased energy density: 50 – 63 Wh/kg

B.2. Sodium-ion room temperature batteries

Compared to the state-of-the-art high temperature sodium batteries, the new sodium-ion battery technology is operating at room temperature. The sodium-ion battery has a similar working principle to the Li-ion battery. Sodium ions also shuttle between the cathode and the anode to store and release energy. As sodium resources are cheap and widely distributed and considering the technological

similarities with existing Li-ion batteries, the industrialization process of sodium-ion batteries will be accelerated.

For cathode materials, the most important part of sodium-ion batteries, Prussian blue analogue, layered metal oxides, and NASICON (sodium (Na) Super Ionic Conductor), each has its own advantages in different aspects.

Based on potential application scenarios, higher energy density, longer cycle life and better low temperature performance are the most critical indicators. In total, the cost and safety advantages of sodium batteries will gradually gain in prominence. Therefore, it is likely that sodium-ion batteries will be used as traction batteries in two-wheeled vehicles, such as e-scooters, 12V starter applications, A0 and A00 passenger vehicles for A-level EV charging, and electrical energy storage (EES), as an effective supplement to Li-ion batteries.

The specific capacities of anode and cathode materials are:

Anode:

- C: 300-500 mAh/g
- Sn: 500-1,000 mAh/g

Cathode:

- Prussian Blue Analogue: 120-160 mAh/g
- Layered Metal Oxide: 100-180 mAh/g
- NASICON: 100-140 mAh/g

Recycling targets for sodium-ion batteries will be maintained at the current level of 50%, but active material recycling is expected to increase from 50% to 90% by 2030.

Generations of sodium materials considered for further development by 2030 are:

State-of-the-art	NaS, NaNiCl
>2025	Wide-temperature and long lifespan (>7,000) Na-Ion (RT)
>2027	Anode-free and high Energy Density Na-Ion (RT)
>2030	All Solid-State RT Na-S

Sodium based technologies – key performance parameters for state-of-the-art in 2023 and targets for 2030:

	Sodium-Ion 2023	Sodium-Ion 2030
Recycling Rate (%)	50	90
Calendric Life (Years)	15	30
Energy Throughput (Full Cycle Equivalent)	4,000	6,000 – 12,000
Fast Recharge Time (Min)	30	5
Volumetric Power Density (W/l)	500	600 - 850
Gravimetric Power Density (W/Kg)	300	380 – 700
Volumetric Energy Density (Wh/l)	310	350 - 700
Gravimetric Energy Density (Wh/kg)	160	200 - 450

Asian players are the most active in the race. Several companies are in the advanced qualification stage at both the vehicle and stationary storage system levels and are starting to operate GWh-scale cell manufacturing facilities. Several material suppliers are also already offering battery-grade products. Several of these companies developed proprietary chemistries, with slightly different active materials. Each SIB chemistry will have different characteristics and performances, will be tailored for different applications

Despite the shuttling mechanism being common in both LIB and SIB, changing the shuttling ion from Li to Na requires the formulation of new active (host) and inactive battery materials. At the negative electrode, SIB generally use either soft or hard carbon, with the latter generally considered as the active material of choice, due to its high storage capacity, relatively low working potential, as well as good lifetime. On a longer-term horizon, materials like tin (Sn) and sodium metal are also considered as potentially promising as negative electrode active materials. At the positive electrode, three different chemistries are seen as the most promising and are actively being commercialized, namely

- i) Layered oxide with general formula NaMO_2 , with M a transition metal, such as Ni, Cu, Ti, Fe, Mn. These materials are also often referred as P2

and/or O3 type, due to the position ("site") of the sodium-ion in the crystal structure;

- ii) Prussian Blue Analogues (PBA), with general formula $\text{Na}_x\text{M}_y(\text{CN})_6 \cdot z\text{H}_2\text{O}$, and M a transition metal, such as Fe, Mn. These can be further classified as Prussian white, Prussian blue, and Prussian green
- ii) Polyanionic compounds, such as those with general formula NaMPO_4 , and includes several typical crystal structure types, such as so-called Na Super Ionic Conductors (NASICON), olivine and several others. One typical example of this class of materials is $\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$ (NVPF)

Electrolytes are generally sodium analogues of conventional lithium-ion based electrolytes, such as NaPF_6 dissolved in organic carbonate-based solvent. A final interesting advantage of SIB versus LIB at the material level is the possibility of using aluminium as negative electrode current collector instead of copper (commonly used in LIBs), which can help reduce cell cost.

SIB should be considered as a potentially lower cost, lower energy alternative to LIB. Depending on the positive and negative electrode chemistry, gravimetric energy at the cell level can be comprised between 80 up to about 200-250 Wh/kg, with

current generation state-of-the-art cells having energies of about 160 Wh/kg. SIBs also generally exhibit good power capability and good low temperature performance. There is an expectation that SIB-based battery packs will be cheaper and easier to transport, due to the possibility of being fully discharged to zero volts, making the risk of thermal runaway lower compared to LIB.

SIB could also be used in so-called “AB battery packs” or “hybrid/mixed chemistry packs”, for example, mixing LIB and SIB. All these characteristics, however, are still not fully demonstrated at scale, as results from cell and system development, particularly for larger scale applications such as electric vehicles and stationary storage, are still confidential between battery producers and customers, and mostly led by Asian companies, which are in the technology scale-up phase. While the SIB is generally considered a “drop-in” solution, adjustments in manufacturing lines and system integration are likely required. Another major challenge, which will require global effort, will be the creation of a new value chain.

B.3. Post Li-ion battery technologies

B.3.1. Lithium all-solid-state battery technologies (Li-ASSB – Gen 4b & 4c)

Solid state batteries use an electrolyte made of solid material instead of the usual liquid electrolyte. The electrodes are also made of solid material. With solid state batteries, there is the possibility that part of the solid electrolyte can be incorporated into the electrodes. For example, lithium metal anodes can also be used, which further improve performance.

The main advantages of future solid state batteries are that the energy density of the cells will increase significantly in the future and the risk of fire will also decrease due to the less pronounced flammability of the electrolyte. The use of cobalt can also be significantly reduced.

The actual increase in energy comes through the elimination of the graphite by the metallic Li anode, i.e. through the transition from the Li-ion solid state (Gen 4c) cell to the Li solid state cell – Gen 4b. In this case (NMC) by a factor of 1.5.

Table 2: Classification Li-generation technologies with characteristics and estimated timeframe to enter the market

Gen 3b	Cathode: HE-NMC, HVS (high-voltage Spinel)	Optimised Li-Ion2025	2025
	Anode: Silicon/Carbon		
Gen 4a	Cathode: NMC	Semi Solid State Li-ion	2027
	Anode: Si/C		
	Solid electrolyte		
	Semi Solid State Li-ion		
Gen 4c	Cathode: HE-NMC, HVS (high-voltage Spinel)	All solid state	>2030 - 2035
	Anode: lithium metal		
	Solid electrolyte		
Gen 5	Solid electrolyte Li O ₂ - lithium air/metal air	New cell gen: metal-air/	>2030 - 2035
	Conversion materials (primarily Li S)	Conversion chemistries/	
	New ion-based systems (Na, Mg or Al)	New ion based insertion chemistries	

Figure 3: Comparison specific energy Lithium Gen 4a. with Gen 4b.

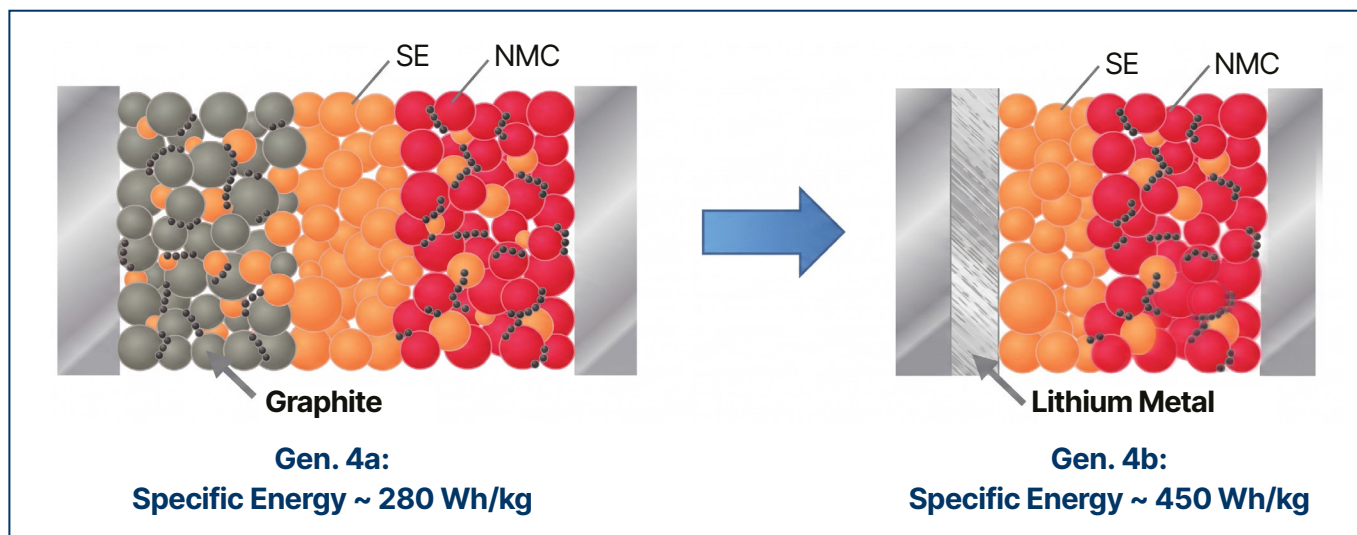
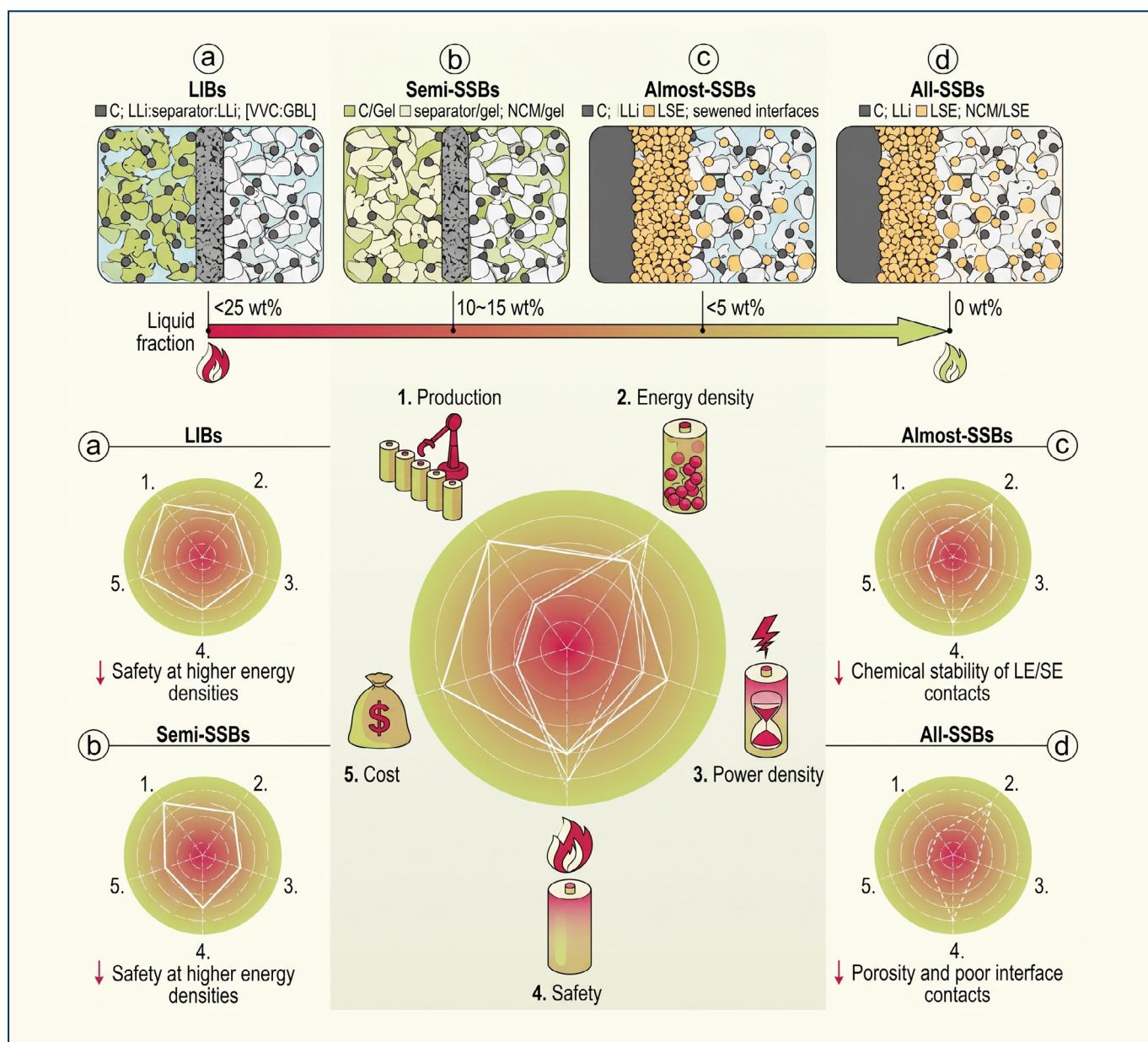


Figure 4: Comparison of various cell concepts with different fractions of liquid components¹



Advantages of solid-state batteries in comparison to liquid electrolyte cells are:

- Higher energy density than Li-Ion
- Safety, instead of flammable organic liquid electrolyte, use of a Solid state electrolyte (ceramic, polymer)
- No electrolyte leakage
- Solid polymer Li-ion cells can be made as thin as 0.1 mm or about one-tenth the thickness of the thinnest prismatic liquid Li-ion cells
- Lower manufacturing cost potential
- Excellent shelf life

Disadvantages of solid-state cells compared to liquid electrolyte cells are:

- Power limited by low ionic conductivity of electrolyte
- High interfacial resistance
- Poor interface contacts
- Costly manufacturing process when using vapour deposition process

The solid-state cells use different polymeric electrolytes: crystalline and glass electrolytes.

It should also be noted that the term “solid-state battery”, with different adjectives and identifiers (all-, semi-, quasi-, almost-, pseudo-), is used to describe a vast portfolio of battery technologies (or chemistries). We believe it is best to refer to the classifications in the figure 3.

B.3.2. Lithium-sulphur battery technologies (LiSB – Gen. 5)

Lithium-sulphur batteries (LiSB), using lithium metal as the anode, an organic liquid electrolyte and sulphur composite as the cathode, could have a high theoretical capacity (1675 mAh.g⁻¹) and specific energy (2567 Wh.kg⁻¹).

Lithium-sulphur (Li-S) batteries have been proposed and investigated since the 1960s as an effective energy storage device via reversible electrochemical reactions. As the fast development and commercialization of Li-ion battery technologies kept moving forward, critical technical issues facing Li-S batteries have not been solved since then. In the 2000s, Li-S batteries again

attracted significant research interest owing to their low-cost advantages and high theoretical specific energy of 2600 Wh kg⁻¹, which is at least 3 times higher than the current Li-ion technology.

The low cost and high abundance of sulphur (i.e. the active cathode material), make Li-S batteries more appealing than Li-ion given the fact that the latter use critical materials such as cobalt and nickel in the manufacturing of the cathodes. Moreover, the high energy and low-cost features make Li-S batteries a promising energy storage technology in practical applications, such as portable devices, electric vehicles and grid storage when coupled with the harvesting of renewable solar or wind energy. The ultimate goal of achieving 500 Wh kg⁻¹ for Li-S battery will make it more competitive for widespread commercialization.

Li-S batteries are promising because of the high energy density, low cost and natural abundance of sulphur. However, these advantages can be achieved only when the Li-S battery uses elemental sulphur as the cathode active material and the sulphur approaches the theoretical capacity with low process cost. In recent years, great improvements in the cycling performance of Li-S batteries have been made. However, all these achievements are obtained in exchange for the energy density and process cost. Nanostructured sulphur composites based on various types of carbon materials and conducting polymers have driven the specific capacity of sulphur to a level approaching the theoretical value with acceptable cycling efficiency and cycle number.

Syntheses of the composites are very costly and, furthermore, the cathodes using these composites contain low sulphur content (< 60%) and low sulphur loading (< 2 mg/cm²), which dramatically reduces the energy density of Li-S batteries. On the other hand, Li-S batteries are fundamentally a liquid electrochemical system, in which elemental sulphur must dissolve into the liquid electrolyte in the form of long-chain PS and serve as the liquid catholyte. Dissolution of PS in the liquid electrolyte on the one hand facilitates the electrochemical reactions of insulating sulphur species, and on the other hand causes severe redox shuttle and parasitic reactions with the Li anode.

B.3.3. Lithium–air battery technologies (Gen. 5)

A lithium–air battery contains a lithium electrode and porous air electrode separated by a membrane and an electrolyte (aqueous, aprotic or solid). Lithium–air batteries possess great potential for efficient energy storage applications to resolve future energy and environmental issues.

Although lithium–air batteries attract much research because of their extremely high theoretical energy density, there are still various technical limitations to be overcome before their full transition. Major drawback right now is the low round trip efficiency. It is well-recognized that the performance of lithium–air batteries is governed mainly by electrochemical reactions that occur on the surface of the cathode.

Widespread interest in various carbons and their applicability as cathode materials in lithium–air batteries arises as a result of their highly specific surface area and porosity, their light weight and their low production cost.

B.4. Redox Flow Battery Systems

Fundamentals

Redox flow batteries (RFBs) are a unique type of battery where energy is stored in liquid electrolytes containing redox-active species. These electrolytes are housed in separate tanks and circulated through a cell containing electrodes and a membrane to convert energy. The energy and power of RFBs can be independently scaled by adjusting the size of the electrolyte tanks (energy) and the electrode area (power). This flexibility makes RFBs adaptable to various applications. They also offer high cycle stability and recyclable electrolyte materials.

Chemistries

Several redox chemistries are used in RFBs, including vanadium/vanadium, zinc/bromine (Zn/Br), iron/iron (Fe/Fe), iron/air, and organic molecules. The vanadium redox flow battery (V-RFB) is the most mature, but due to the high cost and limited supply

of vanadium (a critical EU raw material), alternative chemistries are being actively researched.

Technology

V-RFBs are commercially available and used primarily for energy storage systems (ESS). They can be adjusted for different power-to-energy ratios, typically offering storage durations of 5 to 10 hours, ideal for buffering renewable energy sources like wind and solar. Challenges for RFBs include a limited operating temperature range (5–40°C for vanadium-based systems) and lower round-trip efficiency compared to lithium-ion batteries. Advances in electrode materials and flow field designs could enhance efficiency and temperature tolerance.

Applications and Market Relevance

RFBs are currently used only for stationary energy storage, with systems ranging from a few kWh to several hundred MWh. Their future market relevance will largely depend on reducing the cost per stored kWh. Progress in cheaper and more abundant RFB chemistries could significantly influence large-scale adoption.

Resources, Supply Chain

The materials required for RFBs vary by chemistry. Vanadium, while not rare, is not mined in Europe and is listed as a critical raw material by the EU. Therefore, chemistries like Zn/Br, Fe/Fe, and organic options are being explored for their potentially lower costs and better material availability.

Sustainability

The sustainability of RFBs depends on the production processes and materials used, which vary by chemistry. Non-vanadium chemistries might improve sustainability, cost, and material availability, making RFBs a crucial technology for medium to long-term stationary energy storage in Europe.

PART 2

Battery R&D Priorities Driven by End-user Applications

The continued electrification of major application segments is one of the key drivers for battery innovation in Europe. As batteries become increasingly central to mobility, energy systems, industrial equipment, defence, and digital technologies, battery R&D must increasingly be guided by the specific requirements of the end-user applications they are intended to serve. This application-driven approach is essential to ensure that battery technologies developed today can meet the performance, cost, safety, sustainability, and reliability requirements of tomorrow's markets.

