EUROBAT 2035

BATTERY INNOVATION ROAD MAP

WHITE PAPER BATTERIES INNOVATION ROADMAP 2035

Versions V3.0 • June 2024

Technical Annexes

Pb Li Ni Na

EUROBAT

ASSOCIATION OF EUROPEAN AUTOMOTIVE AND INDUSTRIAL BATTERY MANUFACTURERS

Building upon the foundations laid out in the Innovation Roadmap version V2.0 from June 2022, this new Roadmap incorporates the most recent advancements in technological innovations and re-assesses the market evolution and outlook up to 2035.

The new version takes into account recent EU policy initiatives and the ongoing implementation of the Battery Regulation 2023/1542 from July 2023 to re-assess:

- **Technological review of the four mainstream battery technologies**
- **Identification and review of the most promising future battery technologies**
- **Sustainability, circularity, and digitalization aspects from the Battery Regulation 2023/1542**
- **Evolution of further electrification in end-user battery-operated applications**

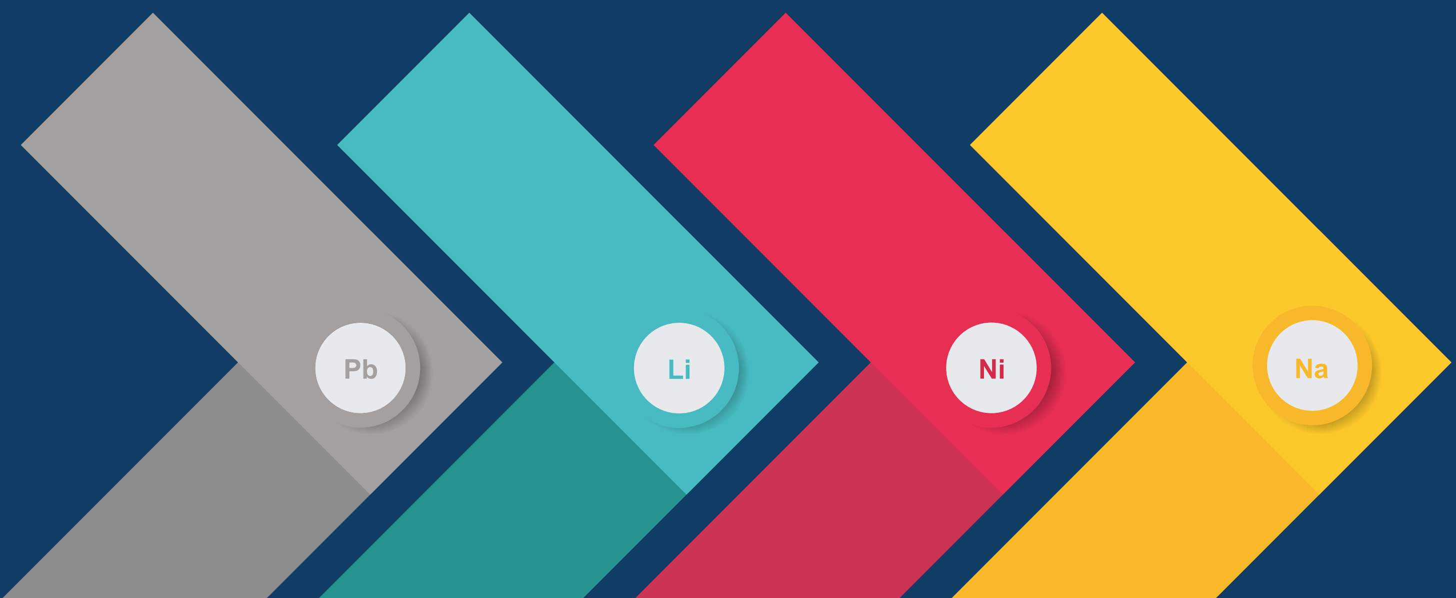
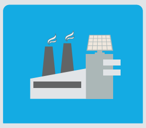


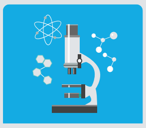
Table of Contents

WHAT IS EUROBAT?

EUROBAT is the leading association for European automotive and industrial battery manufacturers, covering all battery technologies, and has more than 40 members. The members and staff work with all policymakers, industry stakeholders, NGOs and media to highlight the important role batteries play for decarbonised mobility and energy systems as well as all other numerous applications. www.eurobat.org



MORE THAN
30
battery manufacting plants



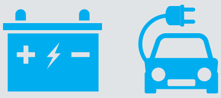
16
research centers

MORE THAN
40
manufacturers and Associate members from across the value chain

APPLICATIONS

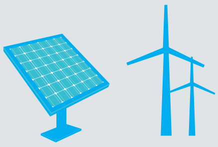
AUTOMOTIVE

Batteries contribute to the decarbonisation of the European transport sector - reducing CO_2 emissions via start/stop batteries and innovative solutions in xEVs.



STATIONARY ENERGY

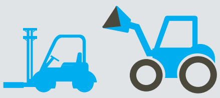
Batteries are indispensable for storing renewable stationary energy coming from solar and wind farms in on grid and off grid solutions. They also contribute to a more stable and reliable grid.



MOTIVE POWER

MATERIAL HANDLING

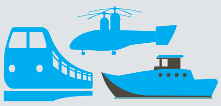
Batteries are a perfect fit for powering industrial vehicles such as forklifts and cranes, while also reducing noise and emissions.



MOTIVE POWER

OFF-ROAD TRANSPORTATION

Batteries are widely used in rail, marine and air transportation.
The concepts of smart charging of road vehicles to support the energy system is also relevant for off-road because their wide deployment and large energy capacities.



ALL BATTERY TECHNOLOGIES

EUROBAT represents the manufacturers of all four existing battery technologies: **Lead-, Lithium-, Nickel- and Sodium- based**. Each chemistry has its own advantages and is best suited for specific applications.

Pb — LEAD BASED
ADVANTAGES
Affordable, proven safe and sustainable

Li — LITHIUM BASED
ADVANTAGES
High energy density, low weight

Ni — NICKEL BASED
ADVANTAGES
Long life, reliability

Na — SODIUM BASED
ADVANTAGES
Relatively high energy density, low weight

Scope and Purpose of the Technical Annex

This document illuminates the overall technological maturity of industrial energy storage, focusing on its main application areas in terms of sustainability and the circular economy. It discusses approaches for developing new technologies and the electrochemical storage technologies expected to dominate in 2030 and 2035, aiming to achieve the goal of climate neutrality by 2050.

The sustainability of batteries must be ensured throughout their entire life cycle. Batteries that are sustainable over their entire life cycle are crucial for achieving the central goals of the European Green Deal—climate neutrality, sustainable competitiveness of the industry, green transportation, and clean energy.

The Technical Annex to the EUROBAT White Paper Battery Innovation Roadmap V3.0 offers a more detailed technical examination of mainstream and future battery technologies up to 2035. Divided into two sections, it provides in-depth insights into:

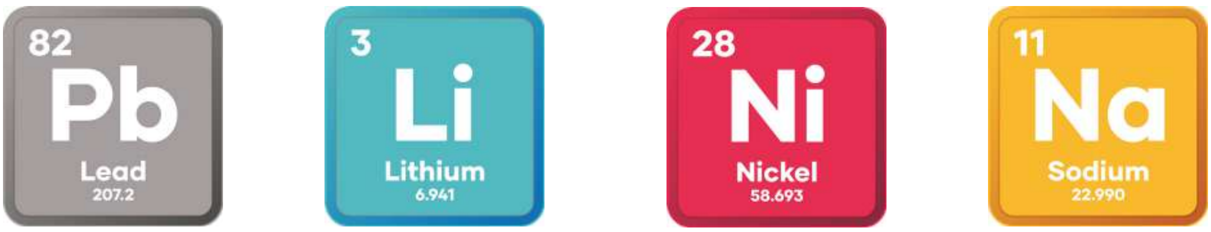
- The analysis of current battery technologies, including lead, lithium, nickel, and sodium-based batteries, focusing on their intrinsic performance, safety, and environmental aspects, and identifying areas for improvement (Part 1).
- Examination of mainstream battery technologies within critical applications that support the objectives of the Green Deal. This section considers battery key performance indicators (KPIs) per application, aligning innovation priorities with specific application requirements (Part 2).

Part 1. Battery technologies and their potentials

The battery technologies considered in the White Paper have been selected because of their potential for further improvement and their significant contribution to meeting the objectives of the European Green Deal and the new Batteries Regulation.

The first chapter of the White Paper delves into the mainstream battery technologies of today, encompassing lead, lithium, nickel, and sodium-based batteries. Meanwhile, the second chapter explores the most promising upcoming technologies identified to complement the progress achieved with existing technologies.

A. Mainstream battery technologies



LEAD BASED	LITHIUM BASED	NICKEL BASED	SODIUM BASED
ADVANTAGES	**ADVANTAGES**	**ADVANTAGES**	**ADVANTAGES**
Affordable, proven safe and sustainable	High energy density, low weight	Long life, reliability	Relatively high energy density, low weight

A.1. Lead-based technologies

Pb

State-of-the-art

The lead battery has been the predominant energy storage device for the industrial and automotive markets for over a century. Different designs of lead-based batteries are available, with an important choice to be made between flooded or 'vented' and valve-regulated batteries (VRLA Batteries).

These batteries can be connected in large battery arrangements without sophisticated management systems. Lead-based batteries differentiate from other technologies by their low cost per kWh installed and low cost per kWh electricity throughput.

Lead batteries have continuously incrementally innovated in response to new requirements in terms of functionality, durability, robustness, and cost. The recent mainstream introduction of Absorptive-Glass-Mat batteries (AGM batteries), enhanced flooded batteries (EFBs), battery monitoring sensors, and battery management systems (BMS) are obvious examples of continuous improvement.

Improvement potential

To compete with upcoming electrochemical storage technologies, there is a need to accelerate innovation. This could be achieved through better static and dynamic charge acceptance, uncompromised high-temperature durability, or improved energy and power densities with enhanced cycle life.

Specific power could be improved by developing new advanced additives to decrease internal resistance, while the cycle life could be lengthened through design enhancements such as corrosion-resistant lead alloys. More intelligent battery operation modes could also be developed. Apart from fundamental research to improve the electrolyte, materials, and components used, other improvements can still be made. These include material innovations on synthetic expanders, nano-based carbon materials, new alloy compositions, and improved Thin Plate Pure Lead (TPPL).

Additionally, bipolar cell design is key to further development in view of future requirements in a multitude of applications. TPPL and Carbon Enhanced are promising candidates for increased service life, PSOC operation, and improved power density. The outstanding feature in this process is that these improvements have been tailored to particular applications.

Environmental aspects

Occupational exposure to lead is under control because the battery industry has proactively taken measures to limit employee exposure to blood lead contamination during the manufacturing process. Europe should allow the market to drive change, and recent progress in lead battery research should not be discounted. The further development of lead batteries in a variety of enhanced technologies will serve.

Lead-based Battery Circular Economy Targets: Recycling targets for lead batteries will be maintained at a very high level, with efficiency over 90% and recycling of active materials at 99%, achieving a circular economy which will benefit the whole battery value chain and improve Europe's independence on raw materials imports needed to build the batteries.

In order to achieve or even exceed the secondary lead targets, the usage of secondary lead can be further increased. Further R&D should be carried out to better refine in order to remove more impurities during the recycling process.

A.2. Lithium-based technologies

Li

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 a combination of the following available anode and cathode materials

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	175 – 200 mAh/g
	NCA	200 mAh/g
	LFP	150 mAh/g
	LMO	105 – 120 mAh/g
	NA+	135 mAh/g

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

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

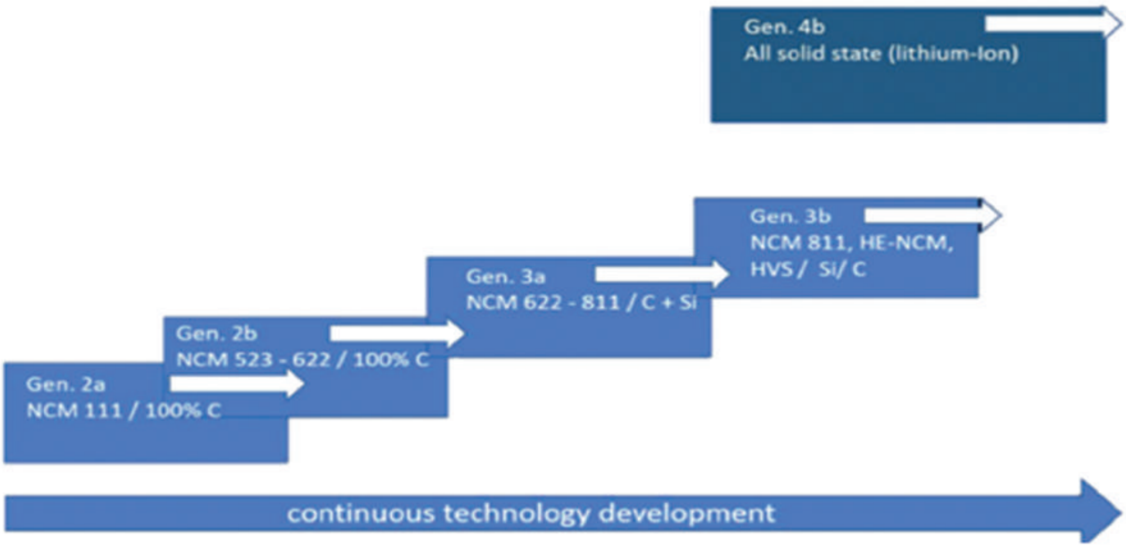


Chart: Generation of lithium materials considered for further development with horizon up to 2035

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 verses 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 residential ESS. These packs will have to comply with the Safety level requested for these 2^{nd} 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 part of the market share for some applications, entry level EVs, delivery trucks, construction machineries, stationary storages, where weight, dimension and autonomy are not an issue. Sodium-ion could become more prevalent than LFP, as the energy density improves, and the cost of material becomes lower. As Sodium salt are 40 times more abundant than Lithium salt, if the lithium carbonate price increases with the demands for EVs, Sodium-Ion can be a very competitive alternative.

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
- 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 responding 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.

