EUROBAT 2035
BATTERY INNOVATION ROAD MAP

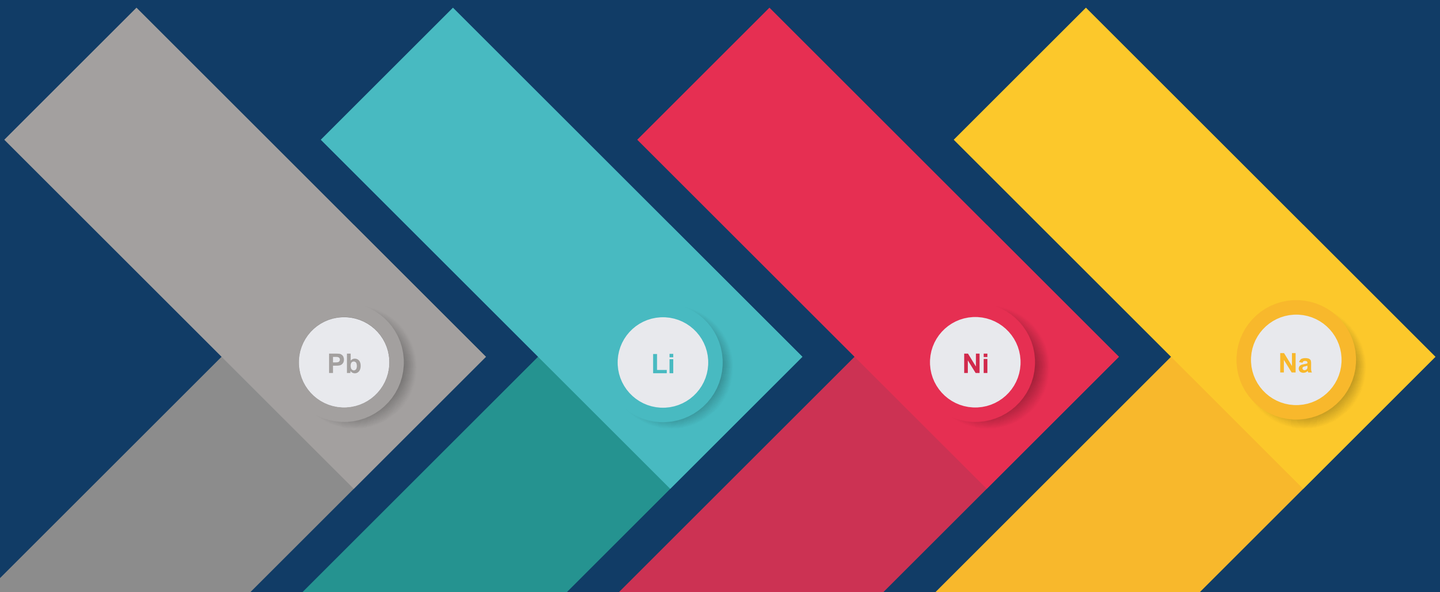
WHITE PAPER
BATTERIES INNOVATION ROADMAP 2035

Versions V3.0 • June 2024

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



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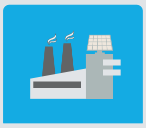
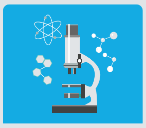
WHAT IS EUROBAT?

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



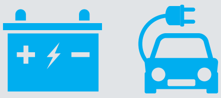
16
research centers

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

APPLICATIONS

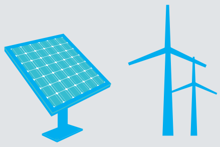
AUTOMOTIVE

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

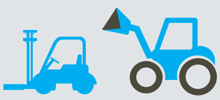
Batteries are indispensable for storing renewable stationary energy coming from solar and wind farms in on grid and off grid solutions. They also contribute to a more stable and reliable grid.



MOTIVE POWER

MATERIAL HANDLING

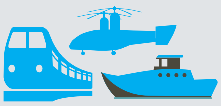
Batteries are a perfect fit for powering industrial vehicles such as forklifts and cranes, while also reducing noise and emissions.



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

1. Executive Summary

This EUROBAT White Paper Innovation Roadmap is an updated guide to navigating the rapidly evolving landscape of mainstream and most promising battery technologies. Building upon the foundations laid out in Roadmap version 2.0 from June 2022, this latest iteration incorporates the most recent advancements in both technological innovations and their market evolution.

Key features of this new roadmap affecting R&D on batteries, include:

- An update of the innovation potential of the mainstream battery technologies
- Identification and analysis of the most promising high-TRL technologies
- New R&D challenges related to circularity and critical raw materials aspects
- The role of digitalization and the introduction of the Battery Passport
- Impact of further electrification of end-user battery-powered applications
- Updated battery markets & expected growth, driven by factors mentioned above

While further electrification in all end-user battery-operated applications is strongly driving R&D on the mainstream battery technologies in the market, the changes in the EU's policy objectives, primarily with the ongoing implementation of the new EU Battery Regulation 2023/1542, introduce new challenges, also driving innovations towards more sustainable, safe, and efficient battery solutions, aligning with broader EU environmental goals and sustainability trends.