Against this background, five R&D end-user application areas have been identified in which batteries are recognized as key enabling technologies for Europe's decarbonization objectives, while simultaneously contributing to greater energy security and reduced dependence on fossil fuels:

- Area 1 – Automotive Mobility Applications
- Area 2 – Motive Power and Off-Road Applications
- Area 3 – Stationary Energy Storage Applications
- Area 4 – Defence Applications
- Area 5 – Robotics & Internet of Things (IoT)

Part 2 of this document takes a market- and application-oriented approach to battery R&D. It provides an overview of the current technical battery requirements associated with each application area and identifies the performance levels that are considered technically and industrially feasible to target towards 2030 and 2035. The objective is not to prescribe a single technology pathway, but rather to translate evolving end-user needs into clear technology requirements and R&D priorities.

Based on these application requirements, battery experts have identified the key performance indicators (KPIs) that should guide technology development across the different battery chemistries and technology platforms. These KPIs provide a basis for assessing technology gaps, prioritizing R&D activities, and aligning battery innovation with the expected evolution of end-user markets.

The approach recognizes that there is no single optimal battery technology for all applications. Different use cases impose different combinations of requirements related to energy density, power density, fast charging, cycle and calendar life, operating temperature, safety, reliability, sustainability, manufacturability, and cost. Understanding these trade-offs is therefore critical for directing R&D investment towards the technologies and performance improvements that can deliver the greatest impact in each application segment.

The five application areas presented in this chapter should consequently be viewed as complementary pillars of a European battery R&D strategy. Together, they provide a framework for connecting end-user needs and market developments with technology roadmaps and R&D priorities, helping to identify where further innovation is required and where emerging battery technologies could provide significant advantages by 2030-2035.

1. Automotive Mobility

- Batteries for 12V SLI & AUX applications
- Traction Batteries for xEV



2. Motive Power & Off-Road

- Material handling & Logistics
- Off-road industrial vehicles, railway, marine & aviation



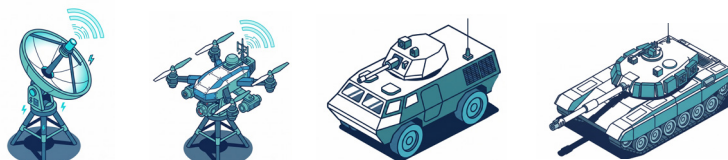
3. Stationary Energy Storage

- UPS & Telecom
- Residential/Commercial (BTM) & Grid Scale (FTM)
- Off-grid Applications



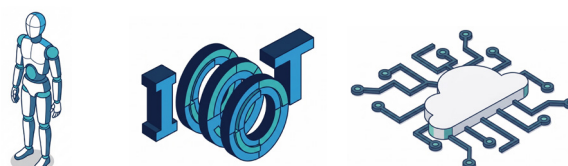
4. Defence

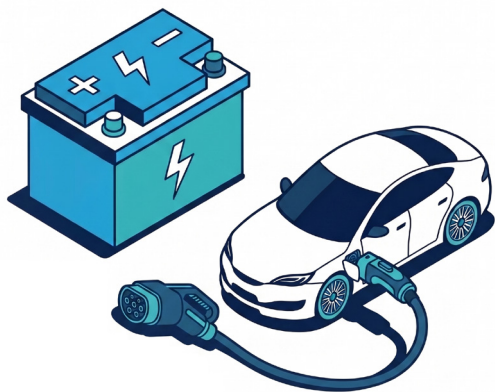
- Drones, unnamed systems
- Electrified military platforms



5. Robotics & IoT

- Autonomous Residential/Industrial robotics
- Connected devices





R&D Application Area 1 – Automotive Mobility

The automotive mobility area covers the largest and most strategically significant segments of the European battery market, encompassing 12 V batteries for starting, lighting and ignition (SLI) and auxiliary applications, as well as medium and high-voltage traction batteries for electric vehicles (xEVs).

1.A. Automotive Mobility – Batteries for 12V SLI & AUX Applications

The road transport sector is responsible for over 20% of the EU's total CO₂ emissions. It has a strong potential to contribute to the net-zero emission target, with batteries as key enablers for increasing energy efficiency for all drive trains (Start/stop, mild, full HEV, plug) in HEV and BEVs.

Consumer pressure as well as regulator drivers are forcing changes in the vehicle technology towards a higher degree of electrification. Although today there is still a strong focus on battery electric vehicles (BEVs) there is also a wide potential for the role of batteries to evolve further to increase energy efficiency in different degrees of hybridization. The Worldwide Harmonized Light Duty Vehicles Test Procedure (WLTC) brought a shift to using real driving data to assess fuel consumption and emissions from these vehicles, with the main

challenge for automotive batteries to capture the car's kinetic energy.

Demand for battery performances such as charge acceptance and quicker rechargeability is driven by the need to **offload the constraints on the ICE vehicles**, and to **improve CO₂ efficiency**. It also requires **higher trust in auxiliary systems** as classified by ASIL levels ensuring backup power in the event of traction battery failure, as well as peak shaving to stabilize demand.²

12V Auxiliary and SLI batteries are considered as they also contribute to the potential of energy saving as well as ensure the safety and proper functioning of the vehicles. For that reason, all the different battery types should continue to co-exist and this is why we focused on the following applications in this area:

- 12V Auxiliary Batteries
- 12V Start-Lighting-Ignition Batteries (SLI batteries)
- Heavy Commercial Batteries (HCV batteries)

EUROBAT is an associate member of the EGVIA private-side association of the co-programmed 2ZERO Horizon Europe Partnership and the ERTRAC working group on Energy & Environment to accelerate the transition to carbon-neutral European road transport by 2050.

Battery Market

In the automotive sector the application of 12V batteries will remain significant in all vehicle architectures.

Taking into account the KPMG study "A Global Battery Market Outlook to 2030"², the auxiliary battery market is a fast-growing market with a CAGR of +23% (in GWh) for lead batteries. Advanced lead and Li-ion batteries are the dominant technologies on this market.

Today, the worldwide 12V SLI battery market value is \$29bn, according to the above-mentioned KPMG study, and will remain stable over 2030. Lead (mainly AGM and EFB) will continue to dominate this market because of good cross-section of cost versus specified technical needs from automotive

producers' specific features. Lithium will have a moderated penetration by 2030, however Na-ion technology is emerging as potential for this application. The SLI market segment would still remain very important in the next years to come.

Concerning Heavy Commercial Batteries, the market is growing. The estimated annual production of lead batteries in Europe is 18 GWh by 2030³. Currently only lead is in this market, but lithium may also breakthrough in future, however, the temperature window and the total cost of ownership for lithium will be a challenge, suggesting only limited market penetration by 2030 and continued dominance of lead batteries within this application.

Sustainability, Safety and Standardisation Aspects

Lead-acid batteries can be produced 100% out of old batteries, provide a more solid and secure supply chain, and allow using recycled material currently up to 85% in the production flow. The new Batteries Regulation 2023/1542 sets clear targets for recycling content within batteries, being 85% for lead and 12% for lithium by 2031. The safety aspect for the auxiliary services is also crucial, EFB and AGM battery types will remain the preferred option due to superior safety features such as minimized over-voltage risk and self-disconnection of the battery. On the other hand, embedded BMS with higher customization and more reliable SOF (State of functions) calculations could represent an advantage for Li-ion batteries in relation to safety features that are demanded of auxiliary batteries for EVs.

As standards of reference, EN50342-1 "Lead acid starter batteries part 1: General requirements and methods of test" is under update to align with recent EU Reg. 1542/2023. In addition, IEC 60095-8 "Lead-acid starter batteries - Part 8: 12V Batteries used in automobiles for auxiliary or backup purposes" is under finalization and will be publicly available soon. IEC has recently launched a working group for standardization of 12V Na-ion batteries performances and methods of test for SLI and auxiliary applications.

1.A.1. Batteries for Automotive 12V Auxiliary Applications (12V AUX Batteries)

Application Profile

12V Auxiliary batteries for passenger cars applications, are used as auxiliary energy storage and power source in vehicles, not featuring the classical function of engine starting/cranking. This includes applications in battery-electric vehicles, as well as in vehicles with an internal combustion engine (ICE) with different electrification levels (micro-hybrid, mild-hybrid, hybrid and plug-in hybrid).

According, to the IEC 60095-8 draft standard on 12 V batteries used in vehicles for auxiliary and back-up purposes, auxiliary batteries can typically be associated with one of the following three categories:

→ **Category (1)**: 12V central-storage (main) battery, with most functions of car batteries with exemption of engine starting. These functions typically include: power supply during parking, vehicle activation and after-run, over-the air update and as well transient power delivery and absorption, along with voltage stabilization, during normal vehicle operation.

Requirements for category (1) shall take into account significant capacity throughput during life and appropriate voltage response when supporting high-rate discharge currents.

→ **Category (2)**: 12V backup battery that is stabilizing voltage and providing emergency power for a sensitive – often safety relevant – electrical component or sub-net of the power supply system.

Requirements for category (2) shall take into account limited capacity throughput during life and appropriate voltage response when supporting high-rate discharge currents, which can be variable depending on applications and vehicle manufacturers.

→ **Category (3)**: 12V auxiliary batteries in stop/start or micro-hybrid vehicles that stabilize system voltage during engine restart, which would be powered out of the 12 V starter battery. This application is similar to the backup case described above, but battery discharge occurs frequently during normal operation and is not functional safety relevant.

Requirements for category (3) shall take into account relevant capacity throughput during life and limited power requirements.

Description of the Battery Features

Lithium and lead technologies differ in terms of performance, recycling and cost. For auxiliary applications, the advantage of Li-ion batteries is in their energy and power densities and durability at ambient temperatures. However, high cost, safety and recyclability, as well as extreme temperature performance, must be improved in order to become competitive with lead batteries in this application.

On the other hand, lead batteries are advantageous for their high temperature tolerance, wide operating temperature range including useful low temperature performance, recycling efficiency and cost, with current advancements focused on improving energy density, life span and diagnostics. The technology choice is, therefore, mainly based on specific applications and market segments.

For lithium-based batteries, lithium iron phosphate (LFP) and lithium titanate oxide (LTO) will be the chemistries of use for such applications. Flooded and absorbent glass mat technology (AGM) batteries will generally be preferred. Na-ion technology is starting to be considered in auxiliary application, in particular Prussian blue analogue (PBA), Polyanionic (PA) and Layered Oxide (LO) as most potential chemistries

Research and Innovation Scope

Key Performance Indicators (KPIs) selected for auxiliary automotive applications in all hybridization types, from micro HEVs to full EVs, are:

→ Energy density, expressed in Wh/kg

- Volumetric power density, expressed in W/l
- High temperature life, expressed in units performed (EN THE test or SAE j2801 / 75°C test)
- Low temperature power performance, known as Cold Cranking Ability (CCA AUX test), with power pulse characterization (PPC) as expressed in IEC 60095-8 standard draft
- Charge recovery in terms of state of function (SOF) and state-of-charge (SOC)
- Recycling efficiency (%)
- System cost in €/kWh
- Life span (years)

Today, lithium batteries overperform lead in energy density and life span, whereas lead batteries exceed lithium in KPIs such as high and low temperature performance, recycling efficiency, and system cost. The same trend will also be observed through to 2030, narrowing the gap for high and low temperature performance.

The dominant technology for this application today is lead, both EFB and AGM. Together with lead, lithium, mostly LFP, will also fulfil future requirements and is forecasted to reach approximately half of the market share for this specific application. Opportunities for technology improvement could be found in energy density and life span for lead batteries and in extreme temperature performance, recyclability and system cost for lithium batteries.

12 V Auxiliary Battery landscape - by 2035

Fast-growing market with a CAGR₍₂₅₋₃₀₎ of +23% (in GWh) for lead batteries **2 dominant technologies**

- Advanced lead, AGM & Flooded
- Lithium-ion, LFP & LTO
- Sodium-ion technology penetration to some extent is anticipated



In Conclusion

KPIs selected for auxiliary automotive applications in all hybridisation types, from micro HEV to full EVs, include energy density, volumetric power density, high temperature life, low temperature power performance, system cost, recycling efficiency and life span.

1.A.2. Batteries for Automotive 12V Start-Light-Ignition Applications (12V SLI Batteries)

Application Segment

Micro and mild-hybrid road vehicles run with a 12V lead starter battery because of the battery's internal combustion engine (ICE) cranking function. Opportunity charging to capture the kinetic energy of the car will be key to improving energy efficiency. High voltage (HV) and low voltage (LV) Li-ion systems are developing further. 'Dynamic charge acceptance' is a key innovation for batteries in such applications.

Based on the EN-50342-6 standard recent revision, for lead batteries an additional the target of 0.3 A/Ah was introduced and 0.5 A/Ah appear achievable, without compromising high temperature durability and water loss typical features.

With an increasing number of micro and mild hybrid vehicles on the road and the replacement market to serve for many years after, this application is a key enabler for Europe to meet its CO₂ reduction targets. **Further improvements for CO₂ reduction for this application will require Li-Ion battery systems. These system largely improve the dynamic charge acceptance and therefore the CO₂ reduction.**

Application Profile

Cranking a thermal 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 thermal engine and providing energy to multiple accessories when the engine is not running has become a major challenge to meet the ever-increasing demands of the widespread start-stop micro-hybrid architectures that are introduced in the original equipment market (OEMs).

The dominant technologies today are lead AGM and EFB but flooded will retain a substantial market share. Together with lead, lithium will also fulfil the requirements in future. Both lead and lithium technologies will co-exist in this category in the future. **Lead-based batteries maintain a strong position, dominating the market also in 2035, despite of lithium and sodium-based technologies entering this market. Currently,** Na-ion technology is getting more and more consideration in SLI application, in particular in China region.

Key Performance Indicators and Innovation Potential

With the successful introduction of start-stop micro hybrid architectures, which are becoming increasingly powerful with longer stop phases and higher currents during vehicle stand-still, for example when cutting the engine before the car stops, the requirements of this application are increased high cycle life and energy/power densities.

The key performance indicators for the innovation are increased vibration endurance, energy and power density, system cost, energy throughput, dynamic charge acceptance (DCA), and weight reduction to ensure that recent progress is maintained, improving the operating temperature range and recycling rate whilst ensuring no trade-off in key parameters such as the CCA.

In Conclusion

Start-stop micro hybrid architectures are becoming increasingly powerful, with longer stop phases and higher currents during vehicle stand-still, for example when cutting the engine before the

car stops. The requirements of this application are increased high cycle life and energy/power densities.

Opportunity charging to capture the kinetic energy of the car will be key to improving energy efficiency. High voltage and low voltage Li-ion systems are developing further, but lead can also support the capture of excess energy.

12 V SLI Battery landscape - by 2035

Worldwide 12V SLI battery market is 330 GWh for lead batteries to remain stable **1 dominant technology**

- Lead-based, mainly AGM & EFB but flooded to remain a substantial share
- Lithium-ion to compete, but remain small penetration
- Sodium-ion technology penetration to some extent is anticipated



Pb ~95%



Li ~5%



Na <3%

1.B. Automotive Mobility – Traction Batteries for Electric Vehicles (xEV)

Application Segment and Technical Characteristics

BEVs are used across several transportation categories, each with different duty cycles and battery demands. The BEV application that is covered by the roadmap is related to Passenger Vehicles (sedans, hatchbacks, SUVs with a large variety in size), Commercial Light-Duty Vehicles (delivery vans and small trucks) and Heavy-Duty Vehicles (Electric buses and freight trucks, including public transportation).

BEV batteries are optimized to **balance, range, lifespan, safety, and charging speed**. More specific profile shifts per segment depending on whether the vehicle is used for personal mobility, logistics or for heavy-duty transport.

Key Performance Indicators & Mainstream Battery Technologies

The technologies of choice for BEV and PHEV are Li-ion batteries using lithium nickel manganese cobalt oxide (NMC or $\text{LiNi}_a\text{Mn}_b\text{Co}_c\text{O}_2$ where $a + b + c = 1$) and lithium iron phosphate (LFP or LiFePO_4) as positive electrode active materials, or cathodes. Lead technologies are not suitable for the propulsion of PHEV/EVs but they still have a role to play to maintain the quality of the on-board net and to ensure the safety functions of the main battery (see auxiliary battery section).

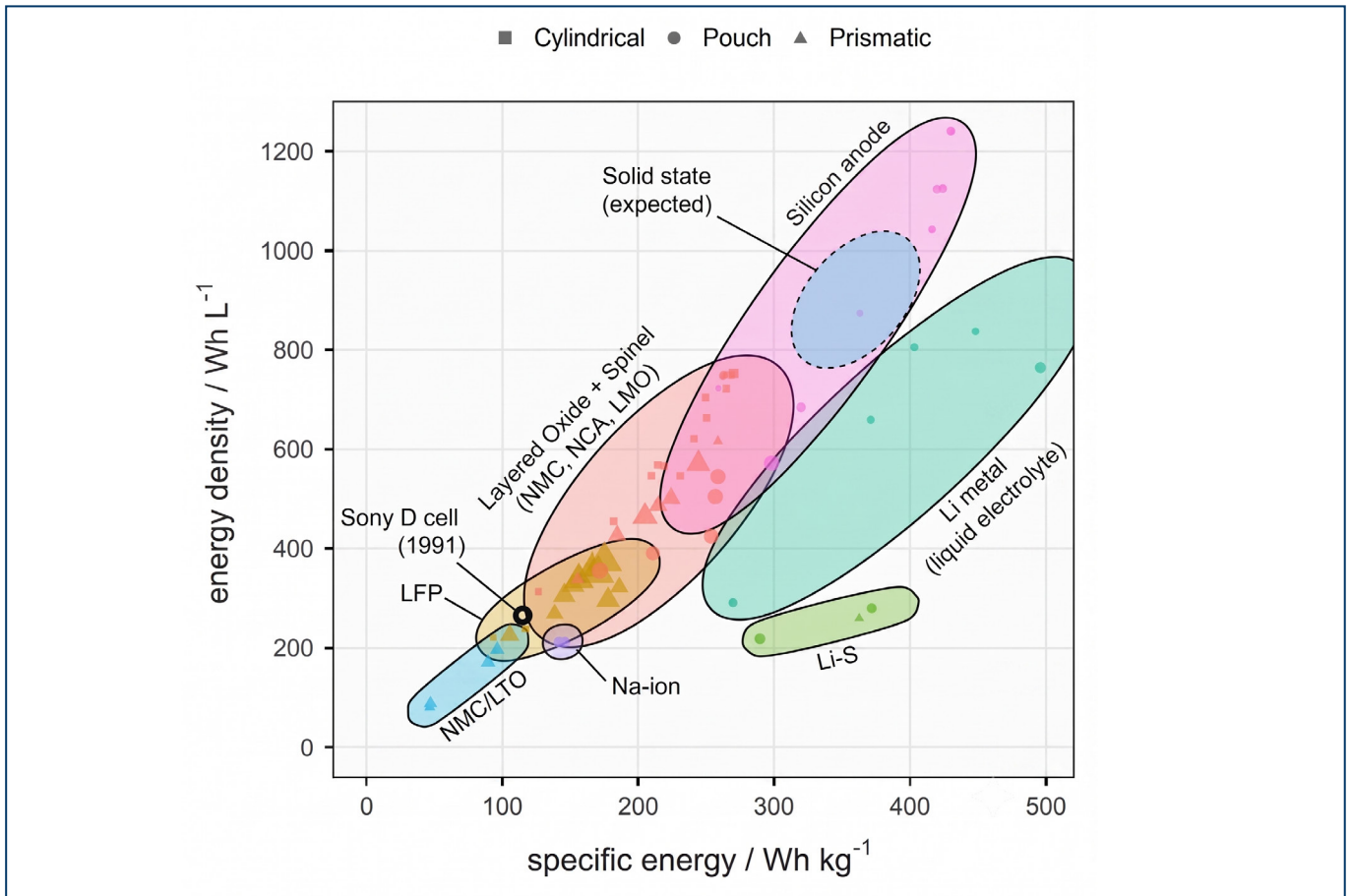
With battery technology for EV applications becoming increasingly mature, the focus today is on reducing battery system cost, and increasing performance, such as gravimetric and volumetric energy. This will lead to electrification of more and more segments. Also, faster charging, combined with safety and security aspects, are key performance indicators to target for innovation.