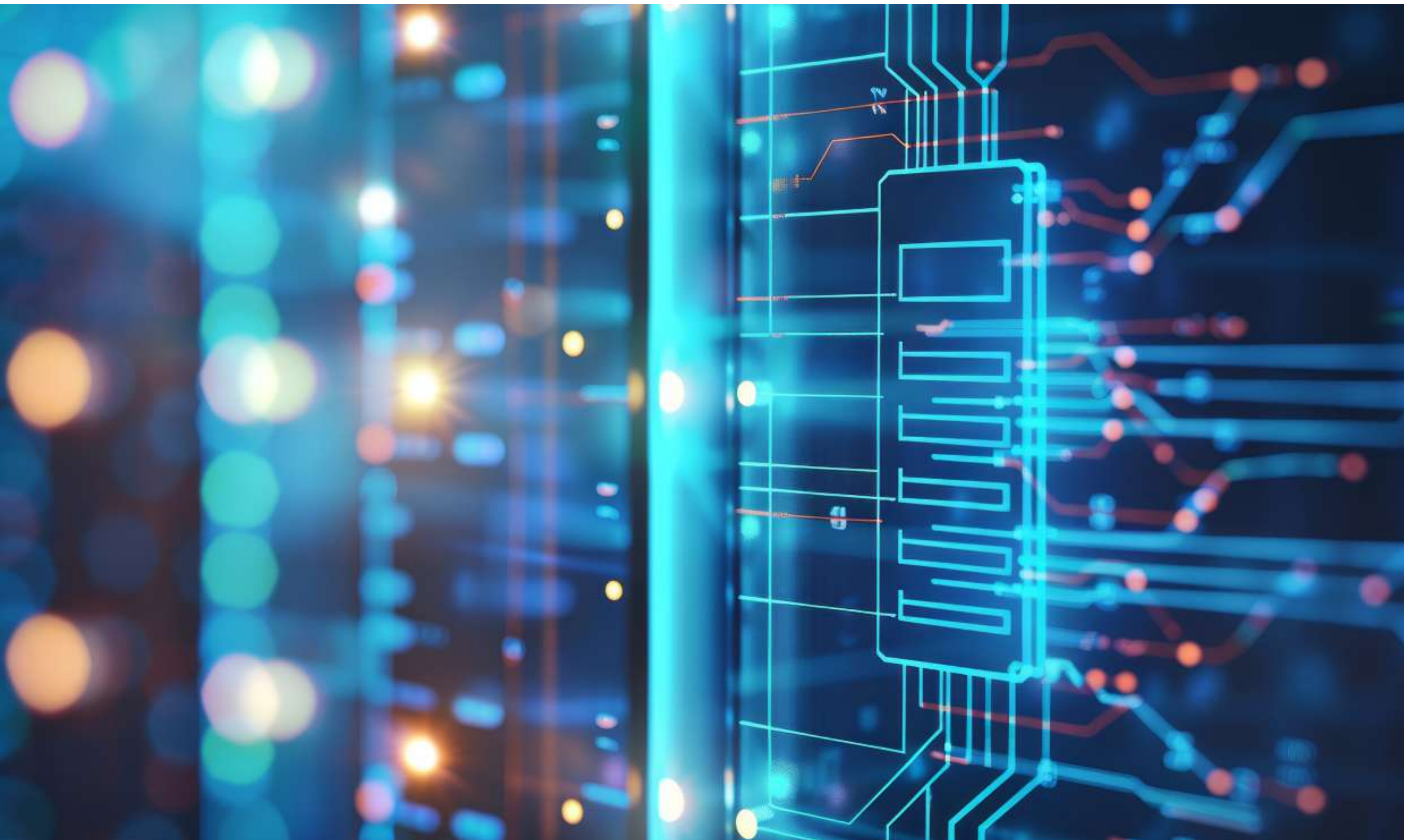
Recycling targets for lead batteries will be maintained at a very high level, with efficiency over 90% and recycling of Recycling targets for lithium batteries will be maintained at the current level of 50%, but active material recycling is expected to increase from 65% to reach 85% by 2035. The recovery of nickel, cobalt and lithium will also be fully commercially viable in future.

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. 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.

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 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 the need 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 divers, with different chemistries and technologies to fit the multitude of applications to target costs and positive carbon footprint results.



A.3. Nickel-based technologies

Ni

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 centers, 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

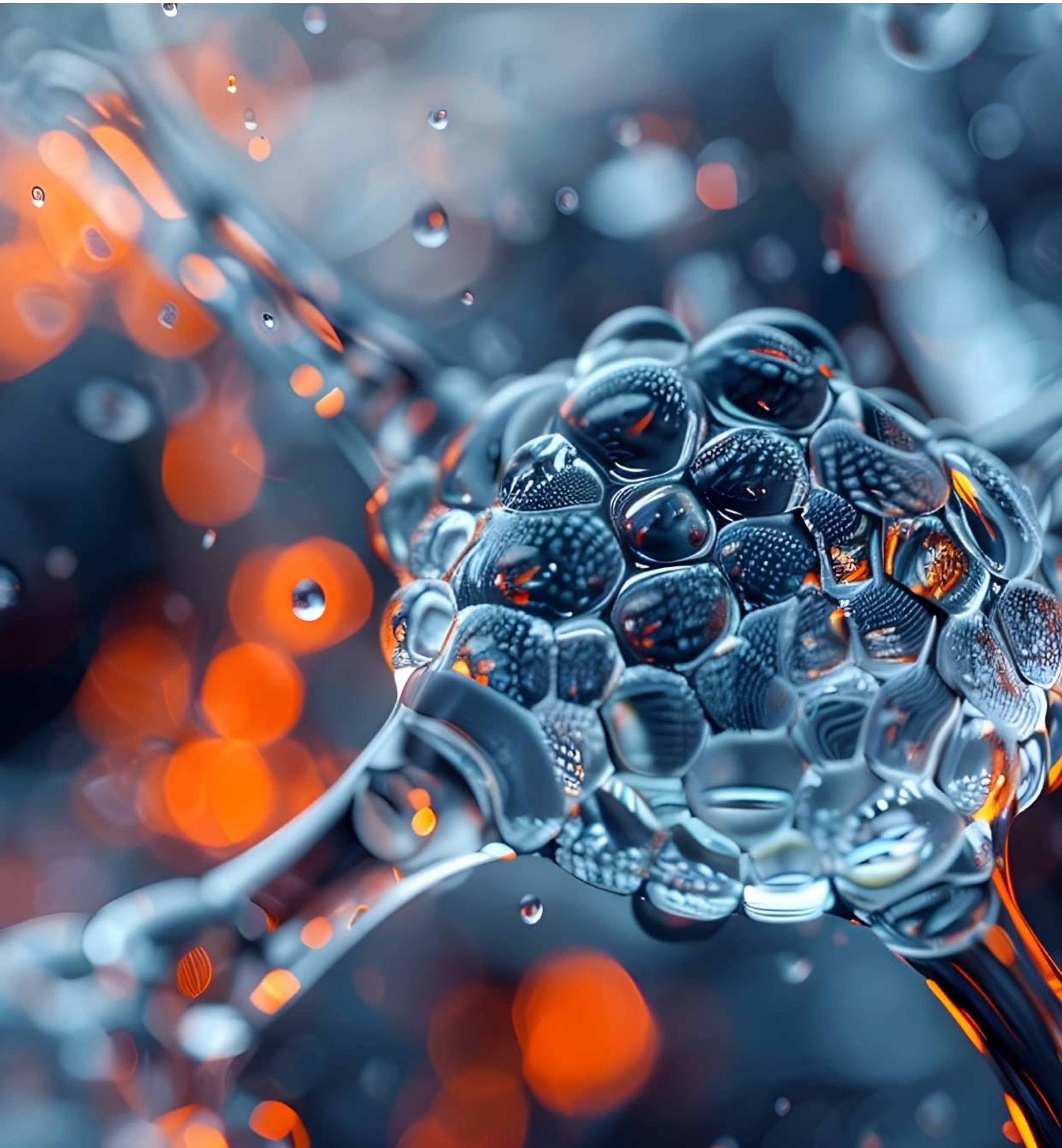
For industrial applications, Nickel-based batteries will most likely remain relevant even in a decade or more. Manufacturers are further improving the already superior characteristics of these batteries such as low maintenance requirements and tolerance to extreme temperatures. Current and possible future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

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.



A.4. Sodium-based technologies

State-of-the-art of high-temperature sodium-based batteries

In contrast to other battery types, high-temperature batteries consist of liquid-electrodes and a solid electrolyte, usually an ion-conducting (e.g. Na^+) ceramic. These batteries require relatively high operating temperatures of >300°C to keep the sodium-based electrode in the liquid state and to increase the conductivity of the solid electrolyte.

Commercially available representatives are sodium nickel chloride (NaNiCl) and the sodium-sulfur battery (NaS) batteries.

Sodium nickel chloride batteries:

The positive electrode mainly consists of a porous nickel matrix as a current conductor with nickel chloride ($NiCl_2$), which is impregnated with sodium aluminum chloride ($NaAlCl_4$). The negative electrode is made of sodium. Ceramic β-aluminum oxide is used as the separator and electrolyte, and act as an electronic insulator. The operating temperature of this type of battery is between 270°C and 350°C so that the electrodes (which include the active materials) are in the liquid state (melted) and the ceramic separator achieves high conductivity for sodium ions. The specific energy of the cells is approximately 120 Wh/kg at a nominal voltage of 2.3V to 2.6V. Advantages over the sodium-sulfur battery are the inverse structure with liquid sodium on the outside, which allows the use of inexpensive rectangular steel housings instead of cylindrical nickel containers. The assembly is simplified in that the battery materials can be used in the uncharged state as sodium chloride and nickel, and the charged active materials are only generated in the first charging cycle. Sodium nickel chloride batteries are used in small series of electric vehicles in fleets and for stationary storage applications.

Sodium-sulfur (NaS) batteries:

The cells consist of an anode made of molten sodium and a cathode made of graphite fabric soaked with liquid sulfur to achieve electrical conductivity as sulfur is an insulator. As in the case of the NaNiCl battery, the solid electrolyte β-aluminum oxide is used as the electrolyte, which becomes conductive for Na^+ ions above a temperature of approximately 300°C. The optimum temperature range is between 300°C and 340°C. During the discharge process, sodium is oxidized to Na^+, and the positively charged sodium ions enter the solid electrolyte from the liquid sodium, releasing electrons in an external circuit. The sodium ions migrate through the electrolyte to the positive electrode, where they form sodium polysulphides. The cell voltage is 2V. This process is reversed during charging. A major advantage of the sodium-sulfur battery is that the internal resistance of the cell is almost independent of the state of charge. It only rises sharply towards the end of the charge because there is a decrease in sodium ions in the electrolyte.

The required operating temperature is maintained in normal operation by the power dissipation of the cells themselves; in stand-by operation it is achieved by an additional electric heater, which decreases the system energy efficiency.

The NaS battery: One advantage of this battery is the high cycle stability of over 4,500 cycles and a long calendar life of over 15 years. The technology was commercialized in 2002, mainly for grid storage with more than 1 MWh of energy. Today, it serves niche markets as other technologies, such as pumped hydro, lead- and Lithium-based batteries have generally better performances.

Both NaNiCl and NaS batteries have service life of over 4,500 cycles and efficiency up to 75% to 86%, due to thermal losses (heating is necessary to maintain the cell temperature). Better thermal insultation can help, in particular if there are longer time periods between charging and discharging.

Room-temperature sodium-ion batteries are often compared to the more commercially established lithium-ion batteries, as they share the “rocking-chair” working principle, where an ion is moved, or “shuttled”, between two host materials at the positive and negative electrode, a concept first proposed in the 1970s. In a SIB the shuttling ion is sodium (Na) instead of lithium. Seminal research on sodium-based active materials dates back to the late 1960s, roughly around the same time as lithium-ion. While lithium-ion was commercialized in 1991, interest in commercialization

SIB started only around 2010, and increased during early 2020s when several companies announcing plans for mass production.

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.

B. Most promising battery technologies

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

Sustainability Aspects: Emphasis is placed on technologies that reduces 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

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 emission.

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. As such, the essential electrochemical storage systems identified are listed hereunder.

B.1. Advanced Lead battery technologies

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

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.

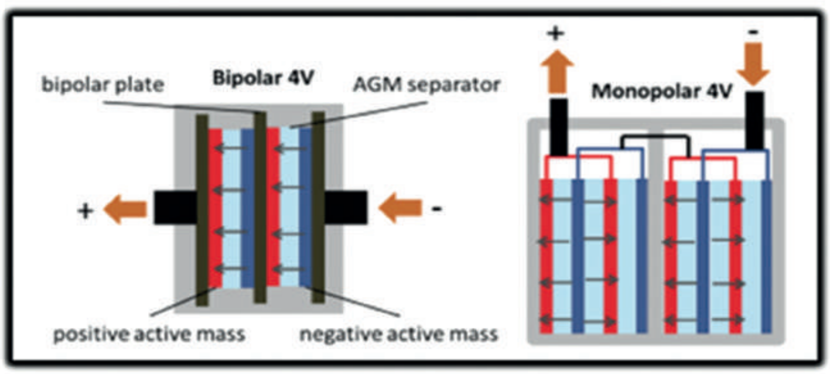


Figure: Bipolar design - the cells are stacked in a sandwich construction

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 industrialisation 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	Na-Ion (RT)
>2027	High Energy Density Na-Ion (RT)
>2030	All Solid State

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 (FCE)	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, in particular, 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 characteristic 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 NaMO2, 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 $Na_xM_y(CN)_6 \cdot zH_2O$, and M a transition metal, such as Fe, Mn. These can be further classified as prussian white, prussian blue, and prussian green
- iii) 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 $Na_3V_2(PO_4)_2F_3$ (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 aluminum 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

Inexpensive and environmentally friendly metals such as sodium and polyvalent light metals should one day replace lithium battery technologies. A major challenge, however, is the development of durable and stable electrodes with high energy density and, at the same time, fast charging and discharging rates.

Gen 3b	▪ Cathode: HE-NMC, HVS (high-voltage spinel) ▪ Anode: silicon/carbon	Optimised Li-ion	2025
Gen 4a	▪ Cathode: NMC ▪ Anode: Si/C ▪ Solid electrolyte ▪ Solid state Li-ion	Solid state Li-ion	2025
Gen 4b	▪ Cathode: NMC ▪ Anode: lithium metal ▪ Solid electrolyte	Solid state Li metal	>2025
Gen 4c	▪ Cathode: HE-NMC, HVS (high-voltage spinel) ▪ Anode: lithium metal ▪ Solid electrolyte	Advanced solid state	2030
Gen 5	▪ Solid electrolyte Li|O_2 - lithium air/metal air ▪ Conversion materials (primarily LiIS) ▪ New ion-based systems (Na, Mg or Al)	New cell gen: metal-air/ conversion chemistries/ new ion-based insertion chemistries	>2030

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

B.3.1. Lithium all-solid-state (Gen. 4)

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.

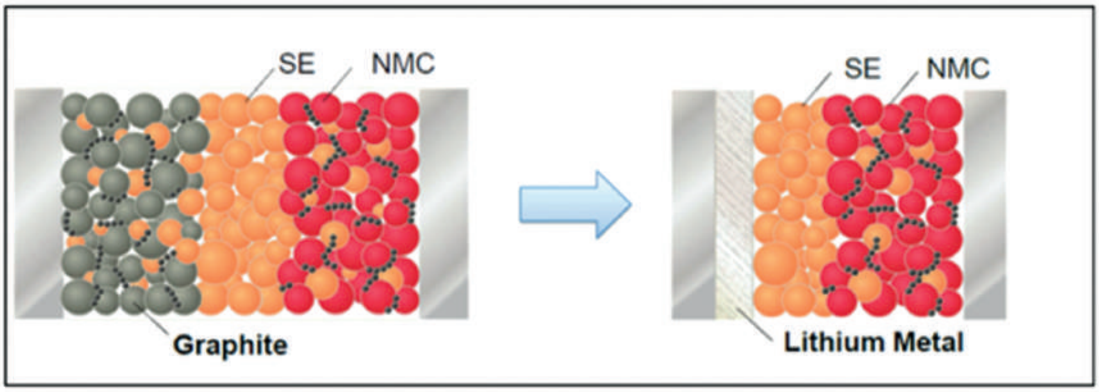


Figure Gen. 4a:
Specific Energy ~ 280 Wh/kg

Figure Gen. 4b:
Specific Energy ~ 450 Wh/kg

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.

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.

B.3.2. Lithium-sulfur (Gen. 5)

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

Lithium-sulfur (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 commercialisation 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 sulfur (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 commercialisation.

Li–S batteries are promising because of the high energy density, low cost and natural abundance of sulfur. However, these advantages can be achieved only when the Li–S battery uses elemental sulfur as the cathode active material and the sulfur 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 sulfur composites based on various types of carbon materials and conducting polymers have driven the specific capacity of sulfur 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 sulfur content (< 60%) and low sulfur 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 sulfur 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 sulfur species, and on the other hand causes severe redox shuttle and parasitic reactions with the Li anode.