Both NMC and LFP technologies are increasingly optimized, with most notable development the resurgence of so-called LMFP-based batteries, where the iron in LFP is substituted with manganese, which can lead to higher working voltage compared to LFP, hence increased performance. This chemistry is currently also being adopted by automakers.

Other chemistries, such as sodium-ion RT, and solid-state lithium-based batteries are at various stages of R&D, with sodium-ion RT currently being the most mature and having reached commercial readiness, mostly in China. , although the relatively low prices of lithium raw materials have cooled demand. An overview of some current and future chemistries, based on publicly available data, is given in the figure below.

For mild and full hybrid traction batteries, the main electrochemistry is also Li-ion, preferably

Figure 5: Range of energy content of different battery technologies at cell level, energy density vs specific energy for selected Li-ion and "post-Li-ion" cells



with NMC/C compositions. Semi solid-state technology may also be expected to be introduced after BEVs after technology uptake in BEV application, especially since semi solid-state electrolytes will not face a disadvantage in specific power requirements due to the lower conductivity of the electrolyte to liquid solutions.

Key Performance Indicators for Innovation

Driven by market demand, policy initiatives and regulations, shared common priorities for passengers, light and heavy commercial vehicle batteries are:

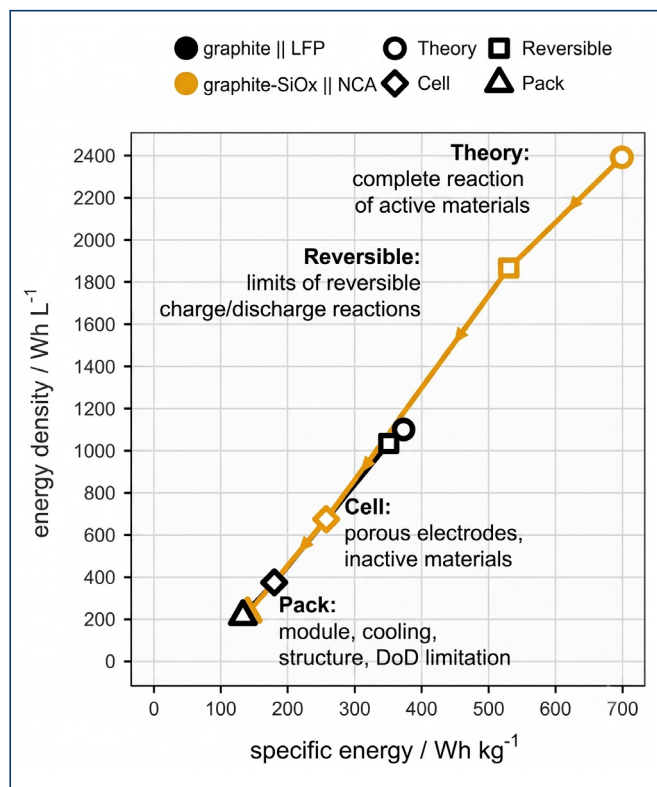
- Energy and power density, enabling drive range typically up to 250 to 600+ km
- System cost
- Charge acceptance, DoD, to manage, often between 70-90% usable capacity to balance range vs longevity, including support for DC fast charging 50 kW to +350 KW

- High Power output for high discharge capability to improve performance and drivability
- Operating temperature range approximative between -20°C to +50°C
- Safety and Thermal stability thanks to advance BMS, thermal management and stable chemistry
- Cycle life, typically up to +3,000 or 8-15 years - with operational SOC between 10-90%
- Energy throughput
- Recycling rate

EV batteries higher power, particularly during charge, is key to enable faster charging rates, while higher energies can extend vehicle range. One long-term strategy is to focus on material research in order to increase the volumetric and gravimetric energy densities. However, in recent years, most gains in battery pack performance have been obtained by optimization of current chemistries together with better design and engineering at the pack level, e.g., by employing more effective cooling systems, safety mechanisms, and ultimately pack design.

Figure 6: Energy losses between theory and system level

Reduction in energy on a weight and volume basis between the theoretical maximum for the active materials and usable pack-level energy density for state-of-the-art NCA and LFP battery technologies



System-level performance is what ultimately matters, particularly safety, which still needs to be assessed for some most promising next generation batteries, such as Li solid-state and Sodium RT. Moreover, Theoretical, Material, Cell and System-level performance does not scale linearly, as evidenced by the figure below, which highlights how, with proper engineering, chemistries with lower theoretical energy can be competitive with chemistries with higher theoretical energy.

Research at pack level is also key to achieving performance targets, as well as support for new chemistries. Some examples of new systems being introduced in the market include:

- Cell to pack design
- “Structural battery”: battery integrated into the vehicle body

- Thermal management
 - Higher efficiency systems and downsizing
 - Coolant selection and flow, system design, including submerged cells
- Advanced pack materials
 - e.g. for pack enclosures
 - Materials for enhanced thermal management

To manage the battery system, research into controls and software will also be necessary for reasons of

- Fast charging
- Health and diagnostics
- Range prediction
- Advanced modelling and machine learning

Finally, it is worth noting that batteries for BEVs and HEVs are generally different. HEVs include a wide range of different vehicles, which are usually categorized on the basis of their hybridization factor. These include, for example, micro-, mild- and plug-in hybrid electric vehicles.

Depending on how electric and combustion engines are connected, powertrain can be designed as parallel, series or series-parallel. **In general, batteries for HEVs need to be optimized for power and long cycle life rather than energy, meaning that different materials might be selected.**

Cell design will favour thinner, more porous electrodes, with electrolyte formulations optimized for long cycle life and both fast charge and discharge. **Battery packs are also generally smaller, e.g., up to 20-30 kWh for PHEVs, and as small as 0.5 to 1 kWh for cars with lower hybridization factors.**

Automotive sub-segments highlighted hereunder are:

Heavy Commercial Vehicles (HCV):

Additional, demands for higher energy density and longer cycle life. They have a wide variation in operation profiles (ex. Trucks and buses) and therefore require multiple solutions. Specific research is needed on packs to support the specific

requirements of commercial vehicles, such as

- Dedicated thermal management solutions to improve durability
- Advanced materials for commercial and heavy-duty vehicle design
 - For pack enclosures
 - For thermal management solutions of high-capacity batteries

Light Commercial Vehicles (LCV)

For light commercial vehicles (LCVs), battery KPIs of BEV has typical focus on balancing range, durability, charging efficiency, and total cost of ownership.

Key indicators include;

- Energy capacity (kWh) and usable energy, which determine driving range;
- Energy efficiency (kWh/100 km), which reflects vehicle and battery performance;
- Charging time and charging power acceptance, which are critical for fleet uptime;
- Battery health and degradation rate, often measured through state of health (SoH), to assess long-term reliability; cycle life and warranty coverage, which influence residual value
- Thermal management solutions, operating life-time, gravimetric and volumetric power and energy densities and cycle life

Increasingly, fleet operators also monitor availability, downtime linked to charging, and cost-per-kilometre attributable to battery performance, making battery KPIs central to both operational efficiency and economic viability in LCV electrification.

Plug-in Hybrid Electric Vehicles (pHEV)

As BEV driving range continues to improve and charging infrastructure expands, battery innovation for plug-in hybrid electric vehicles (PHEVs) is becoming increasingly incremental, while the majority of R&D investment is directed toward battery electric vehicles (BEVs). As a result, next-generation technologies such as solid-state batteries, sodium-ion chemistries, ultra-fast charging, and cell-to-pack integration are primarily being developed within BEV-focused technology roadmaps.

In contrast to BEVs, PHEV battery innovation is driven by different key performance indicators (KPIs), notably power density, cycling robustness, thermal durability, and compact system integration. PHEVs experience aggressive charge/discharge swings, hybrid-mode energy blending, and frequent regenerative braking spikes, requiring high C-rate capability and rapid power responsiveness. Because PHEV batteries undergo many shallow cycles and repeated charge/depletion events on a daily basis, they require superior micro-cycling durability and highly robust cycle-life chemistries. Consequently, PHEVs often favour power-oriented NMC battery chemistries optimized for durability and dynamic performance rather than maximum energy density.

The EV market estimates presented in this chapter include PHEVs. However, because PHEV battery packs are significantly smaller than BEV packs — typically 10–30 kWh compared with 60–120 kWh for BEVs — their impact on overall battery demand expressed in kWh or GWh remains comparatively limited. PHEVs are therefore estimated to account for up to approximately 10% of the total battery market volume considered in this analysis.

Sustainability, Safety and Standardisation Aspects

As domestic battery demand and manufacturing scale up, the recycling market is expected to continue to grow. Also, second life, re-use and re-purposing are innovation areas which help reduce the footprint of EV batteries, however, re-use costs and associated risks remain.

Recycling requirements are defined mainly by the Batteries Regulation (Regulation (EU) 2023/1542), which has is now in the implementation phase. Research will be required on materials, cells and pack design to meet the future targets for increases in:

- The recycling efficiency of batteries
- The material recovery targets for cobalt, copper, lithium and nickel

The importance of the entire battery value chain for the further deployment of BEVs is recognised and supported by the European Commission, with many initiatives under the European Battery Alliance (EBA).

European Battery Market and Production Capacities

The current BEV worldwide market will increase considerably and will be the main driver for increased lithium production in Europe. Worldwide lithium propulsion batteries for the BEV application are expected to continue to rise considerably, representing 85–90% of the total lithium battery market.

Market drivers include favourable government policies and subsidies, rising concerns about emissions and the further development of charging infrastructure, including bi-directional vehicle-to-grid systems (V2G) to support grid functionalities. Lead technologies are not suitable for the propulsion of PHEV/EVs but they still have a role to play to maintain the quality of the on-board net and to ensure the safety functions of the main battery. The mainstream technologies today are lithium-ion based on NMC (e.g., $\text{LiNi}_a\text{Mn}_b\text{Co}_c\text{O}_2$ where $a + b + c = 1$) and LFP (LiFePO_4). Other chemistries, such as sodium-ion, and solid-state lithium-based batteries are at various stages of R&D, the former has already enter the market mostly in China, the latter could enter the market during the next years to come.

Under the current direction of policy (as of 2026), the original **de facto 2035 ICE phase-out is no longer as absolute as it did two year ago**, which would creating room for certain ICE-based technologies—including hybrids, PHEVs, range extenders, and vehicles using low-carbon or synthetic fuels—subject to emissions accounting and offset mechanisms. This still requires legislative approval and details remain under negotiation. So, the most realistic outcome is increasingly a **multi-technology market** after 2035:

- **BEVs** dominate volume sales;
- **PHEVs and range-extended vehicles** remain relevant in some segments;
- **ICE using e-fuels or low-carbon fuels** survives in niche, premium, long-distance, and specific use cases where electrification remains difficult or costly.

Passenger vehicles will remain the largest demand segment, but commercial vehicles—particularly

electric trucks and buses—will account for a growing share due to substantially larger battery pack sizes. Overall growth is expected to moderate compared with the early EV adoption phase yet remain robust, supported by decarbonization policies, fleet electrification, and continued battery cost reductions.

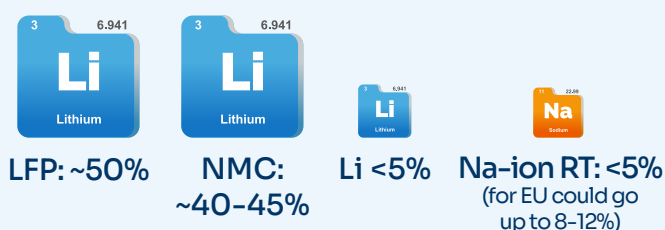
In Conclusion

Driven by market demand and regulation, KPIs for innovation are energy and power density, system cost, energy throughput, charge acceptance, operating temperature range and recycling rate. Pack research (e.g. cell pack design, thermal management, advanced pack materials, etc.) will also be necessary to achieve the targets and to support the EU's environmental objectives, such as increasing the recycling efficiency, recovering cobalt, copper, lithium and nickel, as well as to re-using or repurposing EV batteries. Work on identified bottlenecks identified by the EG VIA2ZERO community

Battery Electric Vehicle (xEV) Traction Battery landscape by 2035*

Global Traction Automotive Battery demand 5 TWh
European Traction Battery demand to reach 1 TWh

- Dominant li-ion 90–95%:
 - NMC/high-Ni – premium / long-range EVs
 - LFP-LMFP – Mass-market EVs
- Lithium-ion to compete, but remain small penetration
- Upcoming technologies entering the market
 - Sodium-ion RT – low cost entry EVs
 - Li Solid State – early high-performance niche



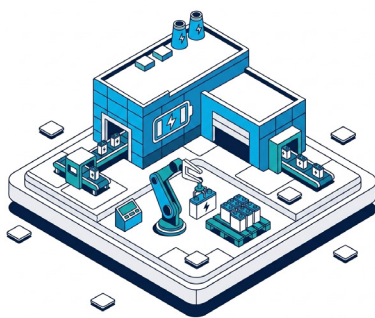
EUROBAT best estimates derived from a broad range of market intelligence and industry projections, including McKinsey & Company, BloombergNEF (BNEF), IEA Global EV Outlook, and other leading industry sources (non-exhaustive list).

R&D Application Area 2

– Motive Power

The **Motive Power R&D area** covers battery technologies and innovation pathways for applications where batteries provide propulsion or power for the movement of vehicles and equipment. It encompasses a broad range of segments, including **material handling and logistics**, such as forklifts, warehouse vehicles and automated guided vehicles (AGVs), as well as off-road industrial vehicles used in construction, agriculture, mining and other demanding environments. It also addresses the specific requirements of **railway, marine and aviation applications**, where factors such as high energy and power density, operational reliability, safety, fast charging, weight optimisation and long service life are critical. The R&D priorities therefore focus on improving battery performance, durability, charging capabilities and system integration while addressing the increasingly diverse operational requirements across these motive power segments.

2.A. Material Handling, logistics & Off-road Industrial Vehicles



2.A.1. Batteries for Material Handling & Logistics

Logistics is an important part of supply chain management. 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, but also inhouse automated guided vehicles (AGVs) and state-of-the-art robotic forklifts.

Application Profile

Material handling vehicles are used in warehousing and distribution for loading and unloading, handling pallets and picking and storing inventory. For this reason, the application requires high power charge and discharge rates, high energy content, high cycle life and long operating times.

Battery Features

One advantage for lead is that it acts as a counterweight, especially for sit-down and high-reach forklifts. Another advantage is the fact that, in one-shift regimes or when using battery swap infrastructures on location, there is enough charging time available. Moreover, operations with opportunity and fast charging, using advanced lead batteries have become quite popular; this technology is now mature and offers increased flexibility and higher availability.

Lithium, that at the beginning entered this market with smaller forklifts, is now used also in bigger machinery with higher tonnage load. It shows advantages in multiple shift operations, which are more energy-demanding and where battery charging time is limited. This is because lithium is less affected by opportunity charging, thus offering an extra advantage for 24/7 machine use. In some applications with intensive use, the total cost of ownership could become lower than for lead, nevertheless the TCO gap between these technologies into material handling application, has been reduced. However, lithium batteries still face issues such as cost, functional safety, operation at low temperature, quicker degradation under high temperature use. Furthermore, most of the forklifts are designed for housing a lead-based battery, the use of lithium-based batteries still requires adding extra ballast to the design to reach the minimum weight required for safety purposes. This problem is being partially overcome with launching on the market of trucks specifically designed by OE for housing a Li-Ion battery from the beginning.

Nickel-based batteries represent a smaller part of the market but also have a crucial role to play as they are used in extreme temperature conditions, such as in drive-in freezers; this application is seeing implementation of Na-Ion batteries too, even if penetration of the market is still at a very beginning.

Research and Innovation Scope

The three mainstream battery technologies, lead-, nickel- and lithium-based-, have complementary features and all have the potential for innovation in these applications. The general technical requirements for the battery systems are high charge and discharge rates, high energy content, cycle life and operating times, high recyclability, low investment cost, low carbon footprint and the need to meet strict safety requirements.

Other increasingly important requirements are high capacities (increased truck dynamics), namely the power density, wide of high temperature performance and energy efficiency, in particular for multiple shift operations with improved PSOC cycling or opportunity charging and need for low maintenance.

As for lead batteries, **lowering the TCO is key. This can be done by increasing the cycle life, reducing the recharging time, as well as producing maintenance-free batteries. Pure lead technology and Advanced Lead-Acid batteries, namely PbA batteries with additives which increase performance, can boost these factors. Other R&D areas for innovation are digitalization and innovation with regards charging.** Use of connectivity on batteries transforms them into smart devices which, for instance in Fleet management application, can highly increase battery life, monitor the use of batteries and anticipating corrective action in case of misuse

Lithium technologies still face a number of issues, such as cost, safety, reduced temperature range use and thermal management. R&D will continue its focus on these features so that these batteries can further penetrate the market.

In all the technologies mentioned AI could give important support in defining the State of Health of batteries predicting and anticipating the end-of-life stage.

Battery Market

Traction and semi-traction batteries for material handling, such as in forklift applications, are historically lead battery focused, currently having around 60% of the global market share, whith a forecasted reduction down to 55% in 2027. Lithium is taking an important part of the market, starting to penetrate since a few years and taken gradually more importance, continuously growing every year.

The worldwide battery forklift market was rated at 37 GWh in 2024, with expected annual growth of around 8%. In 2024 the European market represented around 15 GWh, and expected to grow with CAGR +6%, until 2035. Pushed by noise and emissions legislation, battery forklifts are steadily replacing the ICE propelled vehicles, with a market exceeding 80 GWh by 2035³. This high market

Motive Power – Batteries for Material handling and logistics Technology Landscape by 2035

EU market to increase with CAGR₍₂₅₋₃₀₎ +8% (GWh), due to further replacement of ICE-powered forklifts - total market estimated at 23 GWh (global > 80 GWh).

Two dominant technologies each around half of the market

- **Lead** – fostering its position and continuation to serve the AM
- **Lithium** – double digit growth, replacement ICE
- **Nickel & Sodium RT** – small but substantial for niches (freezers...)
- **Sodium RT** – already playing a certain role in niche markets



50%



50%



Ni, Na: Niche

growth will be mainly driven by lithium-based technologies, while lead-based will keep a steady position in the market.

In Conclusion

Lithium has entered the market for smaller forklifts but currently are widely used for bigger machines, too and has advantages 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.

2.A.2.Batteries for Off-road Industrial Vehicles

This segment covers a wide range of different applications that are not covered in the previous material handling and logistics application categories. We distinguish the following sub-segments:

- **Sweeping/cleaning machines** used in factories, malls and supermarkets for cleaning purposes, as well as **wheelchairs** to assist disable and elderly persons. Different number of 6V to 12V monoblocs with different dimensions and stored energy are typically used, connected in parallel and series.
- **Construction/demolition machines**, such as mini-loaders, and mini excavators, vibratory plates and rammers, scissor-lifts, used in production facilities and construction sites. Batteries in this segment have similarities to those used for material handling. This segment is facing a growing interest in term of product development and the conversion of bigger machine with ICEs towards electric engines.

- **Golf carts and small carts** used for leisure or light human transportation, such as in airports.
- **Automated guided vehicles and carts (AGVs and AGCs)**: These 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 without human interaction and generally use electric drives. A 24/7 shift use is typical in such applications.
- **Other applications not included in the categories above**, such as harvesting trolleys used into greenhouses, other small machines, and RVs.

We target these market segments because of their high potential to significantly reduce emissions to meet the zero emission targets of the European Green Deal.

Battery Features and Key Performance Indicators

Applications for these segments require high energy content, cycle life, operating time and operating temperature range. Since most of the applications do not ask for peak current, high power in charge and discharge rate are typically not required.

For industrial off-road vehicles with high loads and heavy-duty use profiles, major requirements are exceptionally high cycling capability, particularly in partial state of charge (PSOC) operations, extremely low internal resistance, high power density, fast charging capability (15-20 minutes), high charge acceptance, low maintenance intervals to reduce the total cost of ownership and mechanical and electrochemical stability. Especially for construction/demolition field, where vibration is typically and issue, ultra-high mechanical resistance and consequently chemical stability of cells are strictly required.

Mainstream Technologies

Lead-based batteries are currently dominant in most of these market segments, which is likely to remain the case in future years, especially for such

applications where the initial investment is low or where there is not a high energy demand.

Lithium, with high energy and power densities, is entering the powering market successfully because of restricted battery compartments and higher currents due to the heavy loads, hence the need for R&D to increase the volumetric energy and power density, increase the operating range and to work on the recyclability, which are key performance indicators for innovation. These batteries are derived from the traction batteries for material handling applications, and they still share several features with them.

It should also be noted that also here, the robust nickel-based technology NiCd has a niche market to serve where a very broad operating temperature range (-40°C to 60°C) is required, traditionally been the choice for applications in extreme environments,

Target technologies are low maintenance or maintenance-free technologies. Lithium is taking market share (for higher power applications in particular) and it has become dominant in the construction/demolition markets and in segments where emissions and potential liquid spillages are not allowed (e.g. airports supermarkets and pharmaceutical industry). Other important aspects of driving innovation in this segment are safety, circularity and increasing recycling rates.

Innovation Potential

KPIs for innovation in these segments are high energy content, cycle life, operating time and operation temperature range. Since most of the applications do not ask for peak current, high power in charge and discharge rate are typically not required.

For industrial off-road vehicles with high loads and heavy-duty use profiles, major requirements are exceptionally high cycling capability, particularly in partial state of charge (PSOC) operations, extremely low internal resistance, high power density, fast charging capability (15-20 minutes), high charge acceptance, low maintenance intervals to reduce the total cost of ownership.

For the construction/demolition segment, where there is high vibration and tough environment, an ultra-high mechanical resistance and chemical stability of cells are strictly required. Penetration of Lithium-Ion technology in this segment, in particular for excavators, is growing. Other important aspects of driving innovation are safety, circularity, and increased recycling targets.

Battery Market

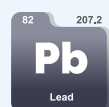
Lead-based batteries are currently dominant in most of these market segments. This is likely to remain in future years, especially for applications where the initial investment is low. Lithium is entering the powering market successfully because of restricted battery compartments, higher currents due to the heavy loads and of replacing the ICE powered vehicles in particular for construction/demolition vehicles. Another sector where lithium is growing is RV, where users prefer batteries with higher energy density and almost no emission in the cockpit; limitation of a complete breakthrough in this market area is due to many products coming from Fareast with missing or lacking in certification, typically required for these applications. Nickel-based technology (NiCd), with its broad operation

Motive Power – Batteries for Off road Industrial Vehicles

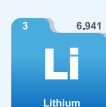
Technology Landscape by 2035

Lead to remain dominant technology and lithium successfully entering the market, each may share half of the market

- **Lead** – remaining dominant
- **Lithium** – to replace larger ICE, ex. in construction/demolition
- **Nickel** – to serve niches for extreme environment
- **Sodium RT** – already playing a certain role in niche markets



50%



50%



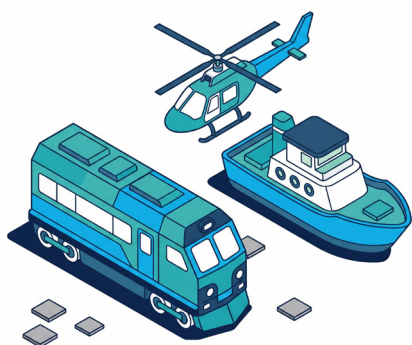
Ni, Na: Niche

temperature range, has traditionally been the choice for extreme environments, but currently it covers only a very niche market for this segment.

In Conclusion

KPIs for innovation in these segments are high energy content, cycle life, operating time and operation temperature range. Since most of the applications do not ask for peak current, high power in charge and discharge rate are typically not required. For industrial off-road vehicles with high loads and heavy-duty use profiles, major requirements are exceptionally high cycling capability, particularly in partial state of charge (PSOC) operations, extremely low internal resistance, high power density, fast charging capability (15-20 minutes), high charge acceptance, low maintenance intervals to reduce the total cost of ownership and mechanical and electrochemical stability. Other important aspects of driving innovation are safety, circularity and increased recycling targets.

2.B. Batteries in railway, marine and aviation applications



2.B.1. Batteries in Railway Applications

Rail infrastructure is the most efficient transportation mode in Europe regarding CO₂ emissions and safety. It is, therefore, of great importance that we develop higher performance batteries to support innovations in both vehicles

and the infrastructure to further increase the performance and energy efficiency of the systems.

Railway batteries are located in the rolling stock and infrastructure. The mainstream technologies used are nickel-based, in particular NiCd, flooded and sealed lead-based, and lithium based batteries. For the rolling stock, we differentiate '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 stand-by applications, we differentiate between batteries for 'trackside line signalling', 'street traffic control', 'signal and control boxes and enclosures' and 'wayside energy'.

Application Profile

New upcoming applications for battery systems are the hybridisation and electrification of rail power traction, mainly for commuter and metro trains, which require high energy, power density and cyclability.

A large proportion of the lines currently operated with diesel vehicles are non-electrified sections "well under 100 kilometres" long. Battery-electric vehicles have the potential in local rail passenger transport to substitute the diesel engines and to make a significant contribution to the net-zero pollution target.

The requisite high energy, power density and cyclability for such applications can be covered by lithium systems, 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. In this sector, there is growing demand for batteries, especially driven by far east Asian markets.

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 operating temperature range.

Mainstream Battery Technologies and Key Performance Indicators

The current installed base in railway auxiliary and infrastructure applications remains predominantly lead-based, particularly VRLA systems. Nickel-cadmium continues to hold a strong position in global value terms, supported by legacy fleets and specific operational requirements.

The development trends for on-board units favour lithium. For **the further hybridisation and electrification of rail power traction**, mainly for commuter and metro trains, the requisite high energy, power density and cyclability is an advantage for lithium batteries, which also ensure maintenance-free and longer lifetime operations. **To power auxiliary functions**, as well as lights and fans in high speed and metro trains, the nickel-based chemistry is the preferred technology because it can function in harsh operational conditions.

As for further developments in infrastructure, different battery technologies will co-exist given the variety of applications. 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 improving energy efficiency, lifetime costs and the volumetric energy density, not only for traction but also for auxiliary applications in new rolling stock platforms. For that reason, market projections indicate a structural acceleration of Li-ion technologies, which are expected to record the highest growth rates during the forecast period.

By 2030, lithium-based systems are expected to be the leading technology in traction applications, driven by hybrid locomotives, fully battery-operated trains and the broader electrification of rail networks.

In auxiliary and infrastructure segments, the market is expected to remain diversified. Lead-based

systems will continue to represent a significant share due to cost efficiency and established qualification standards. Nickel-cadmium is likely to maintain relevance in specific technical and regional contexts but is not projected to define the overall growth trajectory of the segment.

Lithium-based solutions are expected to progressively increase their penetration across both traction and auxiliary segments.

Battery Market

The railway segment is a very fast-growing market, driven by increasing populations and increased demand for rail transport around the world. Asia is highly active in the sector and expected to have a significant impact on the train battery market in Europe.

Earlier forecasts projected strong growth for lithium-based systems and moderate growth for Nickel-Cadmium and lead technologies. Given current market developments, an updated outlook beyond 2025 is required, reflecting accelerated lithium adoption in traction and increasing evaluation of lithium in auxiliary applications.

. Railway is major application for NiCd (alongside aviation and back-up) estimated up to +20% of total Global market to reach 0.8 to 1.2 GWh by 2035. Lead and advanced lead batteries, with increased cycle and service life and low temperature tolerance, will be the main technologies for commuter trains in 2025 with a market share of more than 35%. Lead, both flooded and sealed, may be the dominant technology, but nickel and lithium (LTO mainly) also have a significant share of the market.

In Conclusion

The development trends for on-board traction units favour lithium. For the **hybridisation and electrification of rail power traction**, mainly for commuter and metro trains, the requisite high energy, power density and cyclability is clearly an advantage for lithium batteries, which also ensure maintenance-free and longer lifetime operations. **To power auxiliary functions**, Nickel-based batteries remain widely deployed in existing high-

speed and metro fleets, particularly where robust performance under demanding operating conditions is required.

Nevertheless, the auxiliary segment – being the largest application category – shows increasing technological diversification. VRLA systems currently account for a substantial share, while lithium-ion is projected to experience the fastest growth.

As a result, new rolling stock platforms increasingly evaluate multiple chemistries, with lithium and advanced lead technologies gaining consideration alongside nickel-based solutions.

At the same time, lithium-ion technology is projected to witness the fastest growth across the market. New rolling stock platforms – particularly metros, EMUs and high-speed trains – are increasingly evaluating lithium-based and advanced lead solutions for auxiliary systems where weight reduction, lifecycle cost and maintenance-free operation are critical decision criteria. Therefore, NiCd should not be described as universally “preferred,” but rather as one of several established technologies in a transitioning auxiliary segment.

Regulatory developments and recycling infrastructure should be considered when assessing long-term technology positioning. In several EU countries, Nickel-Cadmium recycling requires cross-border transport, increasing cost and complexity. Environmental regulation and ESG-driven

procurement policies are expected to influence future technology choices in railway applications.

In railway applications, traction is structurally shifting toward lithium-based systems driven by electrification and hybridisation of regional lines. Auxiliary and infrastructure applications remain multi-technology segments where lead-based systems continue to play a major role. Nickel-Cadmium is increasingly limited to legacy fleets, specific regional markets and niche operating conditions, while lithium is gradually expanding beyond traction into selected auxiliary applications.

2.B.2. Batteries in Marine Applications

The transport sector contributes to almost a quarter of Europe's greenhouse gas (GHG) emissions and is the only major sector where emissions remain above 1990 levels.

Waterborne transport emissions represent around 13% of the overall EU greenhouse gas emissions from the transport sector. Under a business-as-usual scenario, these emissions could increase by up to 50% by 2050 relative to 2018 levels (Fourth IMO GHG Study, 2020).

In response, the 2023 IMO Revised GHG Strategy targets net-zero GHG emissions from international

Motive Power Railway Mainstream Battery Technology landscape by 2035

→ Traction applications:

- Exclusively Lithium-based LFP, NMC & LTO (niche)
- Sodium-ion RT: emerging / pilot

→ Auxiliary services (back-up and low-voltage onboard – not propulsion):

- Pb-based, NiCd and Li-ion on same page
- Sodium-ion RT: early niche / pilot



EUROBAT best estimates derived from market intelligence and industry projections, including Mordor and PWConsulting as well as other leading industry sources.

shipping by or around 2050. At EU level, maritime transport has been included in the EU Emissions Trading System since January 2024, and the FuelEU Maritime Regulation has been in full application since 1 January 2025, requiring a progressive reduction of the GHG intensity of marine fuels.

Batteries are key enablers for the transformation of maritime fleets in oceans, seas and inland waters, as recognised by the Strategic Research Agenda of the Zero Emissions Waterborne Transport partnership. According to the Maritime Battery Forum Ship Register (April 2026), over 1,800 battery-electric and hybrid vessels are registered in international service, with more than 1,300 in active operation and a total installed capacity of nearly 1.9 GWh. This excludes significant domestic fleets, notably in China, placing the global total well above 2,000 vessels.

The large majority (83%) operate in hybrid configurations, with less than 20% as fully electric vessels – demonstrating that maritime battery propulsion has moved beyond the pilot stage into commercial-scale deployment. At the same time, the energy needs of the global fleet are complex, as vessels often operate remotely from a home port for extended periods, requiring solutions tailored to a wide range of operational profiles.

- Fully electric smaller vessels (pleasure craft, inland waterways): canal, river and lake boats, typically integrated into fleets with onshore charging infrastructure-voltage (48V/60V) Li-ion propulsion batteries
- Fully electric and battery-hybrid ships – power applications typically offshore support vessels, tugs, DP vessels, ferries etc., with power-optimized batteries up to several hundreds of MWh
- Fully electric and battery-hybrid ships – energy applications typically ferries, cruise ships, short-sea vessels, workboats etc. Energy-optimized batteries up to several hundreds of MWh
- Other batteries in marine on-board and port infrastructure applications

The challenge for a large-scale adoption and implementation of batteries for waterborne transport remains the high cost of battery systems and cells, though costs continue to decline as the market matures.

There is an urgent need to electrify all forms of waterborne transport to support the wider aims of reducing global CO₂ emissions. One particular concern is the longevity of the marine fleet, so battery solutions need to be suitable for retrofit as well as for newbuild vessels.

Lithium-ion, due to their higher energy densities and cycle life, are the established technology for maritime propulsion applications, while lead batteries remain more suitable for on-board auxiliary services, to ensure the on-board safety and security functions and to crank the diesel engines.

For larger vessels, various degrees of hybridisation are in commercial operation, combining battery energy storage with thermal engines or alternative-fuel powertrains. Typical operating modes include: diesel-electric configurations where generators charge batteries to power electric propulsion motors; hybrid load-levelling, where battery systems supplement engine power during high-demand periods to reduce fuel consumption and emissions; zero-emission port entry, operating on battery power alone during manoeuvring and berthing; and peak-shaving, where batteries absorb transient load spikes to allow optimised engine loading.

For the propulsion of smaller vessels, other hybrid electric systems are developed, 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.

The wide range of maritime applications – from high-power peak-shaving on DP vessels to high-energy full-electric ferry operation – requires

battery systems specifically optimized for their respective duty cycles, making cell selection, thermal management and system integration critical differentiators. This is particularly relevant for deep-sea and offshore operations, where vessels operate remotely for extended periods and energy self-sufficiency is essential. Continued improvements in gravimetric and volumetric energy density remain a key innovation priority for these segments.

For inland waterways and river operations, the shorter distances and predictable routes create favourable conditions for shoreside charging infrastructure and swappable battery systems, significantly lowering the barrier to full electrification. Collaborative development partnerships will play an important role in scaling these solutions.

Fully Electric smaller Boats (pleasure craft)

Application Segment

Smaller battery electric boats, such as canal, river and lake vessels, are boats propelled by mechanical systems consisting of an electric motor turning a propeller to reduce noise and operate with zero emissions. Battery electric boats are often integrated into a fleet of vessels with an onshore charging infrastructure in place.

Mainstream Battery Technologies and Key Performance Indicators

In the pleasure craft segment, low-voltage (48V/60V) systems are common. While lead-acid (flooded and sealed) has historically been used, lithium-ion – particularly LFP – is rapidly becoming the dominant technology for propulsion due to its superior energy density, cycle life and weight advantages.

The market for small electric propelled vessels will increase considerably to meet demand. Due to high safety requirements for on-board use – including ventilation, vibration resistance and inclination tolerance – lithium-ion (LFP and NMC) is increasingly preferred. Lead batteries retain a role in auxiliary and SLI applications but are being displaced in propulsion by LFP, which

offers a favourable safety without the ventilation requirements of flooded lead-acid.

Key performance indicators for innovation are energy and power density, energy throughput, charge acceptance, operational temperature range and recycling rate. Apart from R&D, further battery standardization is an opportunity to increase reliability and safety, as well as to reduce the total cost of ownership.

Fully Electric and Battery-Hybrid Ships

Application Segment

Offshore ship applications with power or energy batteries with capacities from 100 kWh to several hundreds MWh

Mainstream Battery Technologies and Key Performance Indicators

The key performance indicators for such typical power batteries and targets by 2030 are listed in the ETIP Batteries Europe Strategic and Innovation Research Agenda and are listed in Table 3 (page 40).

Lithium-ion is the established technology for this segment. The dominant cell chemistries are LFP, NMC, and LTO for high-power applications requiring very high cycle life and fast charging (Maritime Battery Forum, April 2026). The choice between power-optimized (high C-rate, e.g. peak-shaving, spinning reserve, short stopover charging) and energy-optimized (high energy throughput, e.g. full-electric ferry operation) battery configurations depend on the vessel's operational profile. The key performance indicators and targets by 2030 are listed in the ETIP Batteries Europe Strategic and Innovation Research Agenda and are listed in Table 4 (page 41).

This segment includes 12V SLI and dual-purpose batteries, on-board standby and auxiliary power (UPS, emergency systems), and high-performance batteries for personal watercraft. Lead-acid remains present in SLI and cranking applications, while lithium-ion is increasingly adopted for auxiliary and hotel load applications.

In Conclusion – Market Outlook

With well over 2,000 battery-electric and hybrid vessels in operation worldwide – over 1,800 in international service alone (Maritime Battery Forum, April 2026) – maritime battery propulsion has reached commercial maturity. The large majority (83%) operate in hybrid or plug-in hybrid configurations, with 16% as fully electric vessels. The regulatory framework – EU ETS for maritime (since January 2024), FuelEU Maritime (since January 2025) and the IMO net-zero target for 2050 – is creating sustained demand across all vessel segments.

For propulsion, lithium-ion is the established technology. LFP accounts for 62% of maritime type approvals, NMC for 26%, with LTO serving high-power niches requiring very high cycle life. The commercial market is clearly in the high-voltage segment (400V–1000V+), serving ferries, offshore support vessels, tugs, workboats and deep-sea hybrid applications including peak-shaving, spinning reserve, zero-emission port entry and cold ironing. For smaller pleasure craft, low-voltage (48V/60V) Li-ion systems are used. Lead batteries retain a stable but limited role in auxiliary, SLI and engine cranking applications.

Table 3: KPIs for typical power batteries – targets by 2030⁴

Waterborne transport: battery electric or hybrid electric ship with power battery (offshore vessel, drilling vessel, hybrid fuel cell, ...) Typical battery size: 100 kWh – several hundreds of MWh						
KPI	Operating conditions	Description	System/ Pack/Cell level	Unit	2020	2030
PERFORMANCE						
Cell/ESU weight ratio		Full ESU (including rack, gas exhaust system, BTMS, BMS)	Energy storage Unit (ESU)	%	60	70
Cell/ESU volume ratio		Full ESU (including rack, gas exhaust system, BTMS, BMS)	ESU	%	30	60
Operating lifetime expectation		10 years of operation	ESU	hours	~50,000-80,000h	<ship lifetime>
Volumetric energy density	1C charge and 3C discharge, 25°C		Cell	Wh/L	200	400-500
Gravimetric energy density (Wh/kg)	1C charge and 3C discharge, 25°C		Cell	Wh/kg	~100	200
Cycle life (number of cycles)	70% DOD, 25°C, 1C charge and discharge		Cell	cycles	25,000-50,000	>80,000
Hazard level		EUCAR cell-level safety performance	Cell		<= 5	<= 2
COST						
Cost			ESU	€/kWh	300	150
Cost		Full ESU (including rack, gas exhaust system, BTMS, BMS)	ESU	€/kWh	1300	600-700
MARKET						
Typical market size		Source: Fincantieri, Saft internal studies		GWh/an	~0	~2.5

Motive Power Marine Mainstream Battery Technology by 2035

- Propulsion of large- & medium-scale ships (ferry's, cruises, other off-shore...):
 - 100% Li-ion: LFP mainly, also NMC & LTO, Na-ion RT only pilots in niches
- 48V propulsion smaller vessels batteries: lead and lithium both dominate with Sodium penetration
- Auxiliary: lead-based, NiCd for niches, lithium also penetrating



Propulsion HEV/BEV
Large- & medium-scale ships



Propulsion BEV
Small vessels 48V



On-Board & Infrastructure Auxiliary

Reflects EUROBAT best estimates derived from Marine Battery Forum, DNV, IEA, BNEF, and other industry analysis.