B.3.3. Lithium-air (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 draw-back right now is the low round trip efficiency. It is well-recognised 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 Batteries

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. R&D focus of Battery End-user applications

A total of 15 end-user applications are selected in 4 areas where batteries have been recognized as key enablers o significantly contribute to Europe's decarbonization strategy and to make Europe less dependent on fossil fuels, namely:

- **Automotive mobility applications**
- **Motive power material handling and logistics applications**
- **Motive power off-road transportation applications**
- **Stationary Energy Storage applications**

This chapter provides a direction on the current technical battery requirements for these applications and what we believe is feasible to target by 2030/2035. With this market-oriented approach, battery experts identified the KPIs per technology to prioritize R&D to meet the shifting demands in these end-user applications.

A. R&D area - Automotive Mobility

The road transport sector is responsible for over 20% of the EU's total CO2 emissions. It has a strong potential to contributing 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, pushing to further electrify all vehicle architectures. Although today there is a strong focus on battery electric vehicles (BEVs), there is still also a wide potential for the role of batteries to evolve further to increase the energy efficiency in different degrees of hybridization, from start/stop to mild, full and plug)in HEVs (xHEVs). 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.

12V Auxiliary and SLI batteries are also 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 five applications in this area:

- 12V Auxiliary Batteries
- 12V Start-Lighting-Ignition Batteries (SLI batteries)
- Heavy Commercial Stand-by Batteries (HCV Stand-by batteries)
- Mild and Full Hybrid Vehicle Batteries (HEV batteries)
- Battery Electric Vehicles (BEV batteries)

EUROBAT is a 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.

A.1. Automotive 12V Auxiliary Batteries

Application profile

12 V 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).

Accordingly 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.
Such batteries are typically sized for energy or capacity (e.g., to support parking loads for a certain duration) and power or high-rate discharge current (e.g., powering electric chassis actuators) simultaneously. As 12 V batteries in electric vehicles can be recharged out of the traction battery while parking, they can be downsized and also subjected to higher relative cyclic throughput at greater depth -of- discharge, compared to a starter or micro-hybrid battery in an ICE vehicle.
This auxiliary battery category could be required to support emergency power in system architectures where such functionality is not supported by any additional dedicated energy and power source.

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):

12 V 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.
Such batteries are often disconnected from the 12 V loads when alternator or dc/dc converter are not feeding the 12 V system, protecting them from discharge while parking etc. In such cases, the operating state-of-charge (SOC) range may be narrow (and close to fully charged) and cycle-life requirements only moderate or low.

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):

12 V 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 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 are complementary 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 life, low temperature performance, recycling efficiency and cost, but there are improving opportunities for what concerns energy density and life span. 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) lead acid batteries will generally be preferred.

Research and innovation scope

Key Performance Indicators (KPIs) selected for auxiliary automotive applications in all hybridisation 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
- Low temperature power performance, expressed in multiple Cn (A) ensuring suitable voltage level at -30°C for safety manoeuvring required by the application
- Recycling efficiency (%)
- System cost in €/kWh
- Life span (years)

The spider diagram hereunder on the key performance indicators for 12V auxiliary batteries provides an overview of the state-of-the-art and objectives by 2030 for innovation in the mainstream lead-based and Li-ion technologies.

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 flooded 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.

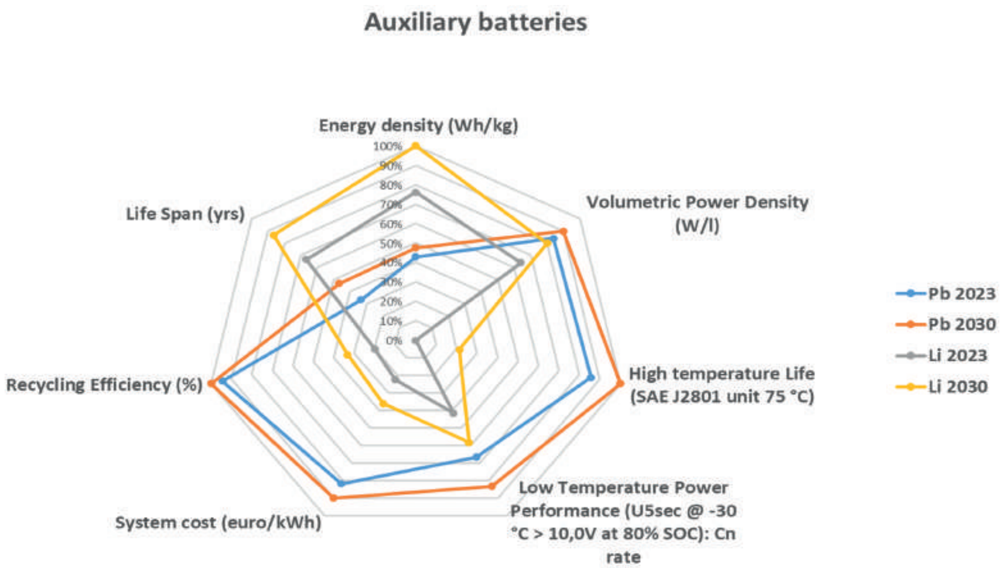
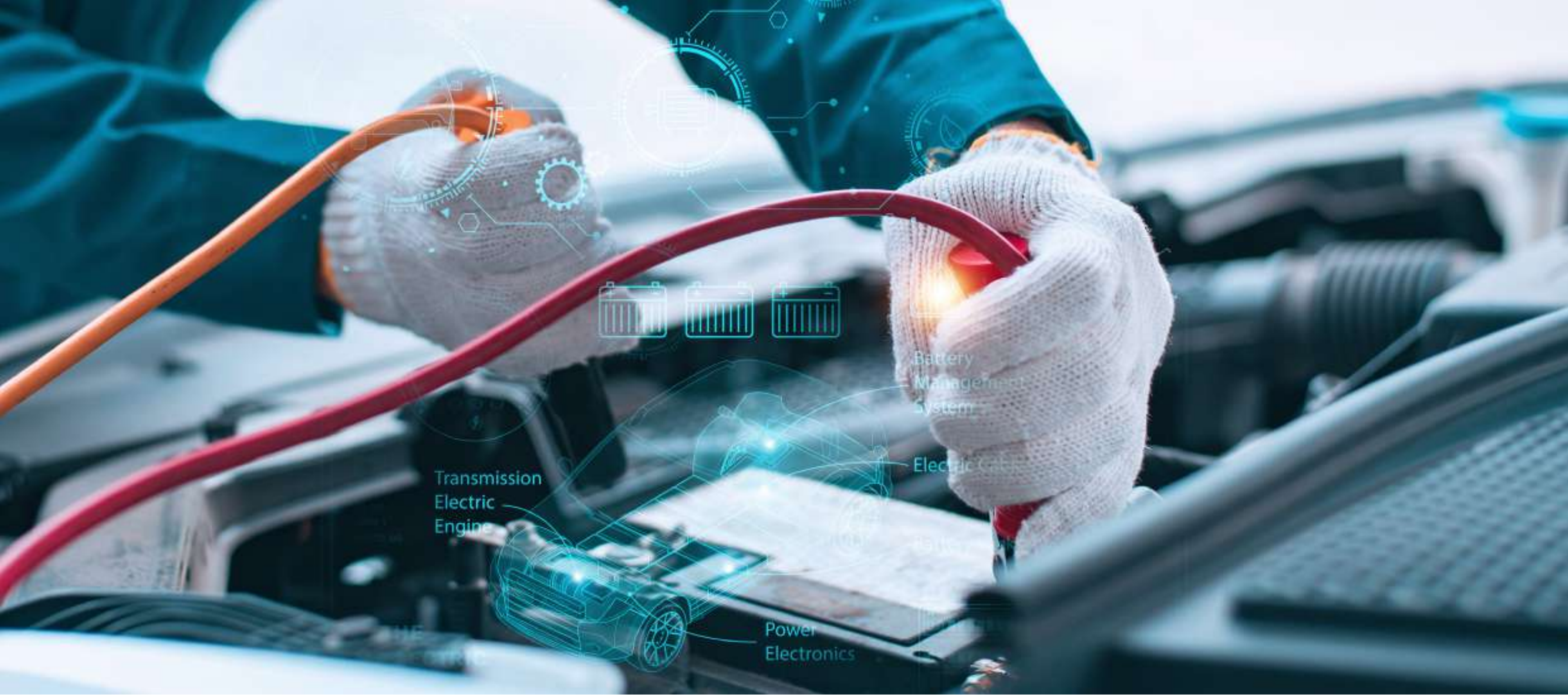


Figure: KPI Spider diagram – 12 V auxiliary batteries



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 up to 65% 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, lead will generally remain the preferred option for both flooded and AGM battery types due to minimized over-voltage risk and self-disconnection of the battery.. On the other hand, the possibility to diagnose the state of charge and state of health of the battery could represent an advantage for Li-ion batteries in relation to safety features that are demanded of auxiliary batteries.

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.

Battery market

In the automotive sector the role of 12V batteries will remain dominant in all vehicle architectures. Taking into account the AVICENNE study commissioned by EUROBAT on supply (production + imports) and demand in Europe (EU28 + EFTA1), the auxiliary battery market is a fast-growing market with a CAGR of +13% (in GWh), expected to rise from 34 GWh in 2022 to 80 GWh by 2030, with 12V lead advanced and 12V Li-ion batteries each serving 50% of the market by 2030.

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.

► 12 V Auxiliary Battery landscape - by 2030

European market estimated at 8 GWh with 2 dominant technologies serving each around half of the market

- Advanced lead, AGM & EFB further taken over from flooded
- Lithium-ion, LFP & LTO
- **By 2035**: Evolution of the technology shares depending on R&D progress on both technologies

Pb	Li
50%	50%

A.2. Automotive 12V Start-Lighting-Ignition Batteries (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, the target of 1.25 A/Ah is expected for the next years and needs to be balanced carefully against high temperature durability and water loss of the electrochemical system.

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).

Mainstream battery technologies

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. **Lithium-based batteries will continue to take over more market share from lead-based battery and we can expect a significant increase within the next decade.**

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.

Sustainability, safety and aspects

The EN-50342-6 standard on dynamic charge acceptance is key for innovation to capture the energy from regenerating systems when braking or slowing down.

European production capacities

Europe has SLI battey giga-factories in place. Today's annual European production for lead batteries is up to 90 GWh. Lithium production, however, is only >0.5 GWh and expected to reach >5 GWh by 2030. The European battery industry leading the international standardization in this market segment, is well positioned to serve the worldwide market.

Battery market

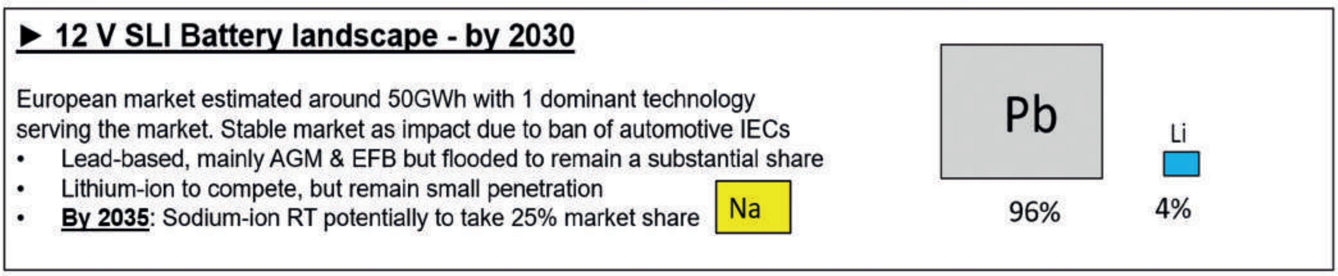
Today, the worldwide 12V SLI battery market is >300 GWh/year and will grow by 1-2% annually to reach >340 GWh/year by 2030. Lead (mainly AGM and EFB) will continue to dominate this market because of its specific features. Lithium will have a moderate penetration of by 2030. A potential lead ban by the EU and/or China for SLI batteries in 2025 in new vehicles is of low probability and with an aftermarket share of 70%, the SLI market segment would still remain very important the next years to come.

Taking into account the AVICENNE study commissioned by EUROBAT on supply (production + imports) and demand in Europe, we consider the 12V battery market segment to remain stable at around 50 GWh, with lead-based batteries strongly dominating this market at 96% and Li-based batteries taking over the small remaining part.

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.



A.3. Heavy Commercial Vehicle Stand-by Batteries (HCV Stand-by Batteries)

Application segment

In many cities today, trucks are not allowed to run in idle overnight when loading or unloading and in some Member States further legislation is being developed that will not allow cars to stay in idle for longer than a few minutes. Legislative changes have led to new battery requirements and resulted in a completely new market developing, in particular for Heavy Commercial Vehicle stand-by batteries (HCV stand-by batteries).

Application profile

The purpose of these batteries is to ensure a high energy supply when both the engine is not running and electric energy demand is high. This requires deep-cycle performance, which cannot be achieved with existing conventional starting or dual-purpose lead batteries. Today, only lead is in this new market, but in future lithium might also break through. 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 lead dominance in this application. **Beyond 2030 the Lithium or alternative battery technoliges like Sodium based chemistry become more dominant in this applications. Reason are the increased energy content and density because of increase service function in the driver cabin.**

When charging or discharging trucks in cities when the engine is turned off, a very high energy supply is needed to serve the heavy electric loads. This requires specifically designed high-energy batteries with deep-cycle performances.

Mainstream battery technologies and key performance indicators

The dominant technology for this application is lead. Together with lead, lithium could also function in this category to cater for future requirements. Key performance indicators for innovation are energy and power density, total cost of ownership, energy throughput, vibration robustness and recycling rate.

Deep-cycle lead batteries have the potential to improve through increasing the charge acceptance and decreasing the total cost of ownership. The current conventional starting or dual-purpose lead batteries cannot meet such deep-cycle performances. Today, only lead is in this new market, but in future lithium might also break through, although the temperature window and total cost of ownership will be challenging.

Sustainability, safety and standardization aspects

Vibration resistance and harsh road conditions by either off-road applications or frame-mounted battery trays provided by the EN 50342-1 V levels also drive the design into a very robust layout. The V4 vibration performance level was added to represent real-life vibration duty observed by the OEMs, which is best provided by lead batteries in the next years.

Battery market

Today, 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 lead dominance within this application. The annual production of lead batteries in Europe today is 10 GWh, which is estimated to reach 18 GWh by 2030 (1).

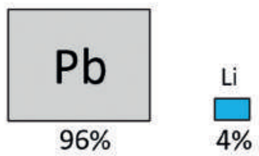
In Conclusion

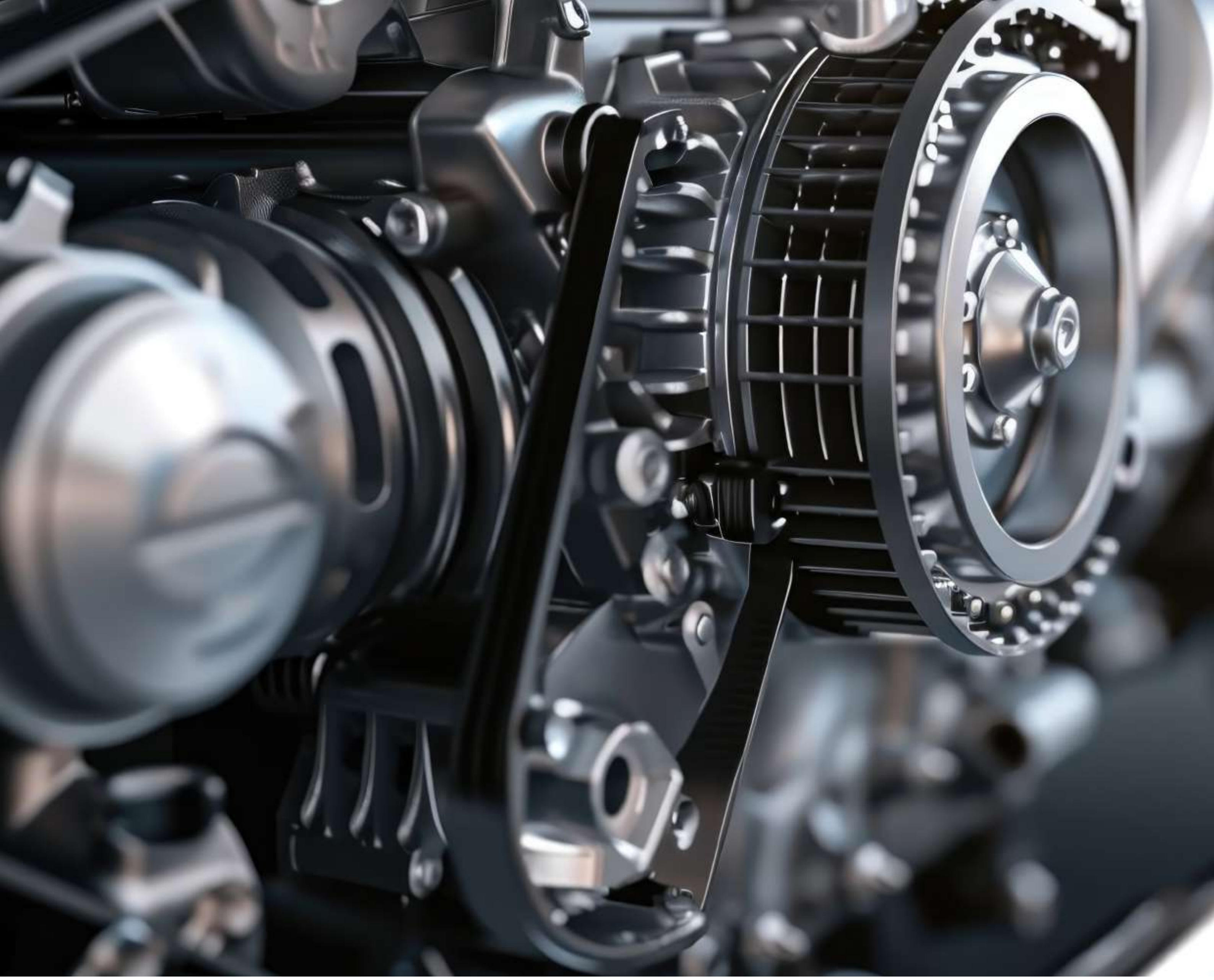
KPIs for innovation are energy and power density, total cost of ownership, energy throughput, vibration robustness and recycling rate. Deep-cycle lead batteries have the potential to improve through increasing the charge acceptance and decreasing the total cost of ownership. The current conventional starting or dual-purpose lead batteries cannot meet such deep-cycle performances. **Beyond above mentioned KPI's, function safety features of the energy storage system become key. Key factor is the transition towards autonomous driving. A preditable energy backup source will become mandatory for this new applications**.

► Heavy Commercial Truck Stand-by battery landscape 2030

European market with a lead-based technology to dominate this market segment

- Lead-based, mainly AGM & EFB but flooded to remain a substantial share
- Lithium-ion difficult to compete, with moderated penetration
- **By 2035**: significant growth driven by regulatory pressures





A.4. Hybrid Electric propulsion batteries (mild an full HEV Batteries)

Application segments and battery features

- 48V – 144V mild hybrids
- The full HEV application (< 2 kWh to stick with the EC classification)

The hybrid electric vehicle segment is considered to range from 48V applications (< 2 kWh, 10-20 kW) to full-HEV applications (< 2 kWh, 30-40 kW). Compared to the power-to-energy ratio (P/E) of pure electric vehicles and plug-in hybrid electric vehicles (**e.g. PHEV 15 kWh, 70 kW Peak**), the P/E ratio of mild-to-full HEVs is considerably higher P/E = 10-20 compared to 2-8 for EVs, which drives a different system integration factor as well as cell and electrochemistry design.
The contribution to the zero pollution targets of the European Green Deal is lower for mild-HEVs (~10% fuel efficiency

gain) and full-HEVs (~25% fuel efficiency gain) compared to PHEV and EVs (up to 100% fuel efficiency gain, though still not GHG CO2 eq neutral)

Mainstream battery technologies and key performance indicators

The main electrochemistry for mild-HEV and full-HEV applications is Li-ion, preferably with NMC | C compositions. Since the P/E ratio is less demanding for usable energy content, dopands on the anode side, such as Si-additives to improve specific energy content, are less expected than in PHEV and BEV applications.
Semi solid-state technology may also be expected to be introduced after BEVs are equipped with this breakthrough step, especially since semi solid-state electrolytes (all-solid-state batteries (ASSB)) will not face a disadvantage in specific power requirements due to the lower conductivity of the electrolyte compared to liquid solutions.

Safety and sustainability aspects

Safety, circularity and recycling aspects are very similar to high voltage Li-Ion battery systems as mandated in the new EU Batteries Regulation. Recovery rates of specific metal components, as well as overall recycling efficiency, should be tied to the new EU Batteries Regulation.

Battery market

EU market demand for HEV batteries raises in 2022 to 4.3 GWh, which is expected to grow +9% annually up to 7 GWh until 2030 with a majority share in the 48V segment (1). While as for the Plug-in HEV, the market in 2022 is 14,2 GWh with expected CAGR decreasing with -4%, estimated at around 7 GWh by 2030.

Over the last decade, the vast majority of HEVs have used the NiMH electrochemistry, with one dominant player in the hybrid fleet. While NiMH will play a role over the next couple of years, only Li-ion technology, with NMC | C. LFP is actual not in use in Europe for HEV's as the energy density is too low, but we expect it will be used in new vehicles by end of this decade. NiMH-powered 25% of HEVs in 2022, but Li-ion is replacing NiMH and will become the sole technology as from 2025-2030. Due to the ban of new ICE vehicles, this market will disappear as of 2035.

Outside of the EU27, we may still see alternative technologies like NiMH being used in HEVs. European production capacities are closely linked to the proliferation of giga-factories because of the similarities and synergies in the manufacturing process compared to BEV battery systems.

In conclusion

Semi-Solid-state technology will be introduced after BEVs are equipped with this breakthrough step. Semi solid-state electrolytes did not face the disadvantage in specific power requirements due to the lower conductivity of the electrolyte compared to liquid solutions.

The very low content of liquid electrolyte will give a much better safety. Circularity and recycling aspects are very similar to high-voltage Li-ion battery systems as mandated in the new Batteries Regulation. Recovery rates for specific metal components, as well as overall recycling efficiency, should be tied to the Batteries Regulation.

► **Mild and Full Hybrid Electric traction Battery landscape by 2030**

European market estimated around 7GWh with a dominant technology to remain in Europe

- Dominant lithium based: NMC mainly and LFP penetration after 2030
- Landscape by 2035: impact due to ban of automotive IECs in EU

Li 100%

A.5. Battery Electric Vehicles traction batteries (BEV Batteries)

Application segment and profile

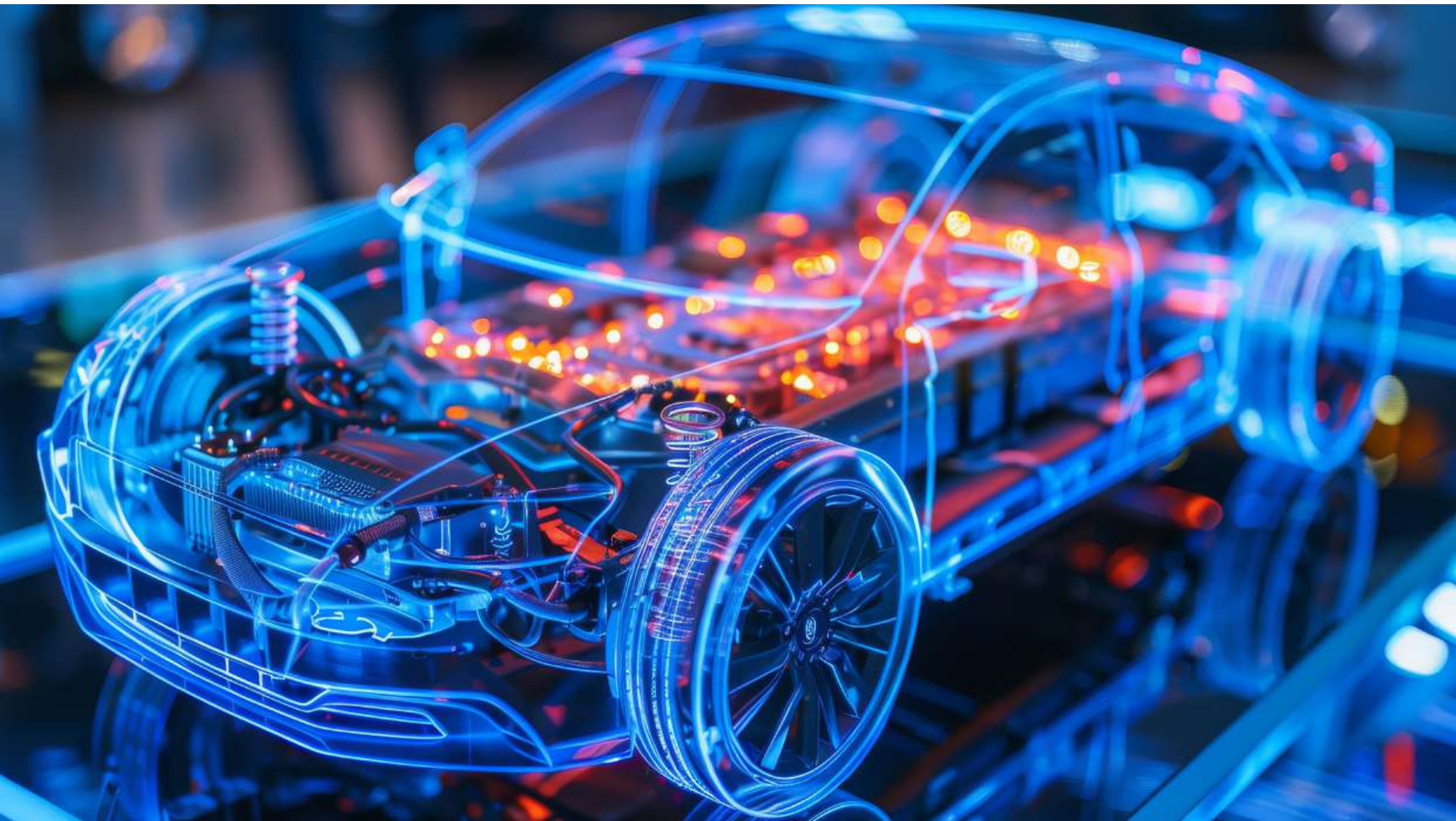
BEV automotive requirements differ due to a large variety of vehicle sizes and applications. Passenger cars vary from small size sports cars to premium large SUVs. Also, light commercial vehicles have different space and business needs, whereas heavy-duty trucks and buses have different use profiles.

Safety is, without a doubt, the most important requirement. For most automotive segments, battery system cost generally comes in second. For road BEVs in general, high power and energy play a key role in determining range and charging speed. With the new Battery Regulation in place, the environmental aspect is also playing an increasingly important role.

Mainstream battery technologies and key performance indicators

The technologies of choice are Li-ion batteries using lithium nickel manganese cobalt oxide (NMC or $LiNi_aMn_bCo_cO_2$ 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.

With battery technology for EV application becoming increasingly mature, the focus today is on reducing battery system cost, and increase performance, such as gravimetric and volumetric energy. This will lead to electrification of more and more segments. As of 2023, it's worth noting that in countries like China, it is possible to buy EVs at a cheaper price compared to ICE-powered vehicles. 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. The most notable development of the 2023 was 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 being adopted by automakers.

Other chemistries, such as sodium-ion, and solid-state lithium-based batteries are at various stages of R&D, and could enter the market during the next years, with sodium-ion currently the most mature, particularly in China. Commercialization of sodium-ion is imminent, 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.

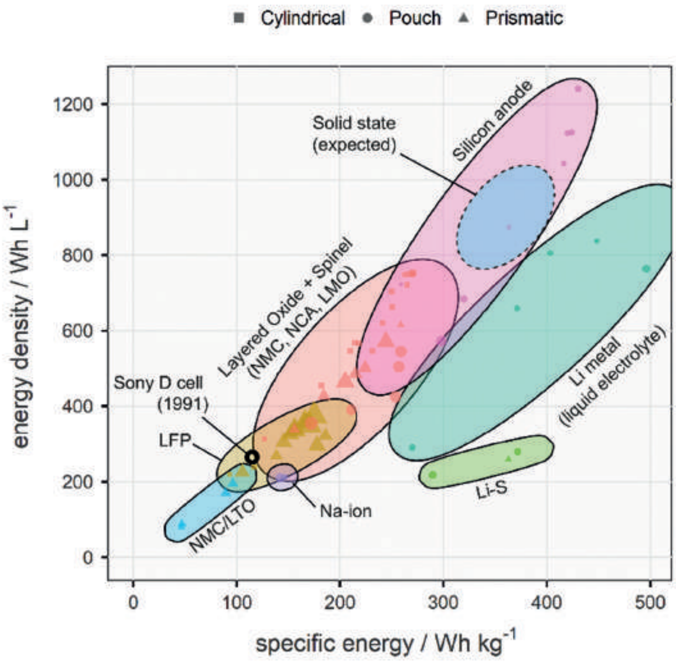


Figure: Range of energy content of different battery technologies at cell level, energy density vs specific energy for selected Li-ion and "post-Li-ion" cells (5)

Key performance indicators for innovation

Driven by the market demand and regulations:

- Energy and power density
- System cost
- Energy throughput
- Charge acceptance
- Operating temperature range
- 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**.**

System-level performance is what ultimately matters, particularly safety, which still needs to be assessed for several so-called next generation chemistries, such as solid-state. 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.

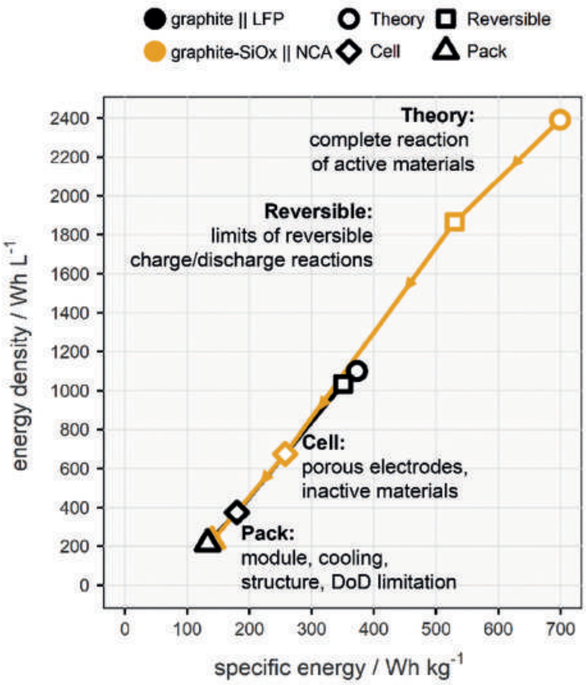


Figure: Energy losses between theory and system level. *Reduction in energy on a weight and volume basis between the theoretical maximum for the active materials and usable pack-level energy density for state-of-the-art NCA and LFP battery technologies (5)*

Research at pack level is therefore key to achieve 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

Moreover, new emerging business models and ecosystems could be promising in making the experience of driving EV more convenient and sustainable. One example, which is rapidly growing in countries like China, and being tested in northern Europe, is battery swapping. Here batteries, instead of being charged while the car is plugged in a charging station, are exchanged in ad-hoc stations. The process generally takes just a few minutes. Batteries in the swapping stations can be integrated in the grid, and be used for stationary storage application, such as energy arbitrage and frequency regulation.