Table 4: KPIs for typical energy batteries – targets by 2030⁴

Waterborne transport: battery electric or hybrid electric ship with energy battery (cruise, ship, ferry, ...) Typical battery size: 500 kWh - several hundreds of MWh						
KPI	Operating conditions	Description	System/ Pack/Cell level	Unit	2020	2030
PERFORMANCE						
Cell/ESU weight ratio		Full ESU (including rack, gas exhaust system, BTMS, BMS)	Energy storage Unit (ESU)	%	60	70
Cell/ESU volume ratio		Full ESU (including rack, gas exhaust system, BTMS, BMS)	ESU	%	30	60
Operating lifetime expectation		10 years of operation	ESU	hours	~50,000-80,000h <ship lifetime>	
Volumetric energy density	1C charge and 3C discharge, 25°C		Cell	Wh/L	400-500	800-1,000
Gravimetric energy density (Wh/kg)	1C charge and 3C discharge, 25°C		Cell	Wh/kg	~180	350
Cycle life (number of cycles)	70% DOD, 25°C, 1C charge and discharge		Cell	cycles	5,000-8,000	>10,000
Hazard level		EUCAR cell-level safety performance	Cell		<= 5	<= 2
COST						
Cost			ESU	€/kWh	150	75
Cost		Full ESU (including rack, gas exhaust system, BTMS, BMS)	ESU	€/kWh	600-700	250-300
MARKET						
Typical market size				GWh/an	~0.2	~4

In Conclusion – Innovation Priorities

Key performance indicators for large-scale adoption of maritime battery systems are gravimetric and volumetric energy density, cycle life, charge acceptance, operational temperature range and recyclability. For power-intensive applications (peak-shaving, spinning reserve, blackout safety), C-rate capability and calendar life are critical; for energy-intensive applications (full-electric ferry operation, hotel load), energy throughput and system-level energy density are the primary differentiators.

Further standardization of battery systems, interfaces and safety requirements represents a significant opportunity to reduce total cost of ownership, improve interoperability and accelerate market adoption across the maritime sector.

2.B.3. Batteries in Aviation Applications

The International Energy Agency (IEA) highlights the growing role of battery storage in decentralised electricity systems, including mini-grids and stand-alone solar systems, particularly in emerging market and developing economies. Battery-supported renewable systems can provide a cost-effective solution for electrifying remote and underserved areas where conventional grid extension is technically or economically challenging. Looking towards 2035, the IEA projects that continued deployment of grid extensions, mini-grids and stand-alone systems will be critical to achieving universal electricity access.⁵ In recent years, electric aircraft have gained increasing attention in the context of the EU Emissions Trading System (EU ETS) and broader European climate targets. However, despite significant technological progress, the current energy density of batteries still limits the full electrification of commercial aircraft propulsion systems.

As an intermediate step toward reducing greenhouse gas emissions in aviation, hybrid-electric propulsion concepts and the emergence of eVTOLs (electric Vertical Take-off and Landing aircraft) are attracting strong industrial and research interest. In Europe, the Clean Aviation

Joint Undertaking, in coordination with the Batt4EU partnership, is supporting the development of advanced battery technologies and related R&D topics to address the stringent performance, safety, and sustainability requirements of next-generation aviation systems.

Application Profile

The aviation battery market can be split into two very different segments:

- 1. High-energy traction batteries** for eVTOLs and hybrid/electric aircraft propulsion
- 2. Auxiliary and starting batteries** for conventional aircraft systems (APU start, emergency power, avionics backup, engine start)

The technology mix will differ strongly between these segments because the performance requirements are fundamentally different.

High-Energy Traction Batteries

Today, electric propulsion in aviation is primarily applied in auxiliary systems on larger aircraft and in smaller electric aircraft, including electric vertical take-off and landing (eVTOL) vehicles. These smaller electric aircraft hold promise for urban air mobility, such as air taxis, aerial ambulances, and cargo drones, typically designed for up to seven passengers or similar cargo capacity. However, eVTOL technologies are still in early development stages with challenges including infrastructure, regulatory frameworks, and technical limitations.

Battery technology, particularly lithium-based batteries, is currently the leading choice for powering these electric aircraft due to their energy storage capabilities. Yet, the energy density of existing batteries is a significant constraint for larger commercial aircraft, where battery weight can be about 30 times that of traditional jet fuel, despite electric engines being more efficient. This makes full electrification of large commercial planes dependent on breakthroughs in battery technology, which several companies are actively pursuing.

Performance requirements for batteries in eVTOL aircraft differ from those in ground electric vehicles. Factors such as the specific use case, aircraft design, availability of heliports and charging

infrastructure, and stringent safety regulations will shape battery development priorities in this sector. Discussions are ongoing to define the necessary battery characteristics that will make practical electric flight sustainable and commercially viable.

In summary, electric aviation shows great potential but requires continued innovation in battery technology, infrastructure, and regulatory support before it can fulfill its promise on a larger scale.

Auxiliary and Starting Batteries

Auxiliary batteries for small aircraft and commercial airliners are more conservative market because certification, reliability and cost dominate over energy density. Typical applications include engine/APU start, emergency back-up power, avionics backup, essential bus support and ground operation activity.

Key Performance Indicators and Future Battery Technologies

High-Energy Traction Batteries:

As conventional Li-ion batteries, using insertion-based positive electrodes active materials and graphite-based negative electrodes are reaching their performance limit, it will be necessary to develop batteries with higher energy and power densities, as well as a longer lifespan. Pursuing batteries with higher energy densities invariably leads to novel active materials, such as metallic lithium and silicon, and to the development of new electrolytes, which will be key to enable these new battery chemistries.

There is a range of different electrolyte chemistries currently under development, using both liquid and solid electrolytes. High concentration, “solvent-in-salt”, or “localized high-concentration electrolytes” are considered as promising to enable a new generation of active materials. So called “semi-solid” and “solid-state” are also considered as promising candidates to be used in these very high cell energy configurations. Potential advantages for this technology are:

- Use of new active materials enabling higher energy densities on the cell level
- Higher safety through a lowered risk of fire or gas formation

- Better thermal properties for higher energy density and lower cost on a pack level.

However, these beneficial properties have yet to be demonstrated for cells manufactured at scale and tested in a controlled environment, under standardized conditions, and in compliance with standards and regulations. Moreover, the situation is even more complex, considering that “solid-state battery” is not used to identify a specific product or technology but rather a whole class of energy storage systems, and very often batteries based on liquid electrolytes are actually categorized as “solid”.

Ultimately, cost, processability, cell lifetime and energy density need to be balanced without compromising safety. These key performance indicators, regardless of the electrolyte, negative and positive electrode chemistries, must meet the requirements of the target sector (e.g., eVTOL). For example, the use of some all-solid-state battery technologies in aviation seems challenging, as they are currently affected by poor rate capability and/or short cyclic lifespan. The undesired rate capability can originate from the low bulk ionic conductivity of some solid electrolyte, or from the poor wettability in the solid-to-solid interface (sluggish interfacial kinetics). As for the short cyclic lifespan, besides electrochemical reasons such as short circuit, mechanical stress will be generated at the electrode level upon charge and discharge, which can lead to loss of physical contact during cycling.

Novel electrolyte materials and cell designs are still required. These electrolytes should ideally possess wide electrochemical and thermal stability windows, high ionic conductivity, improved mechanical properties, higher interfacial compatibility, including good wettability and stability. This could lead to improved rate capability, high-stability, cost-effectiveness, and higher manufacturing yields. This will require focusing on electrolytes which have a low lithium intensity (KgLi/kWh battery pack) and no rare elements. Besides, attention should be paid to a more stable and reliable lithium metal batteries through developing new liquid electrolytes with better lithium stripping/plating behaviour and more sophisticated battery management and safety forewarning systems.

Europe's Clean Aviation Joint Undertaking, in coordination with the Batt4EU partnership, is supporting the development of advanced battery technologies to enable lower-emission aviation and meet the requirements of future hybrid-electric and electric aircraft.

Auxiliary and starting batteries

As 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 VRLA batteries to crank the piston or turbine engine powered aircraft, while commercial and corporate aircraft use nickel-cadmium (NiCd) batteries thanks to a **high cycling capacity that ensures long life** and reduced maintenance and low weight and size. Lithium is increasingly competitive with such auxiliary batteries and is increasing its market share

Top five KPI indicators are (1) safety / thermal runaway resistance, (2) reliability / certification maturity, (3) operating temperature capability, (4) specific power and (5) specific energy (for weight reduction).

Unlike automotive batteries, aviation auxiliary systems do not optimize primarily for cost or maximum range. It is more the safety and certification that dominate the technology selection. Important standards include RTCA DO-311A, EUROCAE ED-14 / DO-160 and EASA special conditions. This is also one of the reasons why lead-based (AGM/VRLA) and NiCd remain very attractive and will continue to play a key role in aviation also after 2035.

In Conclusion – Battery Markets & Innovation Potentials

Global battery demand for the aviation industry is estimated at **~320/330 GWh by 2035**, with **High-energy traction batteries** for eVTOLs and hybrid/electric aircraft propulsion to take big amount of ~300 GWh and **Auxiliary and starting batteries** for conventional aircraft systems (APU start, emergency power, avionics backup, engine start) estimated at **~30 GWh**.

High-energy eVTOL propulsion

Short-range VTOL 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 the making. Moreover, the development of high-performance energy storage technologies for eVTOL will further boost other battery markets. Apart from reducing fuel burn and related carbon emissions, other market drivers are noise reduction and a significant improvement in competitiveness with other mobility types.

Electric aviation propulsion, however, will have more stringent performance requirements for batteries, particularly higher specific energies, which, depending on the application, can be comprised between 500-2000 Wh/kg at the battery system (pack) level, making Li-based batteries one promising electrochemical energy storage technology for this application. Achieving this performance, however, is far from trivial, if we consider that today's state-of-the-art commercial battery systems have energies comprised between 200-260 Wh/kg. To reach 500-2000Wh/kg, we target 2050. It will be necessary to develop new active and inactive materials as well as new pack designs. These high energy systems can pose additional, or even new safety risks, which need to be mitigated and evaluated accordingly (e.g., melting point at 180°C for lithium metal).

Engineering safe higher energy systems is intrinsically more complex, as higher energy per kilo or liter are stored and can be released in case of an incident or malfunction. This heat will need to be dissipated and could lead to quicker cell cascading failure. Most importantly, higher energy can lead to a more violent thermal runaway, exacerbated by the presence of metallic lithium and its melting. New safety measures will likely need to be introduced at both the chemical and at the system level.

At the chemistry level, academic and industrial researchers are currently focusing on new classes of electrolytes. These must enable high energy cell chemistries based on innovative positive and negative electrode active materials, such as

manganese-rich and high voltage materials at the positive electrode, and silicon-rich and lithium metal at the negative electrode. Several novel electrolyte materials are currently under research, including liquid and so called “semi-solid” to “all-solid” state (see technical annex for definitions).

The ultimate goal is to develop solid electrolyte materials with a wide electrochemical stability window, high ionic conductivity, good active material/electrolyte interfacial compatibility, low density and excellent mechanical property. These will need to be manufactured at scale as thin electrolyte layers, e.g., below 20 um, and integrated into cells and packs. Furthermore, there should be investigations into more stable and reliable lithium metal batteries, developing new liquid electrolytes. In parallel, more sophisticated battery management systems (BMS), thermal management systems (TMS), and better safety forewarning systems will also need to be developed.

Auxiliary and starting batteries

The innovation potential for aviation auxiliary batteries is actually quite significant, even though this market receives far less attention than electric propulsion.

Main drivers are increased electrification of actuators and control systems, electric taxiing support, distributed onboard electronics and advanced avionics (navigation, comms, flight control,

monitoring and further automation). This increases the onboard auxiliary power demand, the need for backup energy storage and battery redundancy requirements. The Clean Aviation Joint Undertaking roadmap strongly supports this transition.

Innovation opportunities are developing higher-power auxiliary packs, modular battery architectures and multifunctional onboard energy storage

R&D Application Area 3 – Stationary Energy Storage

The **Stationary Energy Storage Batteries** R&D area covers battery technologies and systems designed to store electrical energy for later use across a diverse range of stationary applications. The market can broadly be divided into several segments, each with distinct performance, reliability, lifetime and cost requirements.

→ UPS and telecommunications (TLC)

applications require highly reliable batteries capable of providing immediate backup power and maintaining continuity of critical services, with long service life and high availability being key priorities.

Motive Power Aviation Mainstream Battery Technology by 2035

→ Global propulsion battery market for eVTOL: exclusively Li-ion

- Solid-state – mainstream next-gen eVTOL propulsion: 45-65%
- NMC high-nickel – : Mature commercial eVTOL 25-40%
- Semi-solid-state – limited low-range applications 10-20%
- LFP – limited low-range applications <5%
- LiS & emerging chems – pilot niche long-range aviation: <5%



eVTOL Traction(100%)

→ Global auxiliary battery market for small aircrafts and commercial airliners:

- Li-ion, mainly LFP dominate in new systems
- Lead (AGM/VRLA) – legacy in small & commercial aviation fleet
- NiCd – Legacy commercial aircraft
- Na-Ion RT – to compete with all three other chemistries



55-60%



15-25%



10-20%



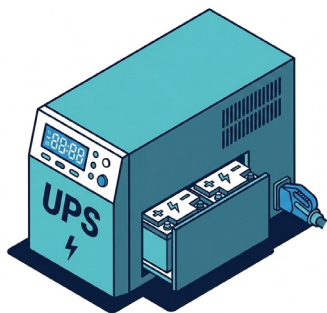
<10%

Auxiliary

EUROBAT best Estimates (GWh) derived from TrendForce, IEA, Clean Aviation JU, Mordor Intelligence, EASE/FAA and other trustworthy sources.

- **Residential and commercial energy storage**, generally referred to as **behind-the-meter (BTM) storage**, is primarily aimed at increasing self-consumption of renewable electricity, reducing energy costs and managing demand, while increasingly supporting flexibility and energy resilience.
- **Utility-scale, or in front-of-the-meter (FTM), storage** comprises larger systems connected to the electricity grid and is used for applications such as renewable energy integration, peak shaving, frequency regulation, load balancing and other grid services.
- Finally, **off-grid applications** provide reliable electricity where connection to the grid is unavailable, unreliable or economically impractical, including remote infrastructure, isolated communities and other decentralised energy systems.

Across these segments, R&D priorities focus on improving energy and power density, safety, efficiency, durability, charging performance, system integration and overall cost-effectiveness, while adapting battery technologies to the specific operational requirements of each market.



3.A. Batteries for Uninterrupted Power Supply (UPS Batteries)

When utility power fails, Uninterrupted Power Supply (UPS) ensures that critical equipment can safely shut down to protect the operation or continue until power comes back. There are various

applications, from small single computers to big data centres, Commercial and Industrial sites and power plants. There is a tendency to use energy storage devices for other purposes, for example UPS as reserve and peak load looping. Virtual power plants and big new data centres are further driving demand for UPS. UPS contributes to zero emission targets through longer bridging times, grid service (instead of building additional power plants) and in combination with renewable energy sources. However, many customers see an extended service, like grid service, as a risk that could jeopardize the main functionality of uninterrupted power supply.

Application Profile

Batteries for uninterrupted power supply (UPS) act when utility power fails in order to ensure that critical equipment can safely shut down to protect the operation. There are various applications from small single computers to big data centres, buildings and power plants. There is a tendency to use energy storage devices for other purposes, for example UPS as reserve and peak load looping. Virtual power plants and new big data centres are further driving the demand for UPS. UPS contributes to zero pollution targets through longer bridging times, grid stabilization (instead of building additional power plants) and in combination with renewable energy sources. Emerging application fields (AI data centre in particular), a UPS fulfils further the grid stabilization function (in case of power fluctuation in the grid).

The growth of the market is due to increased use of big data and the associated need for new data storage centres and implementation of distributed energy resources (DER). Another driver will be the growth of emerging economies, requiring significant UPS capacity, with Europe as a leading battery supplier.

Mainstream Battery Technologies and Key Performance Indicators

The dominant technologies used today are valve regulated lead acid batteries, mainly VRLA with absorbent glass mat technology (AGM), but also still VRLA gel and flooded, as well as nickel cadmium batteries (NiCd) for example in industrial Oil & Gas

industry applications. Li-ion batteries are also entering the market with lithium iron phosphate (LFP), lithium metal polymer (LMP) and nickel manganese cobalt (NMC) cathodes combined with carbon anodes. The technology target by 2030 is Lithium-Ion batteries with LFP and other technologies like Sodium-Ion-batteries.

Increasing the power density is particularly necessary because of the further electrification of critical loads, which require greater output from the battery. Also, as new UPS batteries should provide additional value, such as peak-shaving, time-shift self-consumption of renewable energy and grid service, 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 total cost of ownership for these applications through reduced climatization as one of the main cost drivers and thus the heat exposure to the batteries. The batteries must be able to cope with it. Climatization requirements depend on the different use cases of the batteries (level of endurance) and the thermal management and so the system designer of the UPS needs to take this into account.

Key performance indicators for this application, as typical back-up time in data centres is between 5 and 15 minutes, are energy and power densities, system cost, operating temperature range and reduced cooling. Increases in the power density are required because of the further electrification of critical loads, which require more output from the battery. This affects both lead and lithium technologies. The UPS stand-by application is expected to extend its usage beyond uninterruptible power in order to generate more value, for example UPS and peak-shaving and UPS as reserve power (UPSaaS). Thus, an additional key performance indicator for UPS with such multiple functions will be the energy throughput.

Another development is the connection of smaller UPS batteries in one network to form a larger UPS system or even to form a virtual power plant (VPP). This will become possible thanks to the development of 5G and artificial intelligence to allow distributed energy production, storage and

consumption. Such VPPs could include traditional commercial and industrial UPS batteries from data centres and base transceiver stations, but also batteries from EVs, forklifts, utility grid-scale and batteries behind-the-meter. Because of these innovations, it will be necessary to work on the charge acceptance of the batteries and their robustness to higher temperatures from faster charging, increased power density and reduced climatization.

The technology of choice for the user is not only related to the type of load but also to the climate (temperature robustness), quality of the grid and configuration of the UPS, as well as the energy throughput. Despite the emerging new requirements, there will still be pure stand-by applications with a demand for back-up power only and, of course, the requirements for these use cases are less demanding.

Cost and safety are and will remain key factors. While the cost of Li-ion batteries has already been reduced significantly in the last 15 years but is still more expensive than lead batteries there are still safety concerns for Li-ion. This is attributed to the potential risk of mistreatment by over-charge and discharge that could cause a thermal event that would release a high amount of energy in a short period of time causing a fire and release of hazardous gases. In order to prevent this, a battery management system (BMS) is a mandatory support item for Li-ion batteries. This is not required for lead batteries.

In addition to cost and safety, there will be a stronger focus on end-of-life management and, therefore, the recycling targets and content of recycled material in the battery will become more important.

This is part of the new EU Batteries Regulation. Due to its maturity, lead battery recycling processes have developed and improved over a long time and are nowadays highly efficient and economically valuable. It is possible to recycle a lead acid battery to 99%. The recycling of Li-ion batteries is more complex due to the different chemistries (LFP, NMC, LTO, organic electrolytes) and battery housings that

demand different physical and chemical treatments. This may lead to the preference for one Li based technology over another, based on cost of recycling

In summary, the six key performance indicators (KPIs) selected for the application are end-of-life management, design and cycle life, high temperature, power density and total cost of ownership (TCO).

R&I Scope and Strategic Actions

Lead batteries: Increase the volumetric power density to 200 W/l for short duration discharge, improve the charge acceptance to 40 A / 100 Ah, increase the cycle life at 40% DOD to >500 cycles, increase the calendar life on float at 20°C from 10 to 15+ years and float life at 40°C from 3 to 4 years, cost reduction to 150 \$/kWh.

Li-ion batteries: Increase the volumetric power density to 1,000 W/l for short duration discharge and increase the cycle life at 40% DOD to 8,000 cycles and higher.

Strategic actions for lead batteries: Increase the mass utilization, use corrosion resistant alloys and improve cycle life.

Strategic actions for Li-ion batteries: Development of new anode and cathode materials (NMC, silicon + graphite), cost reduction actions and improve the safety of products (LFP, aqueous electrolytes).

UPS applicable standards are IEC 60896-21 (LAB), IEC 62619-2017 (LIB) and IEC 62620-2014 (LIB).

Compliance with EU battery regulation 1542 will also drive strategic actions.

Battery Market

UPS is an established market in which lead-based batteries have been the dominant technology for decades and are expected to remain so by 2030. The European market demand was 2.4 GWh in 2022 and with cumulative annual growth of +6% to reach 3.6 GWh in 2030. The growth of this market is due to increased production and consumption of data caused by growing digitalization and the

associated need for new data storage centres, as well as the implementation of distributed energy resources (DER). Another driver will be the growth of emerging economies, requiring significant UPS capacity, with Europe as one of the leading battery suppliers.

Energy storage in a UPS application will be required in the upgrades to the utility infrastructure. This upgrade of the infrastructure is leading to longer required back up times and reduced maintenance while being required to fit with the existing, mature infrastructure. In some applications this grid support may require technology with multiple cycles leading to a hybrid standby and cycling requirements.

The dominant technologies used today are valve regulated lead acid batteries, mainly VRLA with absorbent glass mat technology (AGM), but also VRLA, gel and flooded, and li-ion batteries, while nickel-cadmium (NiCd) has a minor share.

Estimated lead battery demand for UPS will increase by 3% from 2025 to 2030 reaching 49 GWh, globally. The expected annual growth rate for lead and lithium is 1.6% and 12% (in value), respectively. Lithium penetration will increase to 30% in 2030 depending on further cost reduction, safety issues and regulatory implications. The extra cost related to Li-ion and potential safety concerns currently limit Li-ion to niche markets for now, such as military and data centres.³

The demand for lead acid UPS batteries is dominated by the Indian market, where annual sales go up to approx. 25 GWh/year in 2030.²

In Conclusion

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 total cost of ownership (TOC) 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 in data centres 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.** As energy requirements increase, the back-up time requirements will move to below 5 minutes to compensate for the increased energy requirements.

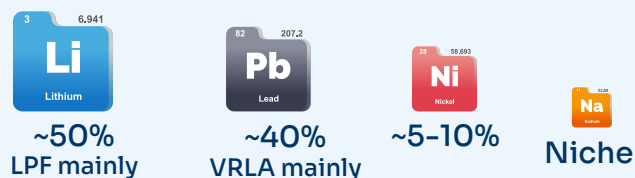
Other developments are the connection of UPS batteries in a single network to form a larger UPS system or virtual power plant (VPP). This will become possible thanks to 5G and artificial intelligence to allow distributed energy production, storage and consumption.

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 the different chemistries and battery housings that demand different physical and chemical treatments.

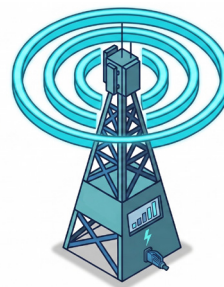
Stationary Energy Storage UPS Mainstream Battery Technology landscape by 2035

→ European market – expected to remain a mixed-technology landscape

- Lead - technology to maintain market (VRLA mainly)
- Li-ion - to take the considerable growth of the market with mainly LFP, also LMP and NMC
- Sodium-RT likely favorable to take part in this market
- NiCd - minor share to serve niches



EUROBAT best estimates derived from market intelligence and industry projections, including BloombergNEF, S&P Global, McKinsey, IEA, IDTechEx, and other leading industry sources.



3.B. Batteries for Telecommunication (TLC Batteries)

A telecom unit is an information and communication technology or telecom site with critical loads. The main applications are Base-Transceiver-Stations (BTS), Outside Plant and Cable Broadband, Central Office and Small Cells.

In case of unavailability or insufficiency of the main power source, telecom batteries provide instant and continued 48 DC voltage 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. In contrast to UPS batteries, telecom batteries serve only telecom applications, connected to the 48V DC electricity supply net.

There are telecom towers in regions with poor grid stability or in locations without grid connectivity at all but in combination 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.

Application profile

Classical Telecom batteries are cells, blocks or modules connected to form a 48V direct current (DC) energy storage system able to supply electricity to an information and communication technology or telecom site when the main power source is unavailable or insufficient. 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 DC voltage 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.

Despite this classical use case, there are more and more off-grid telecom towers combined with renewable energy sources or other hybrid systems, especially in emerging countries with a lack of grids or in remote areas. In these cases, the batteries provide electricity when the energy from renewable sources is not sufficient or not available, for example from solar panels during the night.

The transfer to Virtual Power Plants (VPP) is also demanding a higher energy throughput from the batteries involved and the profile is changing from a floating to a cycling application, very often at partial state of charge (PSOC). Due to a variety of different and new applications (any form of grid stabilization, especially fast frequency response FFR) and the difference in geographical fluctuations of power outages, the battery performance has to meet these customer requirements. This means, for example, that a battery in a pure stand-by function has a significantly lower energy throughput in areas with very stable grids than in areas with very unstable grids. Customer can select the most appropriate solution for their application and consider a valuable ratio between costs and benefits.

Mainstream battery technologies and key performance indicators

The dominant technology used today is the valve regulated lead acid battery (VRLA) with absorbent glass mat technology (AGM) for reliable grids and VRLA with gelled electrolyte (GEL) in poor or off-grid areas. Despite this, Lithium technology penetration is progressing. Due to cost and safety reasons, the predominant Lithium technology is Lithium Iron Phosphate (LFP)

The main features of batteries for telecom applications are energy and power density, energy throughput and hot temperature robustness. Otherwise, safety, TCO and end-of-life management are also key aspects.

While lead batteries are intrinsically safe and very robust against abuse without a Battery Management System (BMS), a BMS is required to run a Li-ion batteries in order to prevent damages caused by over-discharge or over-charge. In terms of product cost lead batteries are the most attractive solution and will remain the cheapest solution in 2030. However, the price decrease for lithium batteries will continue and the gap between lead and lithium will become smaller. This will also depend on the future electrode chemistry of lithium batteries and the availability of required raw materials like cobalt, manganese and nickel.

Important aspects of end-of-life management are product collection, recycling and circularity. The collection rate for the different battery technologies is very similar and already on a very high level. With respect to recycling, lead batteries are amongst the products with the highest recycling efficiency worldwide. Recycling processes are established and recycling plants are well distributed.

Recycling of lithium batteries is not yet mature and the recycling efficiency and economy needs to be developed. Due to the usage of different electrode chemistries like LFP and NMC, different recycling processes are required because of the different chemical behaviour. The new Batteries Regulation is putting a strong emphasis on circularity and demands that batteries must contain recycled materials by 2030, with a target of 85% for Lead and 4% for lithium. Additionally, the use of large number of different electronic components from a multitude of manufacturers creates strong challenges for recyclability and circularity.

Description of the R&I scope and strategic actions

The main drivers in this application are the extension of Wi-Fi and the strong network expansion in China, India, eastern Europe and South America, as well as the introduction of 5G. Further actions to reduce the cost of diesel consumption and emissions, especially in countries and areas with unstable grids, will have the consequence of a higher energy throughput for the battery. One of the main drivers for OPEX reduction is the downsizing

or elimination of air conditioning that will expose the battery to higher environmental temperatures.

Lead batteries: In order to be able to meet new market needs (linked for example to 5G), an increase of gravimetric energy density at system level to 40 Wh/kg is to be expected, together with an increased volumetric power density, always at system level, to 30 W/l for medium-long duration discharge. Cycle life performances should be increased to 2,000 cycles at 40% DOD and an extended battery life to 5 years at 40°C or up to 20 years at 20°C in order 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 utilisation, the use of corrosion resistant alloys, improved cycle life, more maintenance free or reduced maintenance solutions and further cost reduction initiatives like increased content of secondary raw materials and a higher level of production automation.

Li-ion batteries: An increase in the gravimetric energy density at system level to 350 Wh/kg linked to an increased volumetric power density to 100 W/l for medium-long duration discharge is to be expected, together with an increase in cycle life at 40% DOD to 8,000 cycles in order 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 (LFP, aqueous electrolytes).

Battery market

The European market demand is expected to grow to 3 GWh in 2030 (6.7% annual growth in volume). Lead batteries are expected to grow of 2% from 2025 to 2030 reaching 20 GWh globally². In this scenario, lead will remain the dominant technology, but the lithium market share will grow to 27% globally³. This is because lithium is 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 rapid rollout of new Wi-Fi networks, particularly the shift

to 4G to 5G which a need for a denser network of towers². In stable grid countries main drivers are also extended usage, for example UPS as-a-Reserve, Grid Service and distributed energy resources (DER)/VPP to form a platform which helps mostly distribution system operators (DSOs) manage their grids that are mainly based on distributed energy sources (= DERMS or distributed energy resources management system)

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

In conclusion

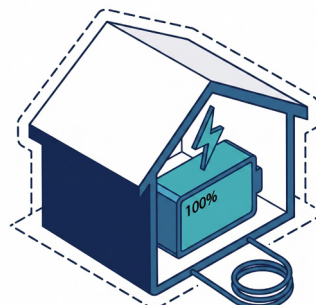
The main features of batteries for telecom applications are energy and power density, energy throughput and hot temperature robustness. In addition, safety, cost and end-of-life management are key aspects. For the end-of-life management, product collection, recycling and circularity are key. With respect 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 mature and the recycling efficiency and economy needs to be further developed. Due to the usage of different electrode chemistries, different recycling processes are required. The new Battery Regulation will put strong pressure on circularity and demands that batteries must contain recycled materials. The target is 85% for lead and 6% for lithium by 2031.

The main targets for lead-based batteries are an increase in the gravimetric and volumetric energy density at system level, while increasing the cycle life performance at different DODs 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 utilisation, 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. Additional aspects will be remote battery monitoring and management, more relevant in remote and off-grid locations.

For Li-ion battery technologies, an increase in the gravimetric energy density at system level, together with an increase in cycle life at different DODs, 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 (NMC, Silicon Graphite), cost reduction actions and an improvement in the safety of products (LFP, aqueous electrolytes).

3.C. Batteries for Residential & Commercial Storage (BTM Batteries)



Stationary Energy Storage Telecom Mainstream Battery Technology landscape by 2035

→ European market – expected to remain a mixed technology landscape

- Lead – technology retains a significant installed base to be maintained
 - In reliable grid: VRLA with absorbent glass mat (AGM)
 - In poor or off-grid: VRLA with gelled electrolyte (GEL)
- Li-ion – mainly with LFP and NMC to take market share
- Sodium-ion RT likely favorable for some niches
- NiCd – minor share to serve niches



~50%



~50%



Niche



Niche

EUROBAT best estimates derived from market intelligence and industry projections, including BloombergNEF, S&P Global, McKinsey, IEA, IDTechEx, and other leading industry sources.

Application Overview

Battery Energy Storage Systems (BESS) have become a cornerstone of modern energy infrastructure, enabling greater flexibility, resilience, and efficiency across both residential and commercial & industrial (C&I) sectors. While the underlying technology is similar, the functional priorities and value propositions differ significantly between these two domains, driven by distinct consumption patterns, economic incentives, and operational requirements.

Across all applications, BESS systems deliver a common set of core capabilities:

- Energy shifting (time arbitrage). Store energy when cheap/abundant and discharge when expensive/scarc.
- Power quality & stability. Voltage/frequency support, smoothing fluctuations.
- Backup power / resilience. Supply during outages or grid instability, e.g. UPS functionality.
- Grid interaction optimization. Reduce grid dependency or provide services to the grid

In residential settings, most paired with rooftop photovoltaic (PV) systems, the BESS is primarily oriented toward maximizing energy autonomy and reducing electricity bills.

Self-Consumption Optimization. Homeowners store excess solar generation during the day and use it during evening hours when consumption peaks.

This is especially valuable in markets with low feed-in tariffs, where exporting energy to the grid is less financially attractive.

Backup Power and Resilience. Residential batteries provide backup for essential loads such as lighting, refrigeration, and communication devices. As grid reliability concerns increase, this function is becoming a key driver of adoption.

Time-of-Use (ToU) Optimization or Dynamic Pricing. BESS enables households to charge during off-peak tariff periods and discharge during peak pricing, directly lowering electricity costs.

Limited Peak Load Management. While less pronounced than in industrial settings, batteries can help avoid higher tariff tiers triggered by peak consumption.

Energy Independence and Prosumer Participation. BESS supports the transition from passive consumers to active prosumers, enabling participation in emerging models such as virtual

power plants (VPPs), where aggregated residential systems provide grid services.

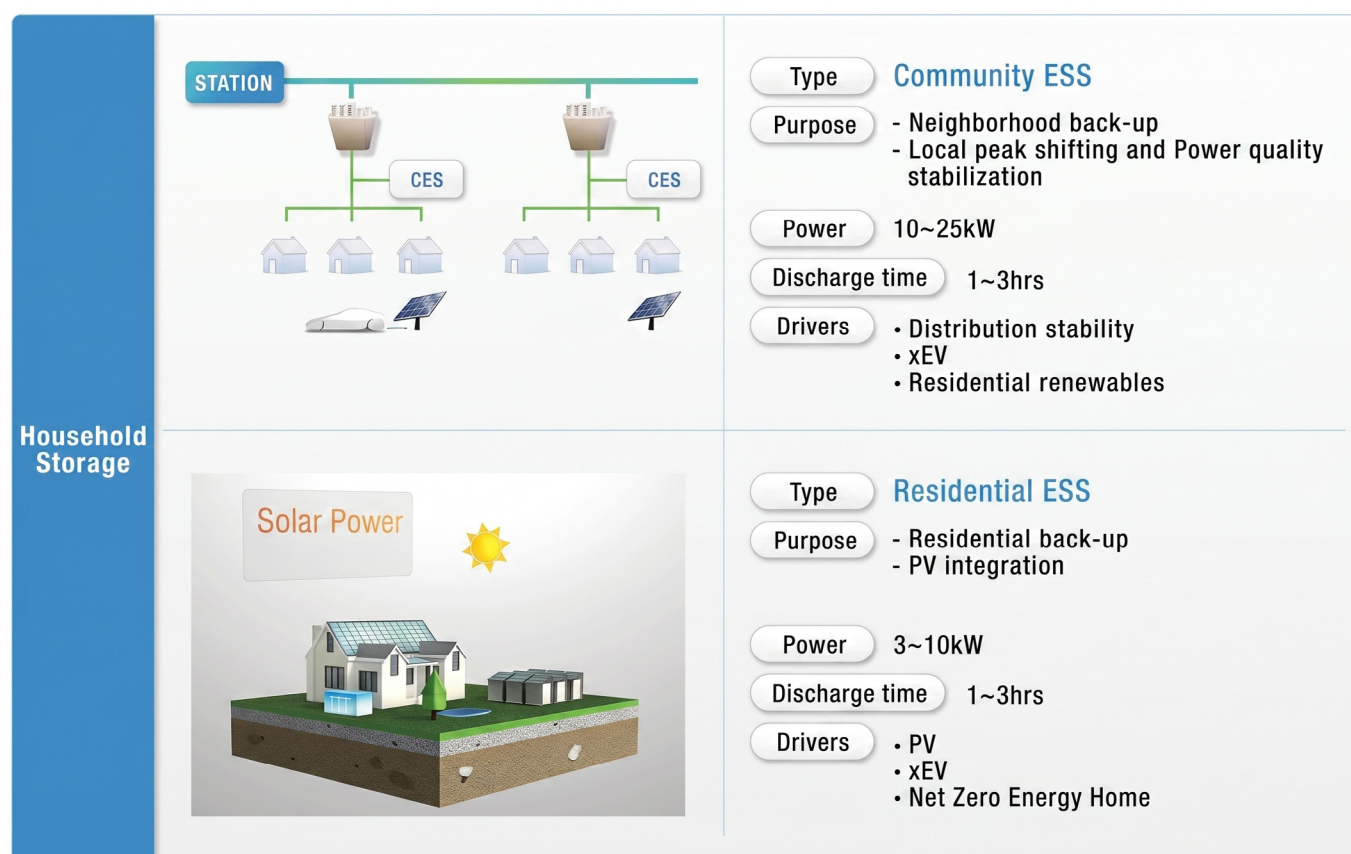
In C&I environments, BESS is deployed as a strategic asset for cost reduction, operational continuity, and revenue generation. These systems are typically larger, more complex, and integrated into broader energy management frameworks.

Peak Demand Charge Reduction. This is often the primary financial drive. Utilities frequently charge businesses based on their maximum power demand (kW). BESS reduces these peaks, significantly lowering electricity bills and improving overall energy cost structure.

Advanced Energy Arbitrage. Unlike residential use cases, C&I arbitrage involves sophisticated optimization strategies that account for dynamic pricing, load forecasting, and operational schedules.

Backup Power and Business Continuity. For industrial operations, downtime can be extremely costly. BESS ensures continuity for critical

Figure 7: Residential and Community Household Energy storage profiles (Energys)



processes, reducing the risk of production losses, data corruption, or service interruptions.

Power Quality and Reliability. Sensitive equipment in manufacturing, logistics, and data centres require stable power conditions. BESS mitigates voltage sags, frequency deviations, and other disturbances that can impact performance or damage equipment.

Renewable Energy Integration. BESS enables higher penetration of on-site renewable generation by smoothing intermittency and aligning production with demand.

Grid Services and Revenue Stacking. In many markets, C&I systems can generate additional revenue by participating in frequency regulation markets, demand response programs, capacity mechanisms, and ancillary service provision. This multi-stream monetization significantly enhances project economics.

Operational Load Shifting. BESS can align energy usage with operational needs, supporting high-load periods in warehouses or coordinating with EV fleet charging schedules.

Mainstream Battery Technologies and Key Performance Indicators

Both lead and lithium-based technologies can support the requirements in this market, each with their own features and characteristics. Inevitably, there is a trade-off between technology capability and cost, which is tied to the market conditions for cost / kWh of grid supplied energy. This can be very country specific and homeowners need to evaluate a number of factors including purchase cost, cost per delivered kWh (from the storage system) and payback time linked to financial incentives, i.e. subsidies vs feed-in tariff rates (FIT), to determine the economic viability to invest in such systems.

Lithium-based storage solutions currently dominate in this market space. Lithium-based solutions have an advantage regarding space, weight and cyclic performance, but safety is a consideration to be further improved for in-house storage applications. For lead batteries, bipolar technology can increase the energy density and advanced chemistries,

such as carbon loaded negative designs, can improve cyclic performance and energy throughput, particularly in partial state of charge (PSoC) operation. One soft aspect to consider for end users is the aesthetics of any battery system that is on offer. Batteries typically have attractive packaging that may be important where installations can be on prominent display.

By 2035, stationary battery technologies to be considered:

LFP: LFP chemistry is today the dominant technology for residential and commercial Energy Storage and will continue to drive the market to 2035.

Sodium Ion: Sodium Ion has lower energy density but with the simplicity of manufacturing and availability of the resources could become more and more popular in the coming year and could replace slowly LFP for this application.

Electric Vehicle battery by V2G and V2L: Vehicle to Grid (V2G) and Vehicle to Load (V2L) will also participate in residential and commercial Energy Storage, as a complementary battery for solar or renewable energy sources. By 2025 more and more vehicles will embed this capability to supply the grid or a load, so this can change the landscape of the Behind the Meter energy system.

2nd life battery pack: With the new EU battery directive for the recycling of Li-Ion, some battery packs from the automotive market, can be re-used in 2nd life applications, in a residential or commercial energy system. As these packs will no longer be suitable for EV use, since the autonomy will be too low, stationary battery applications make sense as a 2nd life for the automotive battery pack. Many car manufacturers as well as industrial mobility manufacturers are already studying this possibility.