Finally, it is worth noting that batteries for BEVs and HEVs are generally different. HEVs include a wide range of different vehicle, 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 favor 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.**

Sub-segment Commercial vehicles

A. Heavy Commercial vehicles

In addition to the KPIs above, batteries for heavy commercial vehicles have additional demands for higher energy density and longer cycle life. They have a wide variation in operation profiles and therefore require multiple solutions. Specific research will be needed on packs to support the specific requirements of commercial vehicles:

- Dedicated thermal management solutions
- Advanced materials for commercial and heavy-duty vehicle design
    - For pack enclosures
    - For thermal management solutions Light Commercial vehicles

B. Light Commercial vehicles

The key performance indicators of BEV light duty vehicles are highlighted in the ETIP Batteries Europe roadmap (cfr. tabulation hereunder) and the Strategic Research and Innovation Agenda (SRIA) of the Batt4EU partnership.

Road transport: Light duty BEV*Typical Battery Size : 20-100 kWh (today), 40-120 kWh (in the future)					
KPI	Operating conditions	System/Pack/ Cell level	Unit	2020	2030
Cell/pack weight ratio		Pack	%	70	80
Cell/pack volume ratio		Pack	%	60	75
Operating lifetime expectation	Minimum guaranteed lifetime (equivalent 80% DOD)	Pack	km	~150,000 (~Vehicle lifetime)	
Gravimetric Power density **	180s, SoC 100%-10%, 25°C	Cell	W/kg	750	1,000
Gravimetric Energy density	C/3 charge and discharge, 25°C, charging with CC and CV step	Cell	Wh/kg	~250	~450
Volumetric energy density	C/3 charge and discharge, 25°C, charging with CC and CV step	Cell	Wh/L	~500	1,000
Volumetric power density**	180s, SoC 100%-10%, 25°C	Cell	W/L	1,500	2,200
Cycle life	80% DOD, 25°C	Cell	cycles	1,000	2,000
Hazard level		Cell	-	<=4	<=4
COST					
Cost		Pack	€/kWh	200	85
Cost		Cell	€/kWh	125	70
MARKET					
Market size	Source: Avicenne Energy, 2019; IEA Global EV Outlook 2020		GWh/year	~40	~1,000-2,500

Tabulation: KPIs for road transport light Duty BEVs (Source: ETIP Batteries Europe Roadmap)

Sustainability, safety and standardisation aspects

As domestic battery demand and manufacturing scale up, the recycling market is expected to grow. . Also, second life, re-use and re-purposing could 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), as well as the battery features and targets being directly introduced in the EU's SET Plan to target the application.

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 rise to considerably, representing 85-90% of the total lithium battery market share by 2030 (1).

Market drivers include favorable 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., $LiNi_aMn_bCo_cO_2$ 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, which could enter the market during the next years to come.

Current European lithium-ion battery demand from xEV, including buses and trucks, is 140 GWh, with an CAGR of +30% to reach Over 800 GWh)(1). The EV market is also expected to grow considerably after as a result of the ICE ban in 2035. In 2030 we expect that around 40% of all new vehicles sold in Europe will be fully electric, while after 2035 new electric vehicle penetration might be around 80%. The legislation is also expected to lead to the disappearance of other battery technologies, such as NiMH, which powered 25% of HEVs in 2022. Li-ion is expected to replace NiMH and will become the sole technology in 2025-2030. Due to the ban of new ICE vehicles, this market will disappear as of 2035.

Annual European effective production of lithium batteries in 2022 was estimated at 30 GWh, with a production capacity of about 76 GWh. Production capacity is forecasted to reach 800 GWh by 2030, depending on the market scenario used, slightly short of an estimated demand of 835 GWh (1)

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 reusing or repurposing EV batteries. Furthermore, specific additional research on heavy and light commercial vehicles will be necessary, as specified in the ETIP Batteries Europe roadmap and the SRIA of the Batt4EU partnership.

► Battery Electric Vehicle (BEV) Traction Battery landscape by 2030

European market estimated over 800 GWh
- Dominant lithium based, NMC & LFP-LMFP
- **By 2035:** we expect sodium-ion RT to play a certain role

Na

Li

100%

B. R&D area - Motive Power Material Handling & Logistical applications

Logistics are 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. 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

Battery features

One advantage for lead is that they act 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 and niche markets with intensive use, the total cost of ownership could become lower than for lead. However, lithium batteries still face issues such as cost, functional safety, operation at low temperature, and high mass energy density. Furthermore, being most of the forklifts designed for housing a lead-based battery, the use of lithium-based batteries still requires to add extra ballast to the design in order to reach the minimum weight required for safety purposes.

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.

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 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. Other R&D areas for innovation are digitalization and innovation with regards charging** . Fleet management, by the use of IoT technology can highly increase battery life, monitoring the use of batteries and anticipating corrective action in case of abuse.

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

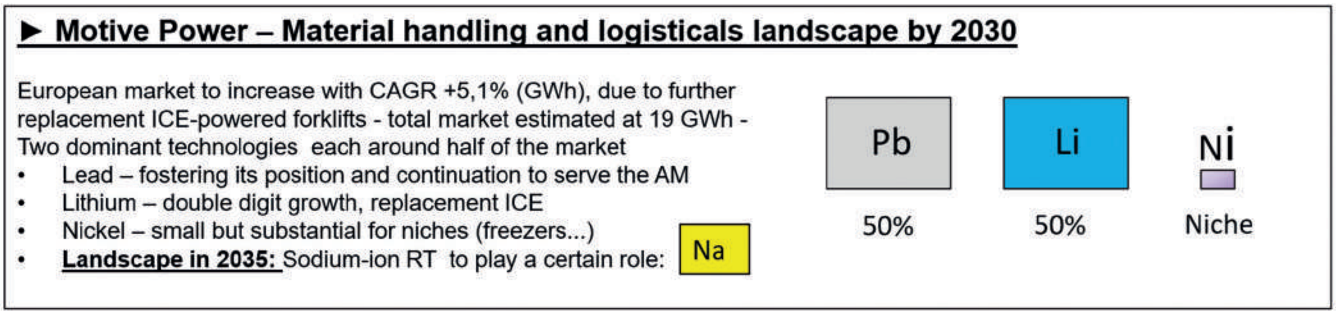
Battery market

Traction and semi-traction batteries for material handling, such as in forklift applications, is historically lead battery focused, currently having around a 70% of the global market share. Lithium is taking important parts 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 32 GWh in 2022, with expected annual growth of around 8%. In 2022 the European market represented 13,3 GWh, expected to grow with CAGR +6%, until 2030. Pushed by noise and emissions legislation, battery forklifts are steadily replacing the ICE propelled vehicles, with a market predicted to reach 67 GWh by 2030. Thi high market growth will be mainly driven by lithium-based technologies, while lead-based will keep a steadily position in the market.

In conclusion

Lithium has entered the market for smaller forklifts 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.



C. R&D area - Motive Power Off-road Transportation

We distinguish the following segments to describe these motive power off-road transportation batteries:

- Off-road multi-purpose industrial vehicles
- Motive power batteries in railway applications
- Motive power batteries in marine applications
- Motive power batteries in aviation applications

C.1. Batteries in 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, 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 and other small machines.

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 application 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 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 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.

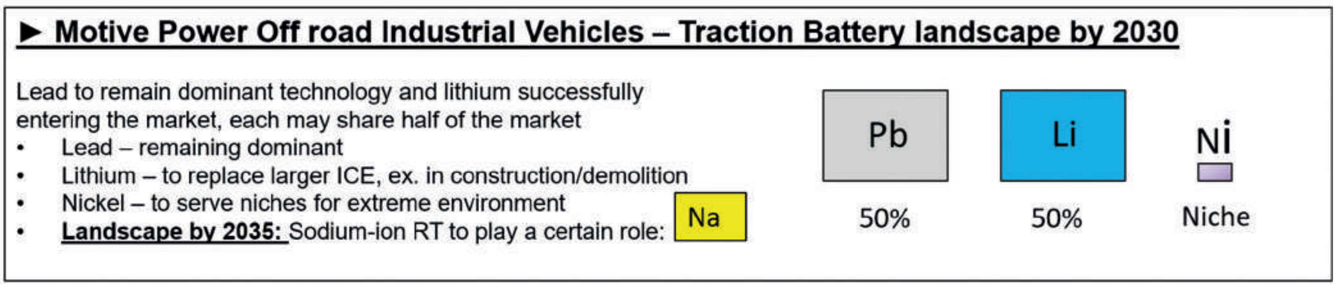
For the construction/demolition segment, where there is high vibration and though environment, an ultra high mechanical resistancve and chemical stability of cells are strictly required. Other important aspects driving innovation are safety, circularity and increased recycling targets.

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. But lithium is entering the powering market successfully because of replacing the ICE powered vehicles, because restricted battery compartments and higher currents due to the heavy loads, in particular for construction/demolition vehicles. Nickel-based technology (NiCd), with its broad operation 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 driving innovation are safety, circularity and increased recycling targets.



C.2. Batteries in Railway Applications

Rail infrastructure is the most efficient transportation mode in Europe with regard to 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 signaling', '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 kilometers" 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 in particular, which are expected to be the fastest growing battery segment due to benefits such as being maintenance-free and having a longer lifetime. For batteries used to power auxiliary functions, as well as lights and fans in high speed and metro trains, the nickel-based chemistry is the preferred technology. 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 dominant technology is lead, both flooded and sealed, but nickel and lithium also have a significant share of the market.

The development trends for on-board units favor 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 rush operational conditions.

As for further developments in infrastructure, different battery technologies will co-exist given the variety of applications, including lead batteries, both flooded and sealed. 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 ranges.

Mainstream technologies by 2030, for traction, Lithium-based and for auxiliary it will be Lead-based and NiCd

Battery market

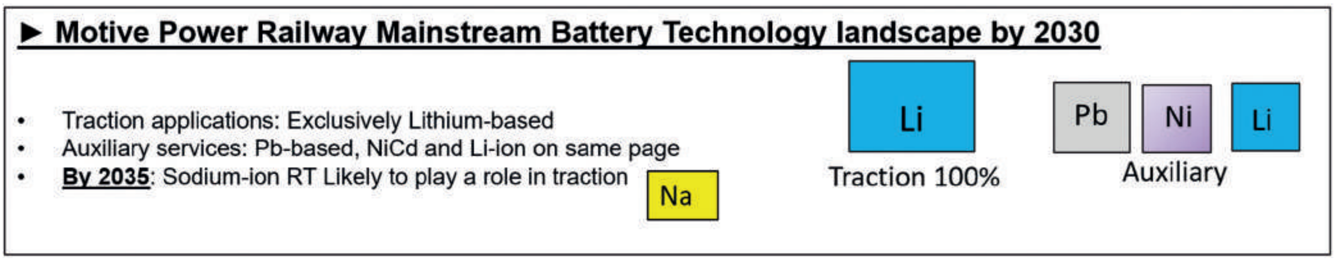
The railway segment is a very fast-growing market, driven by increasing populations and increased demand for rail transport around the world. Asia is highly active in the sector and expected to have a significant impact on the train battery market in Europe.

The overall battery market has high growth potential, with annual growth until 2025 for Li-ion, Nickel-Cadmium and lead forecast to be 25%, 5% and 4%, respectively. 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 favor 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**, 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 rush operational conditions. A large proportion of the lines currently operated with diesel vehicles are non-electrified sections "well under 100 kilometers" long.

Battery-electric vehicles have the potential in local rail passenger transport to substitute the diesel engines and make a significant contribution to the net-zero emission target. Hybridisation and electrification of rail power traction is the fastest growing battery segment for railway applications. High energy, power density and cyclability suit lithium systems best. Key areas for development are volumetric energy density, lifetime and operating temperature range.



C.3. Batteries in Marine Applications

The transport sector contributes to almost a quarter of Europe's greenhouse gas (GHG) emissions. Compared to other sectors, such as agriculture or energy industries, it is the only sector with emissions higher than that of 1990 (7)

Waterborne transport emissions represent around 13% of the overall EU (European Union) greenhouse gas emissions from the transport sector. Moreover, waterborne transport emissions could increase between 50% and 250% by 2050 (4) under a business-as-usual scenario, undermining the objectives of the Paris agreement (8).

The marine sector is thus a strong contributor to CO2 emissions and pollution in Europe and worldwide. Batteries are enablers that contribute to the transformation of maritime fleets in oceans, seas and inland waters, as described in Strategic Research Agenda from the Zero Emissions Waterborne Transport partnership, which is discussing new battery needs in this sector identifies batteries as an enabler, contributing to the transformation of maritime fleets in oceans, seas and inland waters, whilst recognising that the energy needs of the global fleet of ships and other craft is complex as they often operate remotely from a home port for extended periods.

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

▶ **BEV smaller boats:**
canal, river and lake vessels, integrated fleets with onshore charging infrastructure

- 48V propulsion batteries

▶ **BEV and HEV ships:**
off-shore, drilling, fuel cell vessels, etc.

- Power batteries from 100 kWh to several hundreds of MWh

▶ **BEV and HEV ships:**
cruise liners, ships and ferries, etc.

- Energy batteries from 500 KWh to several hundreds of MWh

▶ **Other batteries in the marine application located on-board and in the infrastructure**

- 12V auxiliary 12V SLI and dual-purpose battery markets for sail boats, etc.
- On-board standby and motive power battery applications (including UPS and TLC) typically for harsh climate/weather conditions
- High-performance, high-density batteries for jet skis, surfboards, etc.

The challenge for a large-scale adoption and implementation of batteries for waterborne transport is related to the high costs of the battery systems and cells." Maritime is therefore to be included in the ETS system and the position of EU industry to include maritime in the EU Green Deal and blue economy strategy.

There is an **urgent need to electrify all forms of boat and marine transport to support the wider aims of reducing global CO2 emissions, which is an opportunity for both lead and lithium batteries. One particular concern is the longevity of the marine fleet, so solutions need to be suitable for retrofit as well as new vessels ready.**

Lithium, due to higher energy densities and cycle life, is well-suited to the needs of propulsion, while lead batteries are more suitable for on-board auxiliary services, to ensure the on-board safety and security functions and to crank the diesel engines

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

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

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

There is adequate space in the marine market for lead and lithium batteries to contribute towards the move to a low emissions future. Lithium, due to higher energy densities and cycle life, is well-suited to the needs of propulsion systems, while lead batteries are more suitable for servicing on-board auxiliary services, ensuring on-board safety and security and for cranking of diesel engines. Batteries specifically developed and optimised for power and energy delivery are also needed to support the wide range of applications found in the marine market.

Maritime activities by their nature require long periods of remote operation. This means that energy becomes critical for the self-reliance that this type of activity requires. Increasing energy density to ensure adequate power will always be available to the operators of these vessels.

Where marine activities occur on inland water ways and rivers the possibility of supporting through swapable battery systems and charging infrastructure will be greater. Development partnerships such as the current direct project will form an important part of supporting of this area of Marine operations.

A. BEV smaller boats – 48V propulsion batteries

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

The dominant technology today is lead, both flooded and sealed. Lithium NMC and LFP are also breaking through in this market.

The market for small electric propelled vessels will increase considerably in future to meet demand. Due to high safety requirements for on-board system use with severe ventilation requirements, a reduced need for maintenance, high vibration resistance and horizontal inclination aspects, we predict that both lead and lithium batteries will co-exist. Lead batteries will shift towards valve regulated technologies, both AGM and EFB, and lithium batteries towards NMC, but also LFP, for safety reasons.

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 standardisation is an opportunity to increase reliability and safety, as well as to reduce the total cost of ownership.