Advanced EMS: As BESS adoption grows, the value is shifting from hardware to software-driven optimization. In both residential and especially C&I applications, integration with advanced Energy Management Systems (EMS) is becoming essential. Key enablers include AI-driven forecasting, real-time optimization algorithms and system integration that

coordinates BESS with PV systems, EV charging and other facility assets.

Battery Market

Lithium technologies are dominant in the market today and are expected to remain so. Lead batteries are less present, but R&D advancements to improve energy density and cyclic performance could make lead-based solutions a more attractive proposition.

Across all application sectors, it is anticipated that lead battery demand will remain relatively constant with lead-based technologies dominant in 12V automotive and stationary applications (UPS and telecom), whilst there are significant growth expectations for Li-ion, mainly driven by EV applications with Li-ion expected to become the dominant technology in residential and commercial storage behind the meter.

Lead-based manufacturing capacity in Europe is sufficient to meet demand expectations. Whilst Li-ion demand is heavily reliant on imports today, by 2030 it is expected that there will be an almost 40-fold increase in capacity that will be able to meet demand even at optimistic growth expectations. Ultimately, there might be surplus of capacity vs demand in Europe (1).

As the cost of electricity is increasing, and with the need for decarbonation, the Residential and Commercial ES markets will continue to gain importance. Li-ion will be very popular in this market, complemented with the electric vehicles with V2G and V2L and 2nd life use. The chemistry used for this application will be driven by cost, safety, and carbon footprint. Sodium batteries, or equivalent chemistry, will also becoming very popular for these applications by 2035.

In the second quarter of 2023, the economic sectors responsible for most greenhouse gas emissions were 'manufacturing' (23.5 %), 'households' (17.9 %), 'electricity, gas supply' (15.5 %), 'agriculture' (14.3 %), followed by 'transportation and storage' (12.8 %) – Source Eurostat.

Li-ion is a preferred technology also because of the fact that the electronics and the BMS are

imbedded to help manage the BTM functionalities. The growth of the BMT market is driven to increase self-consumption. The use of different battery technologies provides an overall benefit to the decarbonization of the residential sector and batteries are key enablers for making this happen.

According to KPMG report 2025 commissioned by CBI and ILA, in Europe, 5 GWh for BTM and 4 GWh for FTM in 2022, 13 GWh for BTM and 16 GWh for FTM in 2025, 46 GWh for BTM and 60 GWh for FTM in 2030.

In Conclusion

Lithium-based solutions have an advantage in terms of space weight and cycle performance, but safety is a consideration to be further improved for in-house storage applications. The lead-based bipolar technology can increase energy density and advanced chemistries, such as carbon loaded negative designs, can improve cycle performance and energy throughput, particularly in partial state of charge operations. Another aspect to consider for end-users is the aesthetics of the battery system if it is to be prominently displayed at home or in commercial locations.

Lead today is fully recyclable and has the economies of scale in place that work without subsidies. For Li-ion, further improvements are needed to make it economically viable. Lifecycle (energy throughput) advancements for both technologies will be required to reduce the TCO. The PSOC cycles of the batteries, according to the European reference test standards, should also increase. With advancements in energy density and cycle performance, lead-based solutions could become more attractive in future.

R&D&I development should be focused on improving the cycle life and increasing the lifetime energy throughput (kWh) across the full range of depth of discharges (particularly for lead, such as improving digital communication with the inverter) to provide TCO benefits. Associated KPIs relating to improving charge efficiency and higher energy density should also be pursued. For Li-ion solutions, advancements in recyclability, coupled with improvements in safety (move to solid state) should

also be pursued as KPI for improvement. Improving the round-trip efficiency for batteries is also a key parameter in future aligning with the Energy Efficiency Directive.

The next phase of value creation lies not just in deploying storage, but in optimizing how it is used—leveraging data, forecasting, and intelligent control systems to unlock its full economic and operational potential.

Stationary: Residential & Commercial Battery Storage Behind-the-Meter by 2035

→ Stationary: Residential & Commercial Battery Storage Behind-the-Meter by 2035

- Li-ion – dominant
 - LFP – technology with most suitable characteristics
 - NMC – for compactness and integration flexibility
- Sodium-ion RT – ready for mass commercialization
- Lead based – kept in the loop, depending on further R&D



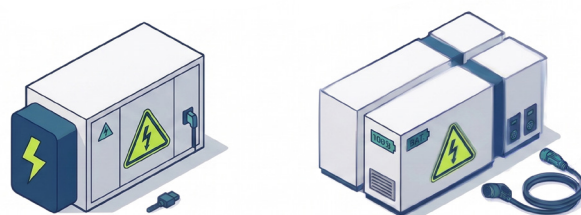
→ Global – Technology mix of this BTM multi-TWh size market:

- Li-ion – dominant with mainly LFP, also NMC
- Sodium-ion RT potentially scaling earlier than in automotive
- Lead based well represented outside Europe in regions with weak grids are in rural area, relevant for backup-oriented systems



EUROBAT best estimates derived from consolidated analyses of multiple recognized industry and market intelligence sources, including BNEF, McKinsey Battery Insights, IEA, SolarPower Europe, EASE and Wood Mackenzie (non-exhaustive list).

3.D. Batteries for Utility Grid-scale Energy Storage (FTM Batteries)



Utility grid-scale energy storage systems are large storage facilities that support penetration of renewable energy in our mix and can provide grid stability in multiple ways. FTM batteries are directly connected to transmission and distribution networks. Grid operators are facing new challenges from the ever-increasing penetration of inherently intermittent and variable renewable energy resources, especially in the field of operational grid management services.

BESS projects can provide a reliable and cost-effective solution, but their full potential remains largely unexplored.

Application Profile

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 on location and scalable to the power and capacity needs of the application.

Batteries can provide grid stability in multiple ways. They can store energy quickly or feed in, in milliseconds, for grid compensation to avoid frequency instability and compensate deviations caused by fluctuations in generation and load. Batteries also provide reserve capacity for the grid to take on the role of spinning reserves provided by conventional power plants. Battery energy storage is also required to restart after a complete power failure (black start) or to supply energy to an island power grid integrated with renewables.

Due to their short response times, in the millisecond range, battery storage systems are also suitable for providing control energy down to the minute range. The provision of control power from pooled, decentralized battery storage is already economical today. The creation and use of local flexibilities to support the network is the key to optimizing the use of distribution grid capacities.

Li-ion is largely predominant in European ESS market. Globally it is estimated that Li-ion, with LFP, may take 75-85% and NMC to take 3-8% of the market so in total Li-ion total market share of +90% market share by 2035, to compete with increasing market share from Na-ion RT and from Flow batteries, expected to take up each with 5 to 8% market share globally. Lead very small for niche, ex. for black-start and specific utility, backup or hybrid systems, Nickel-based for storage in harsh climates.

Depending on the grid function, such as voltage/frequency regulation, arbitrage, black-start, back-

up, investment deferral and grid independent power supply (GIPS), a large variety of operating profiles are considered, in which, depending on the requirements, all mainstream battery technologies can have a role to play.

The tabulation hereunder is from the ENTEC study on Energy Storage from 2023, developed by Fraunhofer ISE. This tabulation gives a more detailed picture on the assessment of four battery technologies, lead-based, Li-ion, sodium-based and redox-flow, in relation to some key storage service applications in the grid.

Research and Innovation Scope and Potentials⁶

General technical requirements and main drivers for energy storage are cyclability (at different DOD and often at PSOC) a, high energy density at battery level and system (project) level, safety, round-trip efficiency (including auxiliary consumption), low

Table 5: In-dept assessment of battery technologies for storage service applications

Storage Service Applications	Storage size range	Lead-acid batteries			Li-ion batteries			Sodium-based batteries 5)			Redox-Flow batteries 6)		
		st	mt	lt	st	mt	lt	st	mt	lt	st	mt	lt
Generation Support Services and Bulk Storage Services 1)	< 100 kWh												
	100 kWh - 1 MWh												
	1 MWh - 1 GWh												
Services to Support Transmission Infrastructure 2)	< 100 kWh												
	100 kWh - 1 MWh												
	1 MWh - 1 GWh												
Services to Support Distribution Infrastructure 3)	< 100 kWh												
	100 kWh - 1 MWh												
	1 MWh - 1 GWh												
Ancillary Services	< 100 kWh												
	100 kWh - 1 MWh												
	1 MWh - 1 GWh												
Services to Support Behind the Meter Customer Energy Management	< 100 kWh												
	100 kWh - 1 MWh												
	1 MWh - 1 GWh												
Vehicle-to-Grid (V2G) 4)	< 10 kWh												
	< 100 kWh												

(st = short-term storage, mt = mid-term storage, lt = long-term storage)

- suitable** The technology represents a common solution for the service or is a promising option for the near future.
- possible** The technology is (still) limited for the service or is mainly not used for this purpose, even if it is technologically possible. Nevertheless, the technology is used in some cases.
- unsuitable** The technology is rather less to not suitable for the service. Through further research & development, however, it could be an option in the distant future.
- not existing** The technology doesn't exist.

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. CO2 footprint and recyclability of the solution are also becoming key drivers in European market.

The development of the multi-use aspect of ESS will also increase the revenue streams. 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 lithium are safety, life duration (nb of cycles), energy density (Wh/L and Wh/m²), cost reduction, recyclability and CO2 footprint reduction. A potential way of reducing costs for Li-ion systems and reduce environmental impact of the solution is the deployment of second-life EV batteries, research on other technologies less dependent of critical raw materials like Sodium-ion are also away to reduce costs and risk of critical material scarcity.

European battery regulation will also lead BESS providers to invest into digitalization with requested implementation of the battery passport.

Intelligently combining batteries other storage technologies, in particular long-term storage over 12h, and lithium-based batteries could also increase the market significantly for those other technologies as it would offer considerable benefits in terms of lower energy reserve costs. Example can be NaS or hydrogen.

For large storage systems, lithium technologies are considered the reference technologies, capturing more than 90% of the worldwide annual battery energy storage market. Lithium-ion batteries show longer lifespan, higher energy density (key driver considering constrained land surface), lower self-discharge, and better efficiency.

General technical requirements and main drivers for energy storage are cyclability (at different DOD and often at PSOC) a, high energy density at battery level and system (project) level, safety, round-trip efficiency (including auxiliary consumption), 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. CO2 footprint and recyclability of the solution are also becoming key drivers in European market.

Research priorities for lithium are:

- Safety: Thermal runaway temperature trigger, propagation prevention at system level, mitigation of explosivity and fire risks
- Energy density at cell level (Wh/L), going from 345Wh/L as standard in 2023 to > 400Wh/L in the years to come,
- Energy density at system level (kWh/m²), increasing the energy density of modules, enclosures, auxiliary systems (e.g. cooling) and reducing layouts / installation on sites
- Life duration (nb of cycles), going from ~6000c/yr in 2023 to 12000c/ yr and above.
- Cost reduction: at cell level (directly linked to lithium price) and system level.
- Recyclability of Li-ion batteries, in particular of LFP materials and system components.
- CO2 footprint reduction, considering localization of production, recycled content, design for sustainability principles.
- Digitalization: digital twin, AI, predictive functions in order to reduce O&M costs, increase life duration, optimize project sizing, and match EU battery regulation requirements for battery passport.

Alternative technologies will also be a key innovation focus for the years to come, mainly Na-ion having the main advantages of reducing risk of scarcity on raw materials supply chain at a low cost. Flow batteries also can bring the advantage of separating the size of the storage (reservoir) and the power sized with the power stacks, offering low cost per kWh, under high volume production hypothesis, for long duration storage (>12h). Being likely to remain marginal in Europe, flow batteries are not further detailed here (and external storage batteries

are clearly excluded from new battery regulation). Hydrogen storage & fuel cell are not considered as out of the scope of this roadmap, who has entire focus on battery systems.

Battery Market

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. Batteries have considerable advantages as they are easy to install at location, scalable to the power and capacity needs of the application and project implementation is much faster.

For large storage systems, lithium technologies are considered the reference technologies, capturing more than 90% of the worldwide annual battery energy storage market. Lithium-ion batteries show longer lifespan, higher energy density (key drivers considering constrained land surface), lower self-discharge, and better efficiency.

According to the Avicenne Study commissioned by EUROBAT in 2023, the European utility grid-scale FTM market expanded to 5,5 GWh in 2023, with an annual growth >30%, to reach 43 GWh by 2030. The growth results not only from increased numbers of units sold but also because of the increased demand for larger storage systems.

In Conclusion

Li-ion is currently clearly the dominating technology and will remain as such until the end of the decade, with continue cost decrease benefiting of the economy of scale from the automotive industry. Renewable energy increase penetration will drive the growth of those grid ESS battery markets. The dependence on imported raw materials is not considered to be a blocking point for European battery industry in its growth until at least 2030. However, efforts are needed to increase local production of active materials, with a specific attention to potential new environmentally sustainable extraction and refining methods in Europe.

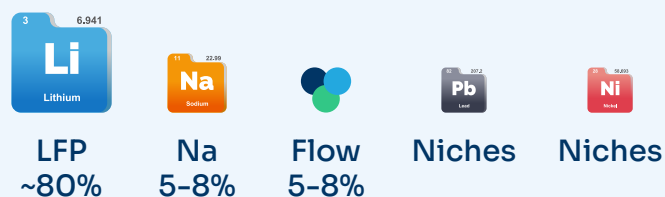
Furthermore, increasing recycling capacities in Europe and improving recycling processes are

critical. Solid State technology currently lacks the necessary maturity for positioning a massive industrial development for ESS before 2030.

Utility grid-scale Energy Storage – Mainstream Battery Technology landscape by 2035

→ Multitude of grid functionalities – FTM battery technologies global mix:

- Li-ion – dominant
 - LFP – most suitable for this market
 - NMC – for high power response & legacy
- Flow batteries – for longer cycles
- Sodium-Ion RT – most promising market for commercialization
- Nickel-based – niche: outdoor storage in extreme climates
- Lead – niches: black-start & specific back-up and hybrid systems



EUROBAT best estimates derived from consolidated analyses of multiple recognized industry and market intelligence sources, including BloombergNEF, IEA, McKinsey Battery Insights, Wood Mackenzie, EASE and SolarPower Europe (non-exhaustive list).

3.E. Batteries for Off-grid Applications

Application Profile

The 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)

Main applications are battery energy storage systems (BESS) in a range from domestic and **industrial/ commercial to community scale usages and back-up power for telecom towers.**

Rural electrification systems typically range from small solar home systems of a few tens of watts to village mini-grids in the 10–500 kW range and larger rural microgrids exceeding several MW. Battery storage capacities can range from below 1 kWh for household systems to tens of MWh for islanded rural utility networks.

Market Drivers and Evolution

Batteries for energy storage can improve the reliability of power supply from renewable and conventional sources, increase the overall system efficiency and provide economic savings across the system life cycle, for example by fuel savings. Market drivers are the worldwide expansion of fluctuating renewable energy sources like PV and wind. This is supported as well by national and multinational funding programs. Despite the growing electrification worldwide there are still hundreds of millions of people located in central and southern Asia and in sub-Saharan Africa without direct access to electricity.

Batteries produced in Europe – following European environmental standards – are exported for use in rural areas worldwide. As such, they significantly contribute to the zero-pollution targets of the European Green Deal outside the borders of Europe. In addition, electrifying rural areas helps address other societal challenges, both in developed and developing countries, including:

- Remote telecommunications installations
- Water purification and/or pumping
- Street lighting
- Security system

Typical power ranges for rural electrification systems vary enormously depending on whether the system serves:

- a single household,

- a village mini grid,
- a productive use microgrid,
- or a regional rural utility network.

Description of the Battery Features

Battery Energy Storage is used across the entire range of off-grid and hybrid mini-grid systems and provides a permanent source of electricity that is independent from variable power generation. It is used to store energy from Renewable Energy Sources and release it when needed at times when RES production is not sufficient. BES is typically sized to keep supplying power for up to 4-10 days. This is necessary to ensure that the application will always be powered should RES be limited for an extended period of time.

The main KPIs are the requirement for high performance in rugged atmospheric conditions, low maintenance, high energy throughput, design life, broad temperature range and affordability (TCO).

Mainstream Technologies

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

The current dominant technologies are lead-based (sealed and flooded) and Li-ion (NMC and predominantly LFP). Lead-based technologies still have the major advantage of being safe and easy to install and to maintain without sophisticated technicians (important for rural and remote installations). If estimated cost targets could be achieved, sodium-ion (RT) could be an alternative storage system competing with LFP and lead in future.

R&I Scope and Strategic Actions

For lead-based systems: Increased energy throughput and the development of operation strategies through the integration of BMS (battery management system).

For Li-ion: Improving the design life and safety

aspects like high temperature operation, costs and recyclability.

For sodium-ion (RT): currently in the phase of technology demonstration (TRL 5): The general qualification of the technology has to be demonstrated.

Sustainability, Safety and Standardisation Aspects

Cycle or lifetime performances are measured differently depending on the battery chemistry and its depth and rate of discharge. Cycling profiles are different in each IEC cell-specific standard, so it is not meaningful to compare across technologies. Instead, an application-specific standard like IEC 61427-1 could be used as a benchmark, but one fact is sure, circularity and recycling requirements will be key parameters for further development of the concerned technologies.

Battery Market

A recent study by the International Energy Agency highlights that off-grid and mini-grid configurations incorporating Battery Energy Storage (BES) are often the most efficient and sustainable solutions for electrifying isolated rural areas and remote commercial and industrial (C&I) sites. Looking towards 2035, continued deployment of decentralized energy systems is expected to play a critical role in achieving universal and reliable energy access, particularly in regions where grid extension remains economically or technically challenging. The IEA⁷ estimates that substantial additional electricity supply will be required through a combination of centralized grid expansion, mini-grid systems, and off-grid solutions, with battery-supported renewable systems expected to account for an increasing share of new installations.

Another important market segment concerns small islands and remote communities, including European islands without mainland interconnections, where electricity generation has traditionally relied on fossil fuels. Increasingly, these systems are transitioning towards renewable-based off-grid and mini-grid configurations supported by battery storage. Key market drivers include the global expansion of

variable renewable energy sources such as solar PV and wind power, declining battery costs, energy security considerations, and decarbonization targets. National and multinational funding programs continue to support these developments.

Despite major progress in electrification worldwide, significant energy-access gaps remain in parts of sub-Saharan Africa and developing regions of Asia. By 2035, decentralized renewable energy systems combined with battery storage are expected to remain essential for extending reliable, affordable, and sustainable electricity access to underserved populations and remote economic activities.

Batteries produced in Europe – following European environmental standards – are exported for use in rural areas worldwide. As such, they significantly contribute to the zero-emission targets of the European Green Deal.

In addition, electrifying rural areas helps address other societal challenges, both in developed and developing countries, including remote telecommunication installations, water purification and/or pumping, street lighting and security systems. The dominant technologies through to 2030 will be lead-based (sealed and flooded) and Li-ion (NMC and predominantly LFP). Lead-based technologies still have the major advantage, as they are safe and easy to install and to maintain without sophisticated technicians, which is important for rural and remote installations. Sodium-ion (RT) batteries could be an upcoming alternative storage system competing with LFP and lead.

In Conclusion

By 2035, the global off-grid battery market still dominated by lithium and lead based technologies, but LFP technology, driven by declining costs, taken market share from lead market, however, lead batteries likely to persist in selected low-cost and legacy installations. Sodium-ion batteries are expected to emerge progressively in stationary off-grid applications. Overall, global off-grid battery deployment could reach several hundred GWh by 2035, supported by rural electrification, mini-grid expansion, telecom infrastructure, and renewable energy integration.”

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 design life, safety aspects like high temperature operation, cost and recyclability are paramount. In recent years there is a growing trend of integration Off-grid systems to smart grids. Furthermore, the system monitoring and data management is extended to cloud based solutions.

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 61427-1 is the reference to benchmark.

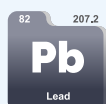
Stationary Storage – Off-grid Batteries Technology landscape by 2035

→ **Rural areas in developing countries, Peri-urban areas with weak grids, in emerging countries and small islands (ex. mini-grids)**

- Dominant technologies
 - Lithium, LFP mainly
 - Lead: 40% sealed & 15% flooded
- Sodium-ion RT growth to reach 8-12%
- Nickel-based: for niches



~55%



~40%



8-12%



Niches

EUROBAT best Estimates - Global off-grid battery technology mix by 2035 (GWh)

R&D Application Area 4 – Defence



Introduction – Drivers for Battery Innovation

The enabling role of batteries, widely recognized for civilian use, is indeed applicable also in the defence application, creating a massive opportunity for innovation. Moreover, military battery R&D is driven by a specific set of technical, operational, and geopolitical pressures that go beyond what drives civilian or consumer applications.

Batteries are becoming more and more strategic in the defence application, globally. At European level, it is acknowledged the importance of the battery industry to boost defence capabilities, underlying their strategic importance⁸.

At the 2025 NATO Summit in The Hague, Allies made a commitment to invest 5% of GDP in defence by 2035. Of that, up to 1.5% can be allocated to initiatives that 'innovate and strengthen the defence industrial base.' The decision to increase the spending on defence will have a technological impact which will be reflected consequently into batteries demand⁹.

Battery Market Estimates

The Global military market for defence application is growing and is divided approximately into 50% ground, 30% air and 20% marine domains.

The largest or fast-growing segments are:

- Portable soldier systems & communications - major share due to sheer numbers of devices.
- Unmanned systems – high growth due to electrification and autonomy.
- Propulsion & platform power – significant revenue share, especially for military vehicles and ships.
- Backup & APU power – key for operational continuity across forces.

Application Segments and Profiles

Batteries in use in defence are varied in size and chemistry as the wide spectra of applications they need to serve.

Main application segments are:

→ Ground vehicles

- Lead acid batteries, especially AGM are the dominant technology for ground vehicles. Li-ion are also used in response to a continued increase of electrical demand, to improve endurance and operational performance, in particular during silent watch.

→ Portable devices – radios, night-vision goggles, GPS units

- Li based batteries are the dominant technology in this application segment. As rechargeable batteries Li-ion batteries are employed both NMC and LFP chemistry. As long standing non-rechargeable options, battery systems based on Li-thionyl chloride and Li manganese oxide are employed.

→ Microgrids

- Lead acid batteries are mainly used in mobile tactical microgrids meanwhile Li-ion are used in microgrid to power critical infrastructures

→ Energy weapons

- **Batteries for energy weapons** (like lasers and high-power microwaves) require extreme power density and high discharge rates. Key technologies include thermal batteries for missiles (LiSi/FeS), high-discharge rate lithium-ion (Li-ion) for portability, custom lithium-polymer (Li-poly) for high-voltage pulse power, and nickel-cadmium (NiCd) or nickel-metal hydride (NiMH) for high-capacity requirements

→ Submarines, surface ships, torpedoes and autonomous underwater vehicles (AUVs)

- Submarines and surface ships are transitioning to Li-ion batteries for energy density, faster charging, reduced weight and longer life. Nevertheless, lead-acid batteries are still the standard for surface ships. Batteries used in torpedoes are Ag-Zn and high energy density Li-ion.

→ Unmanned systems (drones) and fighter jets

- Various types of batteries for drones are on the market, including lithium polymer (LiPo) for their high power-to-weight ratio and discharge rates, lithium-ion (Li-ion) are preferred for longer endurance and efficiency, and nickel-metal hydride (NiMH). Fighter jets use lithium-ion (Li-ion) and nickel-cadmium (Ni-Cd) batteries to provide high power for engine/auxiliary power unit (APU) starts and critical emergency backup.

Mainstream battery technologies and key performance indicators

Historically, batteries were considered as a commodity, and mature technologies have been mainly employed such lead-acid, Ni-Cd and Ni-MH batteries¹⁰. More recently, the use of Li-ion batteries was consolidated for certain applications such as ground vehicles, naval, power banks and drones.

Battery types and chemistries vary depending on performance requirements. These include energy and power density, longevity and safety. Moreover, they must endure heat, cold, shock and vibration more severely than in the civilian applications.

- Energy density in Wh/kg – matters for longer missions with need for high-energy chemistries, structural batteries and hybrid battery-fuel systems
- Reliability in extreme environments – from -46°C to +72°C even broader -54 oC to +88 oC storage, under shock, vibration, salt, sand and humidity or after long storage: need for low-temperature electrolytes and chemistries with long calendar life
- Logistics simplification & standardization – reducing the number of battery types in the field, interoperable power systems across allies (following NATO standards), common charging infrastructure, modular systems and universal power interfaces
- Supply chain security & geopolitics – vulnerability of global supply chains in wartime (sanctions and

export controls); motivates to develop alternative materials (sodium-ion, zinc and aluminium, domestic or allied manufacturing

- The demand for single use standardized battery cells with high energy/power and low cycle life will also rise significantly. These applications demand standardized lowered cost cells, which can be reached by shorter electrode design cycles and fast product integration in 6T standard architectures.

Sustainability, Safety and Standardization

Standardized batteries with slightly lower performance may be more beneficial to defence application than custom batteries with slightly higher performance because of burdens related to certification, cost, supply chains, and logistics.

NATO battery standards, particularly for military vehicles and equipment, focus on interoperability, high reliability, and ruggedness. The core standard is the NATO 6T form factor, commonly used in 95% of military vehicles. Modern NATO standards are transitioning towards lithium-ion (Li-ion) chemistry to improve power density, with advanced, secure Battery Management Systems (BMS) required for safety and performance in extreme conditions. Some national standards are particularly recognized such as the US Std MIL-STD-810, UK Defence Standard 00-035 or VG Norms of German army for all environmental factors to be considered. These are normally applied across multiple services. Besides, with the inclusion of BMS, electromagnetic compatibility (EMC) is generally covered by MIL-STD-461, or DS 59-411, and low voltage (LV) compatibility is covered in MIL-STD-1275 or DS 61-005. The reference international standards are EN50342 and IEC 60095 which many national standards refer to for characterization tests or common battery performance tests.

Batteries dimensioning standard is NATO STANAG 4015 standard which is compliant with IEC 60095-4 to allow replacement batteries from NATO member nations to be accommodated. Small variations are noted in many of the national standards.

Safety and sustainability are very important in a number of applications such as shipboard, ground power, missiles and safety power. To be noted that, with the advent of BMS (either monitoring or management systems) in batteries, cyber security is becoming an important aspect to demonstrate compliance with, along with generic architecture compatibility for supporting modularisation and integration within a wide range of applications.

Solid state Li-ion batteries have a great innovation potential as well as Na-ion batteries.

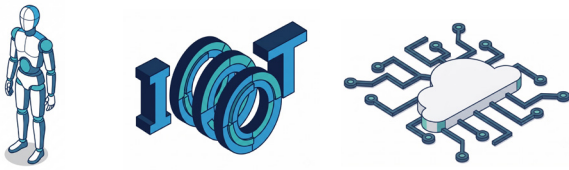
In Conclusion

Opportunities for batteries innovation in defence are multiple. Currently the main technologies applied are lead acid and Li-ion in the ground domain that accounts for about 50% of the global market. In the marine domain (approx. 30% market share), a general and gradual transition to Li-ion batteries is observed. Finally, the air domain, with ca. 20% market shares, sees several battery technologies employed due to the variety of applications, with Ni based and Li based as dominant technologies.

Continuous improvement on lead acid batteries mainly used in the ground domain is required to improve performance such as durability. Safety aspects will drive innovation in solid-state batteries and Na-ion based batteries.

R&D Application Area 5

– Robotics & Internet of Things (IoT)



Introduction

Both applications are overlapping but there are also important differences, impacting Battery R&D:

→ **Typical Robotics Use Cases** are Autonomous mobile robots (AMRs, AGVs), Drones and UAVs, Service and humanoid robots, Industrial inspection robots

→ **Typical IoT Use cases** are Smart meters and utilities, Asset tracking and logistics, Smart buildings and cities, Medical and environmental sensors

Application Segments and Profiles

In **robotics and IoT**, battery selection is driven by **power demand, duty cycle, form factor, and lifetime expectations**. The two domains overlap but have distinct priorities.

Robotics applications: typically require **higher power, robustness, and rechargeability**.

IoT devices: prioritize **long lifetime, miniaturization, low maintenance**, often operating for years without replacement.

Key Requirements for Batteries (KPIs):

Robotics applications

- High power output
- Fast charging or battery swapping
- High cycle life
- Strong safety and thermal management
- Standardized form factor.

IoT applications

- Ultra-low power consumption
- Long shelf and operational life
- Small size
- High reliability in remote locations

Mainstream battery technologies

Robotics Applications

- **Lithium-ion (Li-ion)**
 - Most widely used across mobile robots
 - Good balance of energy density, power, and cycle life
- **Lithium-polymer (Li-Po)**
 - Preferred for compact or weight-critical robots (e.g. drones, humanoids)
 - Flexible form factors, high discharge rates
- **Lithium iron phosphate (LFP / LiFePO₄)**
 - Increasingly used in industrial and collaborative robots
 - Superior safety and long cycle life
- **Nickel-metal hydride (NiMH)**
 - Legacy or niche use; more tolerant to abuse but lower energy density

IoT applications

- **Lithium primary batteries (non-rechargeable)**
 - Lithium-thionyl chloride (Li-SOCl₂) – dominant for long-life IoT
 - Very low self-discharge; 5–20-year lifetimes
- **Lithium coin cells (CR2032, etc.)**
 - Compact, low-power sensors and beacons
- **Rechargeable Li-ion / Li-polymer**
 - Used when periodic recharging is possible
- **Thin-film or micro batteries**
 - Emerging use in ultra-small or medical IoT

Robotics relies primarily on high-power rechargeable lithium batteries, while IoT devices predominantly use long-life, low-power primary lithium batteries optimized for years of autonomous operation.

Market Size & Outlook

Key Trends Driving Battery Markets for Robots

- **Growing adaptation of robots across industries:** automation, logistics, e-commerce, healthcare, agriculture and defence (autonomous and semi-autonomous machinery)
- **Advanced Battery Management Systems (BMS):** Intelligent BMS with real-time monitoring and predictive maintenance improves safety, lifespan and operational reliability, crucial for fleets robots.
- **Lightweight, compact & custom designs:** Robots becoming smaller and more mobile (e.g. drones, service robots, humanoids), need for higher power in lighter and compacter formats
- **Environmental & sustainable factors:** increased focus on recyclable and eco-friendly batteries, along with tightening emissions and waste regulations, influencing design and material choices

Based on publicly available market reports estimate Global Market volume in 2025 at 1.5-2.75 B\$ up to 6.1 B\$ by 2033 (CAGR 9 to 13%).

Key Trends Driving the IoT Battery Markets

- **Rapid expansion of IoT devices:** Globally connected devices are growing fast — forecasts estimate tens of billions of connected devices in the next decade, increasing demand for reliable power sources.
- **Wearables & consumer electronics:** A large share of demand comes from wearables, smart home products, and other consumer IoT devices.
- **Industrial & healthcare IoT:** Sensors and monitors in industrial automation and healthcare contribute significant volume and specialized battery solutions.

- **Battery technology innovation:** Growth in thin-film, printed, and low-power electro chemistries tailored for IoT use continues to expand market possibilities.

Based on publicly available market reports estimate Global Market volume in 2025 at 11-13 B\$ up to 31 B\$ by 2035 (CAGR 10%)

In Conclusion

Robotics

By 2035, advanced R&D on different battery technologies will play a decisive role in enabling the next generation of autonomous and collaborative robotics across industry, healthcare, logistics, agriculture, and mobility. Robotics applications will require batteries with high energy density, rapid charging capability, long operational lifetimes, and enhanced safety to support continuous and reliable performance. Future developments should also focus on designs, intelligent battery management systems, and sustainable manufacturing processes.

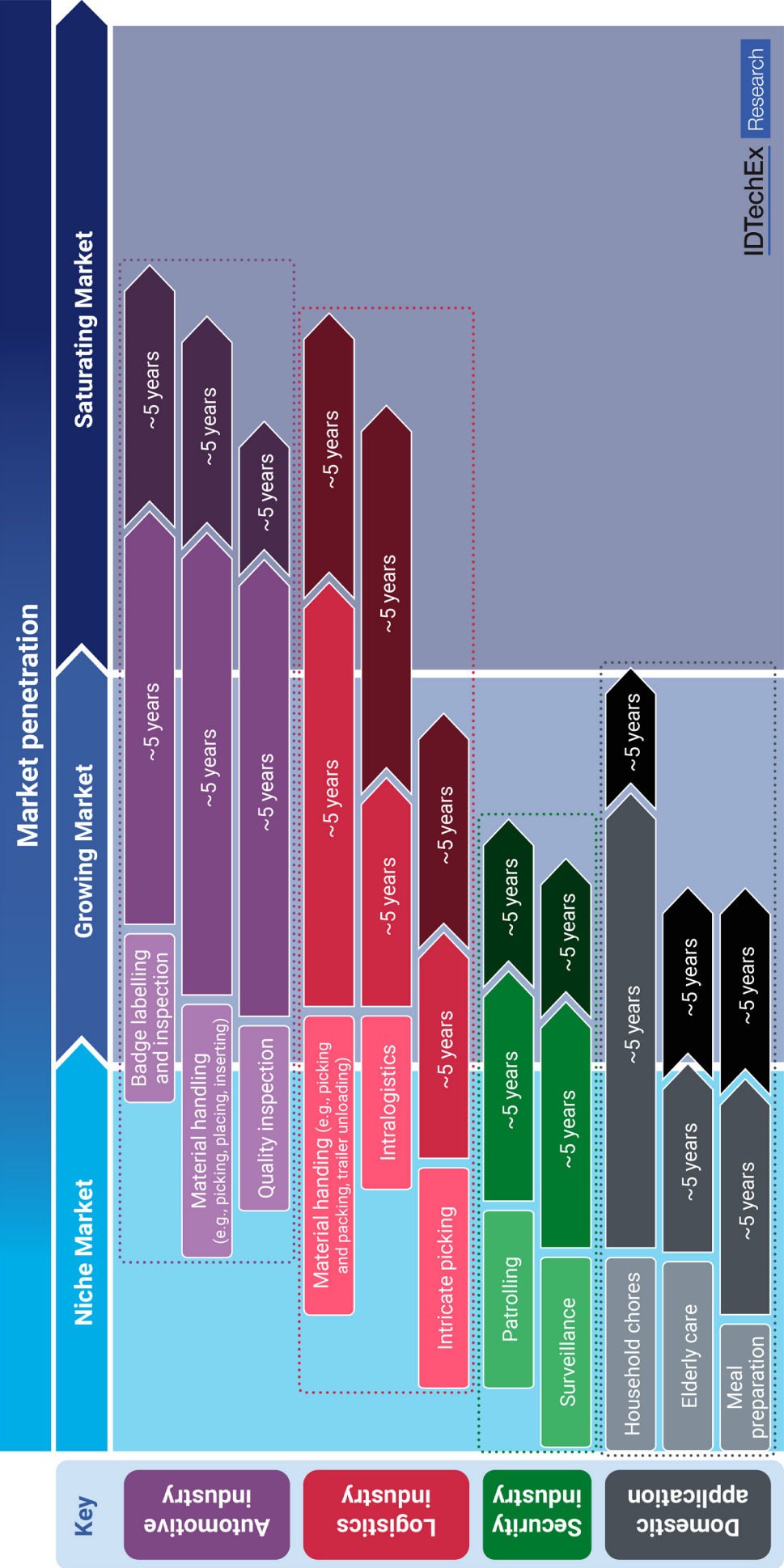
A strong European battery ecosystem will be essential to ensure technological leadership, resilience of supply chains, and the deployment of energy-efficient robotic solutions at scale.

Internet of Things

By 2035, the expansion of the Internet of Things will depend on efficient, compact, and sustainable battery solutions capable of powering billions of connected devices. IoT applications will increasingly require ultra-low-power consumption, long-duration operation, flexible and small-sized battery formats, and maintenance-free performance for remote or embedded systems. Advances in energy-harvesting-integrated batteries will support the scalability and reliability of smart infrastructure, healthcare monitoring, environmental sensing, and consumer applications.

Coordinated innovation efforts and circular approaches will be critical to ensure secure, affordable, and environmentally responsible energy solutions for the connected ecosystems of the future.

Figure 8: Maturity of Commercialization of Humanoid Robots by Application¹⁾



Technology Outlook table – Key Findings

Key Findings

The battery technologies identified as most promising in the Roadmap span a range of technology readiness levels (TRLs).

Sodium-ion room temperature (RT) batteries stand out as a breakthrough, representing the earliest realistic entry point for new technology at meaningful market scale. The ramp-up of Sodium Polyanionic cell production for EV and stationary applications – with an operational temperature range of -40°C to +60°C – is already underway in Asia, and sodium ion RT technology is beginning to enter niche.

European markets such as marine applications. The dominant picture through 2035 is one of continuity alongside emerging competition. Taking into account projected innovation timelines, production upscaling, and market projections from multiple credible sources, lithium-ion and lead based batteries will remain the leading technologies in European and global markets.

Sodium-ion RT, however, is expected to capture a small but meaningful share in specific segments, maturing rapidly through continued R&D investment.

Technology outlook by chemistry:

- **Lithium-based** – by far the fastest-growing segment, with consistent double-digit annual growth
- **Lead-based** – stable outlook, even accounting for the potential EU automotive ICE phase-out in 2035
- **Sodium-ion RT** – a credible and sustainable alternative, gaining competitiveness in targeted markets Continued R&D remains essential across all mainstream chemistries. Incremental improvements in performance and sustainability are needed to meet – and ideally exceed – the requirements of EU Battery Regulation 2023/1542. While the Regulation’s specific requirements vary by technology, its overall direction is clear: batteries must become lower-carbon, responsibly sourced, longer-lasting, and fully circular, with full lifecycle transparency.

Established technologies also retain significant innovation potential through 2035:

- **Lithium-ion** – the breadth of Li-ion chemistries offers a wide array of KPIs available for targeted improvement
- **Lead-based** – branching into digital territory for the first time, with Battery Management Systems (BMS), dedicated software, and digital twin development creating new pathways for optimisation and integration

Looking ahead to 2035, lithium- and lead-based batteries will remain the dominant technologies in both European and global markets.

Hereunder a technology outlook table, capturing the market evolution across the mainstream battery technologies, up to horizon 2035 and beyond:

Summary Table: Market evolution across battery technologies up to horizon 2035 and beyond

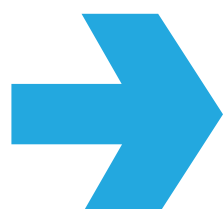
	36,941 Li Lithium	62207,2 Pb Lead	1122,99 Na Sodium	2858,693 Ni Nickel
	NCM, LFP, LMO, NCA, LCO (C; LTO; Si/C); SemiSolid State	EFB – VRLA – AGM, Pb-C, Thin Plate Pure Lead, BiPolar	NaS, NaNiCl (HT), Na-Ion (RT) Gen I (PBA)	NiCd & NiMH
> 2026	Performance and sustainability improvements Semi Solid State	Performance and sustainability improvements Embedded BMS & software	Na-Ion (RT) Gen II (Layered Oxides; Na-Ion (RT) Gen III (Polyanionic)	Continuation of electro-chemistry & cell construction improvements
> 2030	Li-Sulfur, All Solid State	Performance and sustainability improvements	Semi Solid State	Performance and sustainability improvements
> 2035	Li-Air, All Solid State	Performance and sustainability improvements	All Solid State	Performance and sustainability improvements

*Sustainability requirements: in accordance to the Regulation EU 2023/1542

**Link to the WP Batteries
Innovation Roadmap v4.0
Main Document**



<https://eurobat.org/campaigns-and-initiatives/battery-innovation-roadmap-2035/>



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