B. BEV and HEV ships: off-shore-, drilling-, fuel cell vessels, etc.

Application segment

Off-shore ship applications with power batteries with capacities from 100 kWh to several hundreds MWh

Mainstream battery technologies and key performance indicators

Lithium technologies are the best available technologies for the take up of this market

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 hereunder

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			Cell	€/kWh	300	150
Cost		Full ESU (Including rack, gas exhaust system, BTMS, BMS)	ESU	€/kWh	1,300	600-700
MARKET						
Typical market size	Source: Fincantieri, Saft internal studies			GWh/an	~0	~2.5

Tabulation: KPIs for typical power batteries - targets by 2030 (source: ETIP Batteries Europe Roadmap)

C.BEV and HEV ships (cruises, ships and ferry's...)

Application segment

Off-shore ship applications with energy batteries with capacities from 500 KWh to several hundreds of MWh.

Mainstream battery technologies and key performance indicators

Lithium technologies are the best available technologies for the take up of this market. The key performance indicators for such typical energy batteries and targets by 2030 are listed in the ETIP Batteries Europe Strategic and Innovation Research Agenda and are listed hereunder

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			Cell	€/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

Tabulation: KPIs for typical energy batteries - targets by 2030 (source: ETIP Batteries Europe SRIA)

D. Other batteries in marine on-board application or in the infrastructure of shipping ports

A variety of batteries are present, such as:

- 12V auxiliary and 12V SLI and dual-purpose batteries for sail boats and other vessels
- On-board stand-by and motive power battery applications, including UPS and TLC for harsh climate/ weather conditions
- High-performance, high-density batteries for jet skis, surfboards, etc.

The market is typically dominated by lead, with niches for NiCd and lithium also entering this market

In conclusion

Battery market

There is an **urgent need to electrify all forms of boat and marine transport, which is an opportunity for both lead and lithium batteries** as both technologies can contribute and have their place in these markets. This is furthermore promoted by the FuelEU Maritime regulation[1] which aims to support decarbonization of the shipping industry. Lithium batteries have higher energy densities and cycle life, while lead batteries are more suitable for on-board auxiliary services, to ensure the on-board safety and security functions and to crank the diesel engines. In all these segments, the market for electric propelled vessels is increasing to meet future demand. For BEV smaller boats, lead 48V propulsion technologies, both flooded and sealed, are dominant today. Lithium NMC and LFP are also breaking through in this market, while for the propulsion of BEV and HEV medium to large ships, the market is exclusively lithium.

Innovation potential

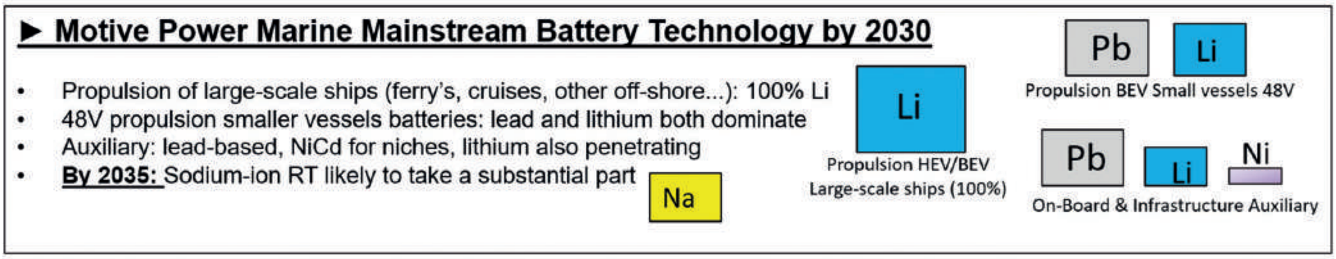
For larger ships and ferries, there are different degrees of hybridisation of the powertrains. Some long-distance cruise ships have thermal engines that charge the batteries via generators to power the electric propulsion engines and reduce fuel consumption and emissions when running at full power for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

For the propulsion of smaller vessels, other hybrid electric systems have been 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. Standardisation is a challenge to reduce costs and meet the high safety requirements of the systems that are used on-board.

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

Key performance indicators for a large-scale adoption and implementation of batteries for waterborne transport are energy and power density, energy throughput, charge acceptance, operational temperature range and recycling rate. More information on the KPIs can be found in the ETIP Batteries Europe SRIA.

Besides R&D, further battery standardisation is an opportunity to increase reliability and safety, as well as to reduce the total cost of ownership.



C.4. Batteries in Aviation Applications

According to the International Energy Agency, the aviation industry produces annually over 800 Mt CO_2 worldwide, and is a notoriously "hard-to-abate" sector. Electric aircraft have been discussed in the last decade in the context of the EU Emissions Trading System (EU ETS) and climate targets. However, with current battery energy densities, it is not yet possible to electrify the propulsion of commercial aircraft.

Potential hybridization and the development of eVTOL (electrical Vertical Take-off and Landing) is a first step to reduce the greenhouse gas emissions of this sector. Europe's CLEAN Aviation Joint Undertaking (Aviation JU), in coordination with the Batt4EU partnership, is developing R&D topics on batteries to meet new requirements in this sector.

Application profile

In 1884, one airship called La France powered by a 435kg Zn||Cl_2 battery took to the air near Paris, which was the first aerial vehicle to complete a controlled, powered round trip flight (8km). This attempt inspired researchers and engineers and paved a way for electric propelled flights.

Today, in aviation, batteries can be utilized for auxiliary services in airliners or to power smaller aerial vehicles, while larger aircrafts are seen as more challenging to electrify. For example, the weight of the batteries needed to power commercial aircraft is roughly 30 times higher than the weight of jet fuel. Even when taking into consideration the higher efficiency of an electric engine, full electric propelled commercial aircrafts require new battery technologies, which are currently under development by several companies.

Powertrain electrification has so far concentrated on smaller aircraft, with both start-ups and established companies proposing several different designs and envisioning future use case scenarios. One example are electric vertical take-off and landing (eVTOL) vehicles. These could be used as air taxis, aerial ambulances or cargo drones, sized to carry a maximum of seven people or equivalent cargo. However, development of these aircraft is still at an early stage, with several infrastructure, policy and technological barriers. To date, there are no viable commercial products, and development is still at the early prototype stage.

Li-based batteries are currently seen as the most promising electrochemical energy storage technology for the propulsion of these vehicles. However, compared with the battery electric vehicles (BEV), eVTOL will have different performance requirements. These will be dependent on several factors, including use case, vehicle design, diffusion of heliports, availability of the charging infrastructure, as well regulations for homologation and safety. Required battery key performance indicators are therefore still under discussion, and dedicated technologies are under development.

Key performance indicators and future battery technologies

In 2021, Yang et al. (10.1016/j.joule.2021.05.001) proposed several hypothetical eVTOL vehicle designs, and modelled battery pack Key Performance Indicators (KPIs) for best-case scenarios, stressing the importance of parameters such as fast charging and discharging (3C-6C), long battery lifetime (1,600 Equivalent Full Cycles, EFCs, per year) and high safety (EUCAR Level 1). In their analysis, they also estimate that battery packs energies of about 200 Wh/kg would be enough for a single intracity commute. Longer commutes, e.g., for short-haul flights, will likely require battery packs with gravimetric energies in the range of 800-2000 Wh/kg.

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".

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 following figure:

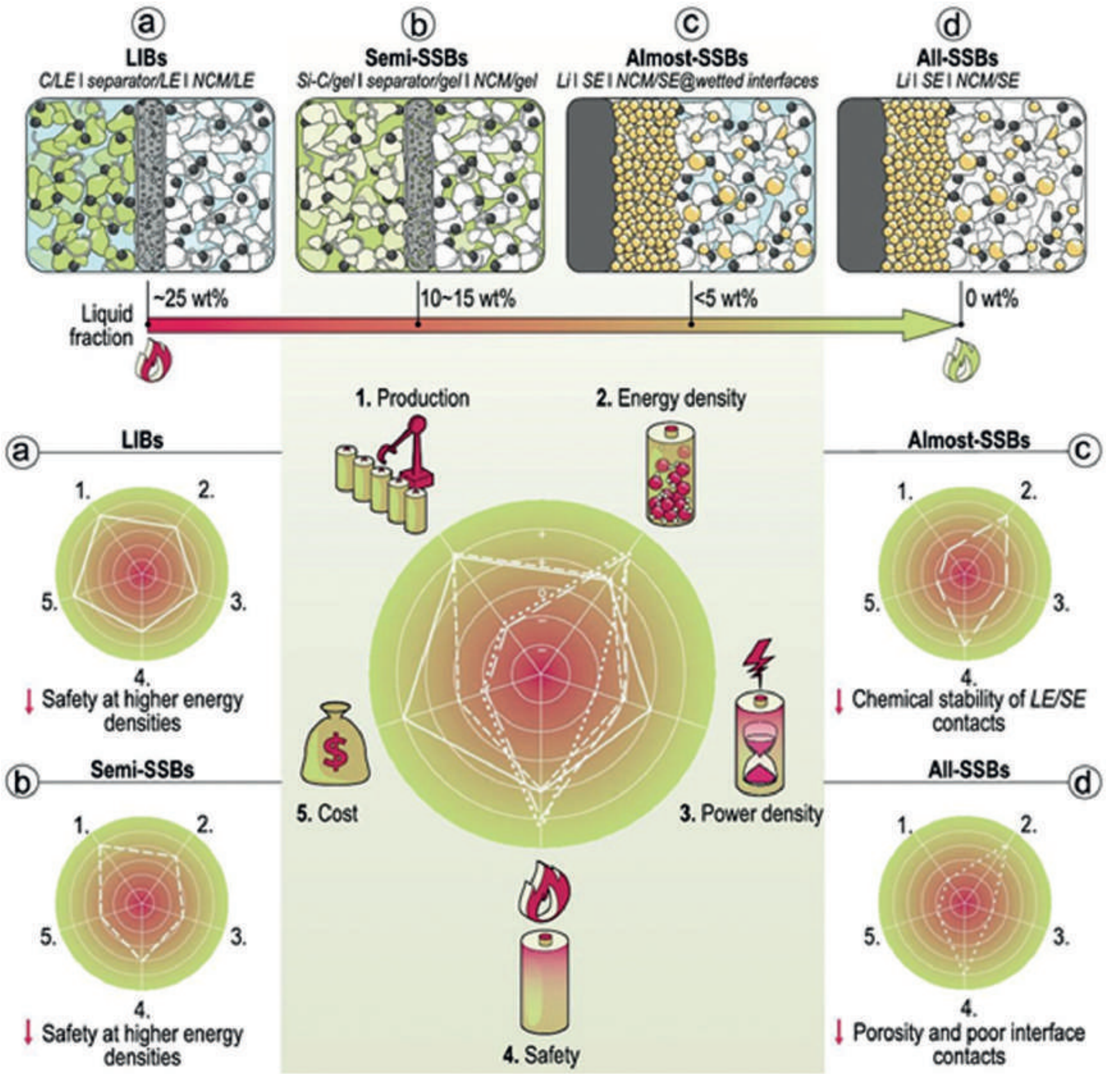


Figure: Comparison of various cell concepts with different fractions of liquid components (9)

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 ($Kg_{Li}/kWh_{battery\ pack}$) 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 behavior and more sophisticated battery management and safety forewarning systems.

Europe's CLEAN Aviation Joint Undertaking (Aviation JU), in coordination with the Batt4EU partnership, is further developing R&D topics on batteries to meet new requirements in this sector to reduce the greenhouse emissions from aviation

In conclusion

Battery market

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. Over 100 firms worldwide have announced work on 1-7 seat short-range urban air mobility vehicles, and while this market is still in its infancy, a 2021 report from Morgan Stanley estimated a total addressable market worth USD1.0 trillion by 2040. 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. In today's markets, aircraft batteries are used for many other 'non-propulsion' functions (e.g. **ground power, emergency power, improving DC bus stability and fault clearing)**. Small private aircraft use lead-based 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.

Innovation potential

Currently, auxiliary batteries in airliners are undergoing a transition from conventional batteries (NiCd and lead-based) to Li-ion batteries, with high energy and power densities, a long lifespan and low cost.

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 (10.1016/j.treng.2022.100134, 10.1038/s41560-018-0294-x), 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. 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 in 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 system (BMS), thermal management systems (TMS), and better safety forewarning systems will also need to be developed.

► Motive Power Aviation Mainstream Battery Technology by 2030

- Propulsion batteries for eVTOL: exclusively Li-ion (LTO...)
- Auxiliary: Lithium to take over NiCd and Pb-based
- **By 2035**: significant growth of the market due to technological progress in high energy density and lower weights

D. R&D Area – Batteries for Stationary Energy Storage

The stationary energy storage sector encompasses various applications, each with distinct requirements and challenges. These applications often necessitate different features and improvements in battery technology. The chapter gives an overview of the four main stationary energy storage segments, namely:

- Uninterrupted Power Supply (UPS Batteries)
- Telecommunication Power Supply (TLC Batteries)
- Residential & Commercial Storage behind the meter (BTM Batteries)
- Utility Grid-scale Storage in front of the meter (FTM Batteries)
- Stationary – Off-grid applications

D.1. 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 a reserve and peak load looping. Virtual power plants and new big 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.

Application profile

Batteries for uninterrupted power supply (UPS) take action 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 a 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 stabilisation (instead of building additional power plants) and in combination with renewable energy sources.

The growth of the market is due to increased use of big data and the associated need for new data storage centres and the 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, and nickel cadmium batteries (NiCd). 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 NMC with carbon-silicon anodes.

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 f these applications through reduced climatisation as one of the main cost drivers and thus the heat exposure to the battery will rise and the batteries must be able to cope with it.

Key performance indicators for this application, as typical back-up time in data centers 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 (UPSaaR). 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 climatisation.

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 2 – 3 x 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.

Hereunder is a spider diagram including the six key performance indicators (KPIs) selected for the application, namely end-of-life management, design and cycle life, high temperature, power density and cost factor

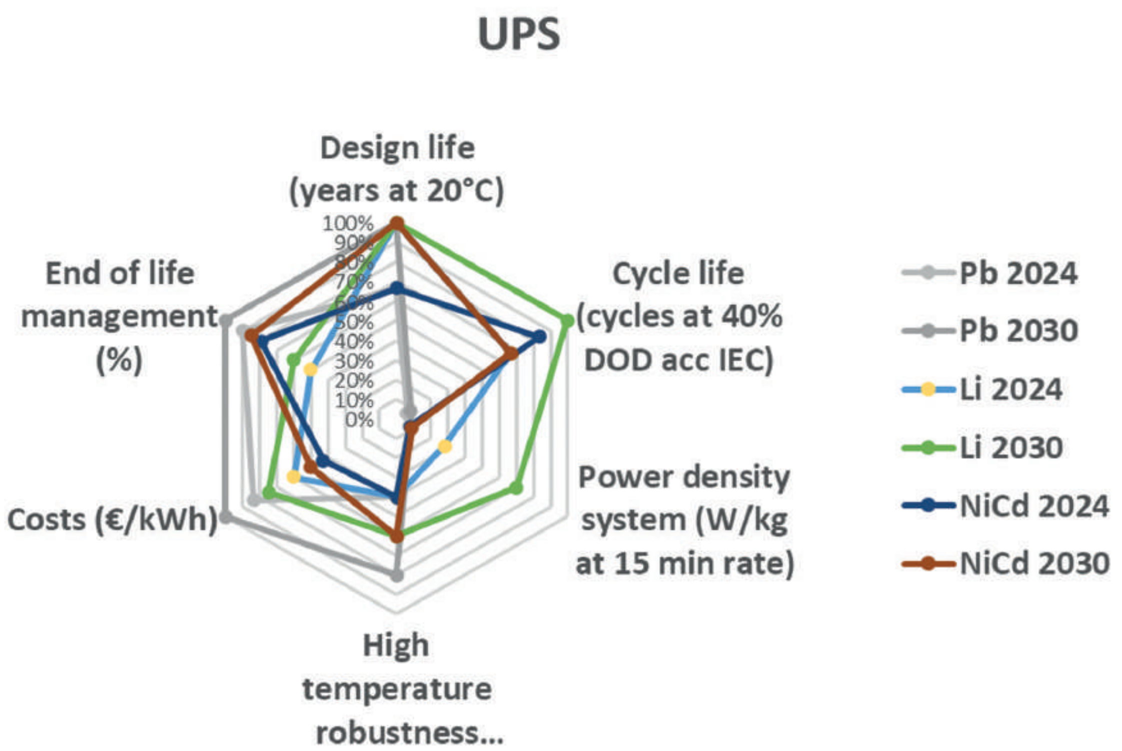


Figure: Six key performance indicators (KPIs) selected for the UPS application

R&I scope and strategic actions

Lead batteries: Increase the volumetric power density to 200 W/l, 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 and increase the cycle life at 40% DOD to 8,000 cycles.

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

Strategic actions for Li-ion batteries: Development 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)

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 a 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.

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.

The expected annual growth rate for lead and lithium is 1.6% and 12% (in value), respectively. Lithium penetration will increase from 22% in 2022 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 centers. (2)

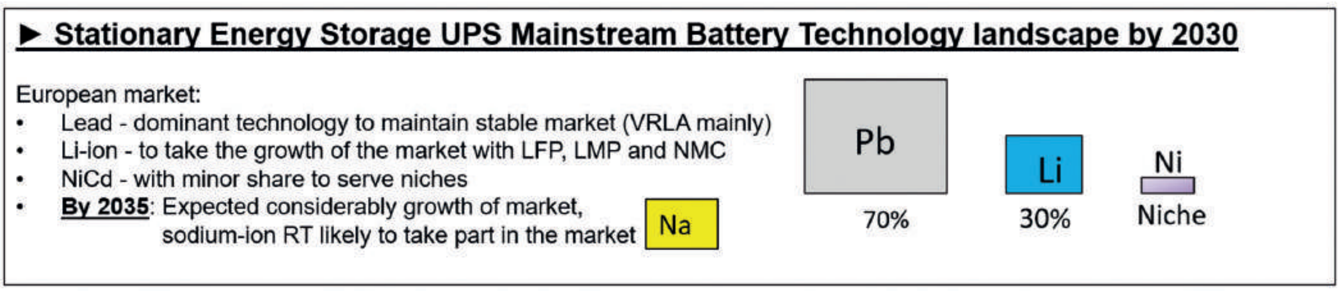
The EU market share in 2020 of the total world market was 28%, which will decrease to 21% in 2030. China, India and others will grow by 11% over this time (2).

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 climatisation 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 centers is between 5 and 15 minutes, KPIs for the application are energy and power densities, system cost, operating temperature range and reduced cooling, as well as safety.**

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

Due to its maturity, lead battery recycling processes have developed and improved over a long time and are already highly efficient and economically valuable, while recycling of lithium batteries is more complex due to the different chemistries and battery housings that demand different physical and chemical treatments



D.2. Batteries for Telecom (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 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. The predominant lithium technologies are lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) cathodes with graphite anodes to target NMC graphite-silicon composite anodes by 2030. Due to cost and safety reasons, there is currently a trend towards the LFP technology

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 (see spider chart hereunder).

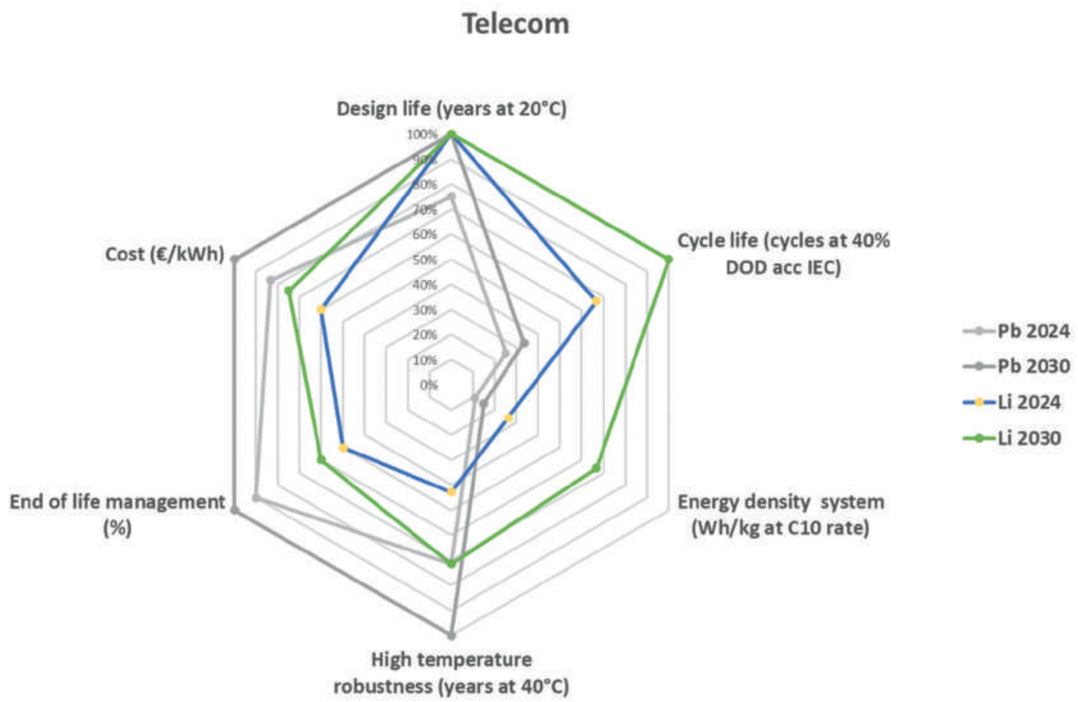


Figure: The six main KPI of batteries for telecom applications now and by 2030.

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 behavior. 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 WiFi 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. Cycle life performances should be increased to 2,000 cycles at 40% DOD and an extended battery life to 10 years at 40°C or more than 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 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 (NMC, silicon + graphite), cost reduction actions and an improvement in the safety of products (LFP, aqueous electrolytes).

Battery market

The dominant technology used today is VRLA with absorbent glass mat technology (AGM) for reliable grids and VRLA with gelled electrolyte (GEL) in poor or off-grid scenarios. The predominant lithium technologies are LFP and NMC cathodes with graphite anodes to target NMC graphite-silicon composite anodes by 2030. Due to cost and safety reasons, there is a trend towards LFP technology.

The European market demand in 2022 was 2 GWh, which is expected to grow to 3 GWh in 2030 (6.7% annual growth in volume). The annual growth rate for lead batteries is expected to be 0.5% and for Li-ion batteries it is expected to be 8.5%. In this scenario, lead will remain the dominant technology but the lithium market share will grow to 11% in Europe. This is because lithium is more expensive than lead (~2-3x), but with a lower total cost of ownership (TCO) than lead in hot climates because of a higher expected lifetime, especially in high temperatures. The main drivers for this application are the extension of WiFi, strong network growth in China, India, eastern Europe and South America, as well as the introduction of 5G. 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)

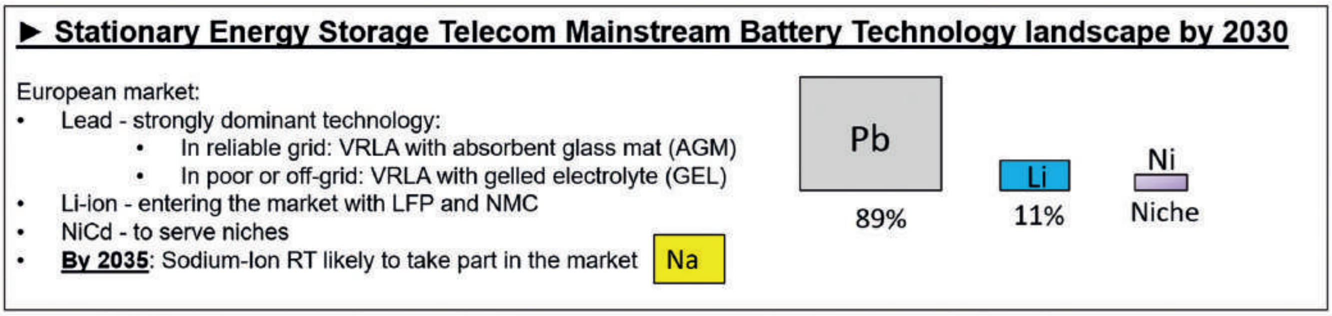
Other drivers are the further actions to reduce diesel consumption and emissions, especially in countries and areas with unstable grids, which will necessitate higher energy throughputs for the battery

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 4% for lithium by 2030.

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).



D.3. Batteries for Residential and Commerical Energy Storage behind the meter (BTM Batteries)

Application overview

Stationary batteries for storing energy from renewable sources behind the meter are used both in residential and commercial buildings (offices, SMEs, etc.) where they can also fulfil additional roles, such as peak shaving or UPS.

The primary task of these batteries is to supply the load when electricity cost is high or renewable power output too low and offer consumers a level of independence from grid supplied energy. In addition to the cost benefits, additional drivers for residential and commercial storage are increased levels of self-consumption with less reliance on grid-based power, combined with reserve to ensure power continuity. Residential storage batteries should be designed and sized according to the location and local power needs.

Stationary batteries can also support peak demand, and help to decarbonize electricity, by avoiding the use of gas or coal and fossil-burning power stations.

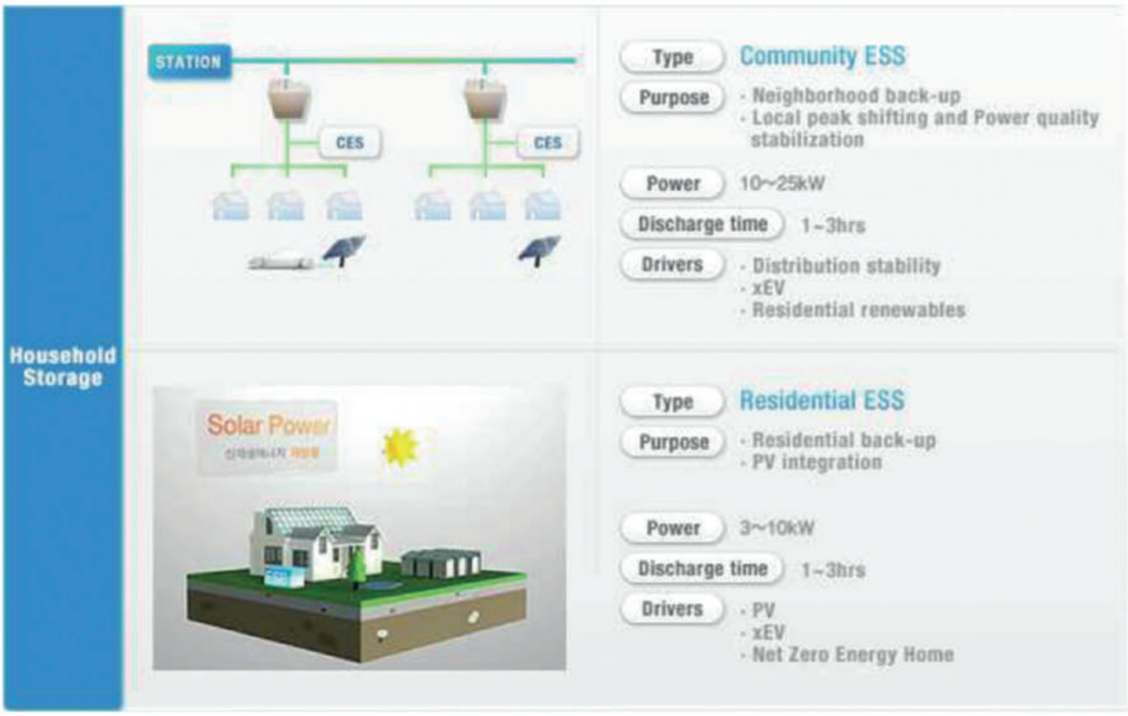
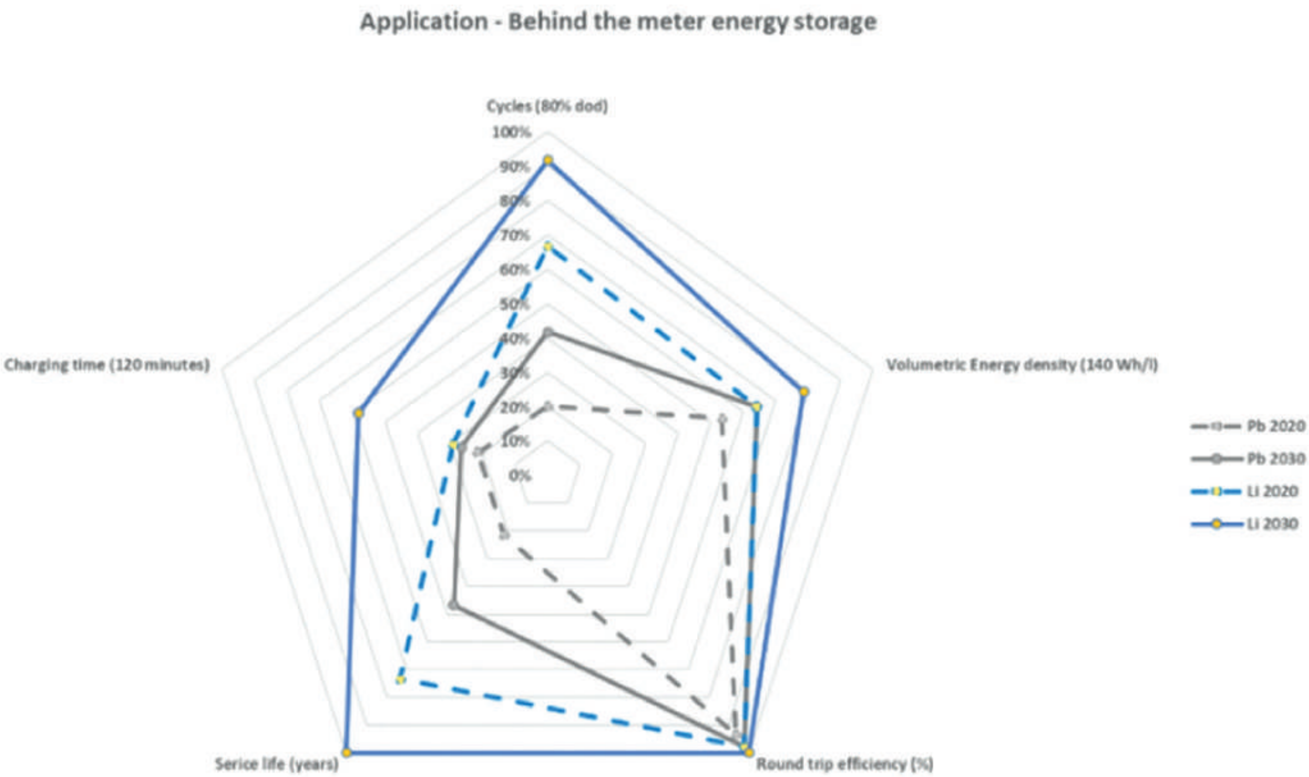


Figure: Residential and Community Household Energy storage profiles (Enersys)

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 home owners 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.



Spider chart: KPI diagram current/future state battery technology attributes for behind the meters applications

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 Storge, 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.

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 (12)

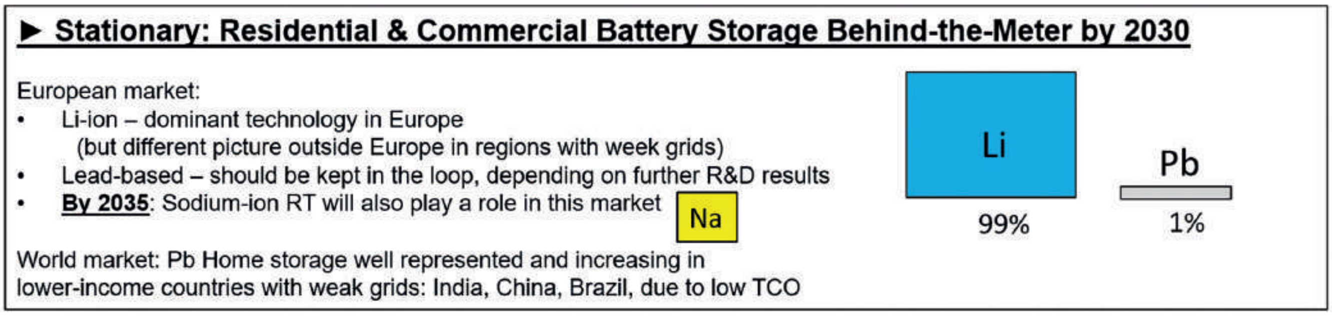
In the Avicenne study 2023 commissioned by EUROBAT the BESS market data, both for BMT (Residential/commercial) and FTM (utility grid scale storage) are expected to grow in Europe. BTM market to increase from 0,5 GWh in 2023 at CAGR +9%, nearly to double by 2030, estimated at +0,9 GWh. Li-ion being the preferred technology thanks also to the electronics and the BMS imbedded to help manage the BTM functionalities. The growth of the BMT market driven to increase self-consumption. The use of different battery technologies provides an overall benefit to the decarbonisation of the residential sector and batteries are key enablers for making this happen.

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 invertor) 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 to align with the Energy Efficiency Directive.



D.4. Batteries for Utility Grid-scale Storage in front of the meter (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. 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 could take 92% market share by 2030 and flow and Na-ion expected to take up together 5% market shares globally before 2030, the remaining 3% covering other battery technologies and other ways of battery storage (10)

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.

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	suitable	suitable	not existing	suitable	suitable	not existing	possible	possible	not existing	possible	suitable	not existing
	100 kWh - 1 MWh	suitable	suitable	not existing	suitable	suitable	not existing	possible	possible	not existing	possible	suitable	not existing
	1 MWh - 1 GWh	possible	possible	not existing	suitable	suitable	not existing	possible	possible	not existing	possible	suitable	not existing
Services to Support Transmission Infrastructure [2)]	< 100 kWh	not existing	not existing	not existing	not existing	not existing	not existing	not existing	not existing	not existing	not existing	not existing	not existing
	100 kWh - 1 MWh	possible	suitable	possible	suitable	suitable	suitable	possible	suitable	possible	possible	suitable	suitable
	1 MWh - 1 GWh	possible	suitable	possible	suitable	suitable	possible	possible	suitable	possible	possible	suitable	suitable
Services to Support Distribution Infrastructure [3)]	< 100 kWh	not existing	suitable	possible	not existing	suitable	suitable	not existing	suitable	possible	not existing	suitable	suitable
	100 kWh - 1 MWh	not existing	suitable	possible	not existing	suitable	suitable	not existing	suitable	possible	not existing	suitable	suitable
	1 MWh - 1 GWh	not existing	suitable	possible	not existing	suitable	possible	not existing	suitable	possible	not existing	suitable	suitable
Ancillary Services	< 100 kWh	suitable	possible	possible	suitable	suitable	suitable	suitable	suitable	possible	possible	suitable	suitable
	100 kWh - 1 MWh	suitable	possible	possible	suitable	suitable	suitable	suitable	suitable	possible	possible	suitable	suitable
	1 MWh - 1 GWh	possible	possible	possible	suitable	suitable	possible	suitable	suitable	possible	possible	suitable	suitable
Services to Support Behind the Meter Customer Energy Management	< 100 kWh	suitable	suitable	possible	suitable	suitable	suitable	possible	possible	unsuitable	possible	possible	possible
	100 kWh - 1 MWh	suitable	suitable	possible	suitable	suitable	suitable	possible	possible	unsuitable	possible	suitable	possible
	1 MWh - 1 GWh	possible	possible	possible	suitable	suitable	possible	possible	possible	unsuitable	possible	suitable	suitable
Vehicle-to-Grid (V2G) [4)]	< 10 kWh	not existing	not existing	not existing	suitable	suitable	possible	not existing	not existing	not existing	not existing	not existing	not existing
	< 100 kWh	not existing	not existing	not existing	suitable	suitable	possible	not existing	not existing	not existing	not existing	not existing	not existing

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

Legend

suitable:	The technology represents a common solution for the service or 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.

Tabulation: In-dept assessment of battery technologies for storage service applications – Fraunhofer ISE (11)

Research and Innovation scope and potentials

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.

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/m^2), 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, 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.

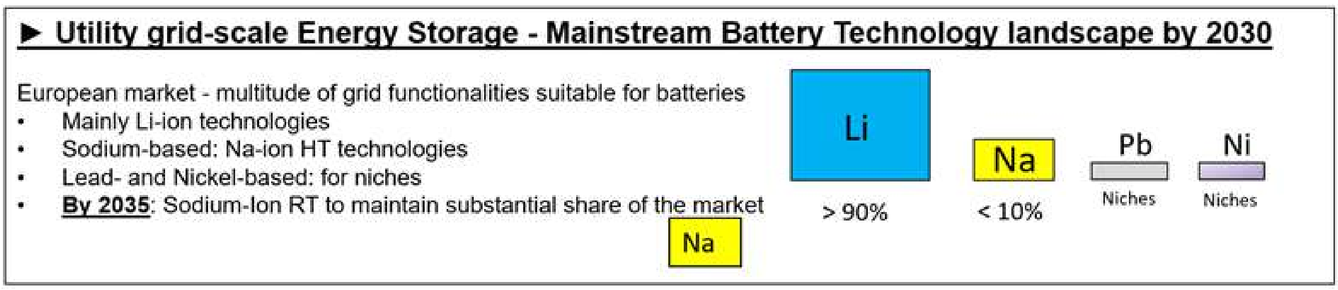
For large storage systems, lithium technologies are considered the reference technologies, capturing more than 90% of the worldwide annual battery energy storage market. Lithium-ion batteries show longer lifespan, higher energy density (key driver considering constrained land surface), lower self-discharge,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



D.5. Batteries in Off-grid Application

Application profile

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

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

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**.

The picture hereunder highlights the typical power ranges for some different rural electrification systems.

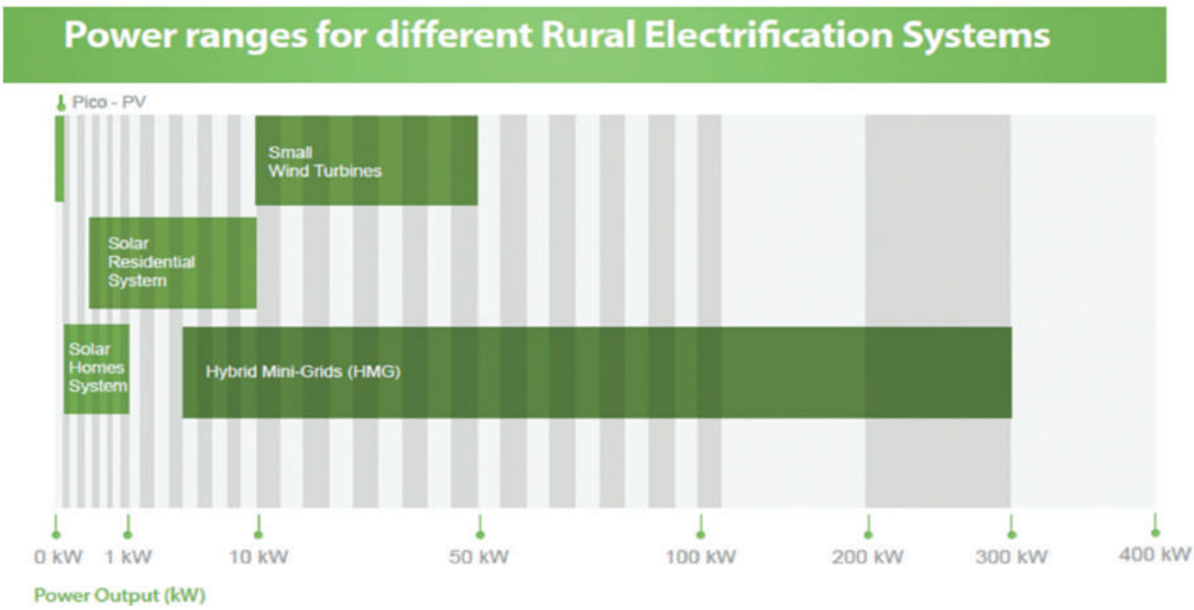


Figure: Power ranges for different off-grid Rural Electrification segments [4]

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 million 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

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 from the International Energy Agency (IEA) quantified that off-grid and mini-grid configurations using Battery Energy Storage (BES) is often the most efficient and sustainable way to electrify isolated rural areas or remote commercial and industrial sites (C&I sites). In order to achieve universal energy access by 2030, the IEA estimates that a further 379 TWh of on-grid electricity generation will be needed, along with 399 TWh from mini-grid systems and 171 TWh from off-grid systems. Another market is on small European islands without mainland interconnections where peak production relies on fossil fuel. Nowadays, there is a clear tendency towards the installation of off-grid and mini-grid renewable energy sources instead. Market drivers are the worldwide expansion of fluctuating renewable energy sources like PV and wind. National and multinational funding programs support these developments. With an increasing global population and despite the growing electrification worldwide, in 2018 there were still 112 million people in central and southern Asia and 548 million people 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-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:

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

For lead-based batteries, increased energy throughput and the development of operation strategies by integration of BMS (battery management system) are important. For lithium-based batteries, improving the design life, safety aspects like high temperature operation, cost and recyclability are paramount. 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 2030

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

- Lead dominant technology – 40% sealed & 15% flooded
- Lithium-ion – LFP to gain from NMC
- Nickel-based: for niches
- **By 2035**: Sodium-ion RT will also come into this market Na

Li	Pb	Ni
~50%	~50%	Niches

Concluding remarks & Recommendations

- **The diversity in battery features needed in a multitude of applications, there is not one technology type that fits it all.**
- **By 2035, both Li-ion and lead-based batteries will remain the dominant battery technologies**
  - Li-ion: The fastest growing market with double-digit annual growth
  - Lead based: Will maintain its position with single digit market growth
- **All mainstream technologies still have innovation potential and, through to 2035, will improve incrementally in order to meet the changing and increasing market requirements in many end-user applications**
  - Lead batteries, with new technology branches, such as pure led, lead-carbon and bipolar
  - Li-ion batteries, because of the diversity in technologies, have a large variety of KPIs to improve
- **Application-specific developments will further push the boundaries for the established technologies, in particular for Li-ion and lead-based technologies**
- With **the new Battery Regulation in place, additional challenges need to be overcome to develop a circular economy; To this regard, not all mainstream technologies are at the same level of maturity, so each technology will need different R&D needs to make progress on different aspects of the circularity economy key sustainability performance indicators.**
- R&D on High-TRL not yet commercialized most promising technologies should be further conducted, such as for **Sodium room temperature (Na-ion RT), which represents the most promising technology** in the near future in terms of cost, raw material availability and performances.
- **Building further on the existing domestic manufacturing industry capacity and their expertise will bring academic innovation faster into new products and production lines to successful serve the mass markets.**

- With focus on time horizon **2035, both Lithium- and lead-based batteries will remain dominant technologies in the European and worldwide markets, however, to compete with Na-Ion Room Temperature (RT), who will take over substantial market share in some specific markets**
  - Lithium-based: fastest growing market with double digit annual growth
  - Lead-based: to remain stable but impact of the potential automotive ICE ban in 2035 to consider
  - Sodium-ion RT: offering a sustainable alternative, getting faster mature with performance competing in specific markets, thanks to further R&D getting more competitive

	Pb	Li	Ni	Na
State of the Art	Flooded & VRLA, Pb-C, Thin Plate Pure Lead	NCM, LFP , LMO,NCA, LCO (C; LTO; Si/C)	NiCd, NiMH	NaS, NaNiCl (Hightemp.)
> 2025	Embedded BMS & software	Semi Solid State		Na-Ion (RT Room Temperature)
> 2030		Li-Sulfur, All Solid State		Semi → Solid State All Solid State
> 2035		Li-Air		

Tabulation: Market evolution across battery technologies up to horizon 2035 and beyond (1)

The established mainstream battery technologies will also continue to hold innovation potential. Through 2035, they will continue to undergo incremental improvements to meet evolving market requirements across numerous end-user applications:

- Lithium-ion: the diversity of technologies provides a wide range of key performance indicators (KPIs) that can be improved upon
- Lead-based: are branching into digital avenues including a BMS-specific software and creation of a digital twin, something that was never done before and is likely to generate new opportunities for improvement, particularly in the integration aspect.

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Authors

EUROBAT TF Innovation

List of Abbreviations

3c: Portable battery market
A0 classification: automotive mini passenger vehicle
A00 classification: automotive small passenger vehicle
AGC: Automated Guided Cart
AGM: Absorbent Glass Mat
AGV: Automated Guided Vehicle
ASSB: All solid-state Batteries
B2B: Business to Business
BEPA: Batteries Europe Partnership Association of the Batt 4 EU partnership
BAT: Best available Technologies
BES: Battery Energy Storage
BEV: Battery Electric Vehicle
BTM: Behind The Meter
C&I: Commercial and Industrial
CAGR: Compound Annual Growth Rate
DER: Distributed Energy Sources
DOD: Dept of discharge
EBA: European Battery Alliance
EC: European Commission
EES: Electric Energy Storage
EFB: Enhanced Flooded Battery
EFTA Member States: Iceland, Liechtenstein, Norway and Switzerland
ETIP: European Technology And Innovation Platform
ETS: Emission Trading System
EV: Electric Vehicle
eVTOL: Electric Vertical Take-off and Landing
FTM: In Front of the Meter
GBA: Global Battery Alliance
CHG: Greenhouse Gases
GIPS: Grid Independent Power Supply
HEV: Hybrid Electric Vehicle
HCV: Heavy Commercial Vehicle
HV: High Voltage
ICE: Internal Combustion Engine
IoT: Internet of Things
IEA: International Energy Agency
IEC: International Electrotechnical Commission
KPI: Key Performance Indicator
LAB: Lead-acid Battery
LCV: Light Commercial Vehicle
LIB: Lithium-ion Battery
LFP: Lithium Iron Phosphate
LiSB: Lithium Sulfuric Battery
LMB: Lithium Metal Polymere
LTO: Lithium Titanate Oxide
LV: Low Voltage
NiMH: Nickel Metal Hydride
NMC: Nickel Manganese Cobalt Oxide
NZIA: Net-zero Industrial Act
OEM: Original Equipment Market
OPEX: Operational Expenditures
PSOC: Partial State of Charge
PHEV: Plug-in Hybrid Electric Vehicle
R&D: Research & Development
R&I: Research & Innovation
RT: Room Temperature
SET-Plan: Strategic Energy Technology Plan
SLI: Start-Light-Ignition
SRIA: Strategic Research and Innovation Agenda
SSB: Solid-State Batteries
SSLiB: Solid-State Lithium-ion Batteries
SSLMB: Solid-State Lithium-metal Batteries
TCO: Total Cost of Ownership
TLC: Telecom
TRL: Technology Readiness Level
UPS: Uninterrupted Power Supply
VPP: Virtual Power Plant
VRLA: Valve Regulated Lead-Acid
xEVs: mild, full HEP, pHEV & BEV

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