Key points addressed in the roadmap

To continue electrifying all sectors, the roadmap emphasizes the importance of continuous development and innovation within each technology domain since no single battery chemistry can fulfill all the different demands of end-user applications. This ongoing progress is driven by the specific requirements of diverse applications, which may prioritize factors such as power density, energy density, longevity, cost-effectiveness, safety, and environmental sustainability. More information is in Chapter 4.1. End-user market demands. The details around 15 end-user battery-powered applications are in Part II of the Roadmap Technical Annex.

The **new Battery Regulation 2023/1542** addressing environmental topics -such as sustainable sourcing of raw materials, improving recycling rates, and reducing the environmental impact of batteries throughout their lifecycle-, has triggered new R&D challenges for batteries. **As not all mainstream technologies -lead, lithium, nickel & sodium-based- are at the same level of maturity** with regards to sustainability aspects addressed in the Regulation, **each technology required tailored R&D needs to make progress on different aspects of the circular economy**. More information is in Chapter 4.2. Sustainability and circularity aspects of the Battery Regulation.

Information on the four mainstream battery technologies and most promising technologies is in Chapter 5. R&D Areas and potentials per Battery Technology. More details on the different technologies are in part I of the Technical Annex.

With **the digitalization and the introduction of the Battery Passport**, new R&D challenges are ahead, using blockchain or similar data management technologies to support tracking and tracing throughout the entire battery lifecycle to ensure compliance with the Regulation, **facilitating transparency, recycling and recovering of material**, at the same time Industry considering benefits to optimize production and to better embed batteries in the application. More inform is in chapter 4.3. Digitalization and introduction of the battery Passport.

The European Battery Manufacturing Industry, encompassing all mainstream technologies, is resolutely committed to aligning with the EU's carbon-neutral objectives and sustainability goals. This commitment entails increasing investments in innovation and scaling up battery production to meet future demand, while fulfilling stringent requirements related to performance, safety and circularity aspects.

2. Introduction Scope & Purpose

2.1. Why this update?

The 3rd edition of the EUROBAT Batteries Innovation Roadmap is to ***compliment*** the EUROBAT Election Manifesto 2024-2029, aiming to provide policy-makers with factual information on the contributions and innovation potential of these mainstream battery technologies.

This edition ***integrates the latest technological developments and updates in EU policy objectives, specifically focusing on the sustainability aspects in the new Batteries Regulation***. It aims to accurately reflect the current technological landscape and the potential of the best available technologies on the market, highlighting how they can support the EU's strategic goals. Consequently, the Roadmap is designed as a living document, subject to potential biennial reviews to accommodate ongoing technological advancements and shifts in policy objectives.

The roadmap is structured to serve both policymakers and the European R&D community, compromising a main document and a Technical Annex:

- **Main document:** Aimed at policymakers, this section outlines the current state-of-play and innovation potential of mainstream and emerging promising battery technologies. It highlights how these technologies contribute to achieving climate neutrality targets and supports Europe's critical raw materials initiative by enhancing the recovery and recycling of battery materials to meet forthcoming environmental legislative demands.

- **Technical annex:** Aimed at the European R&D community, this annex offers deeper technical insights into ongoing research and information efforts towards 2030 and beyond.

2.2. What is new compared to the previous version?

Since the former version of the roadmap (June 2022), EU policymakers have initiated further measures impacting the battery industry and creating new drivers for battery innovation:

- EU policy makers took stronger measures towards decarbonizing industries and the energy system, such as the **RePowerEU** initiative, the new **Electricity market Design**, and the **Clean-Tech Innovation funds**, with the purpose **of boosting battery demands**. This roadmap aims to measure the impact of these latest measures.

- With the **new Battery Regulation** set to take effect one year from now, we also aim to assess the impact on R&I needs for all battery technologies **to improve sustainability and circularity aspects, and to explore the new opportunities that the Battery Passport and further digitalization will bring** in achieving the EU's goals.

- Other EC initiatives, such as the **Net-Zero Industrial Act** (NZIA), the **upcoming Innovation Funds, enhancing the scaling up of domestic battery manufacturing capacity, and the Critical Raw Material Act (CRMA),** are **addressing new challenges to the EU's economic autonomy and securing the supply of primary materials for batteries**.

These initiatives are shaping new R&D needs necessary to achieve the multi-goal transition. **They also require sustained dialogue and cooperation among all stakeholders, which is also the purpose of the roadmap**. Battery manufacturers are committed to increasing investments in innovation and scaling up battery production to meet future demand while fulfilling stringent requirements related to performance, safety, and circularity aspects.

3. Overal Context - Battery Markets & Outlook

Several EC initiatives have been launched under the European Green Deal, boosting market demand for batteries in Europe:

- **The Fit-for-55 Package**, aims to reduce GHG emissions by at least 55% by 2030, encompassing 13 legislative proposals to align policies with reinforced climate-neutrality goals. To achieve decarbonization targets, the shift towards further electrification of transportation, the energy system, and other sectors should be accelerated.

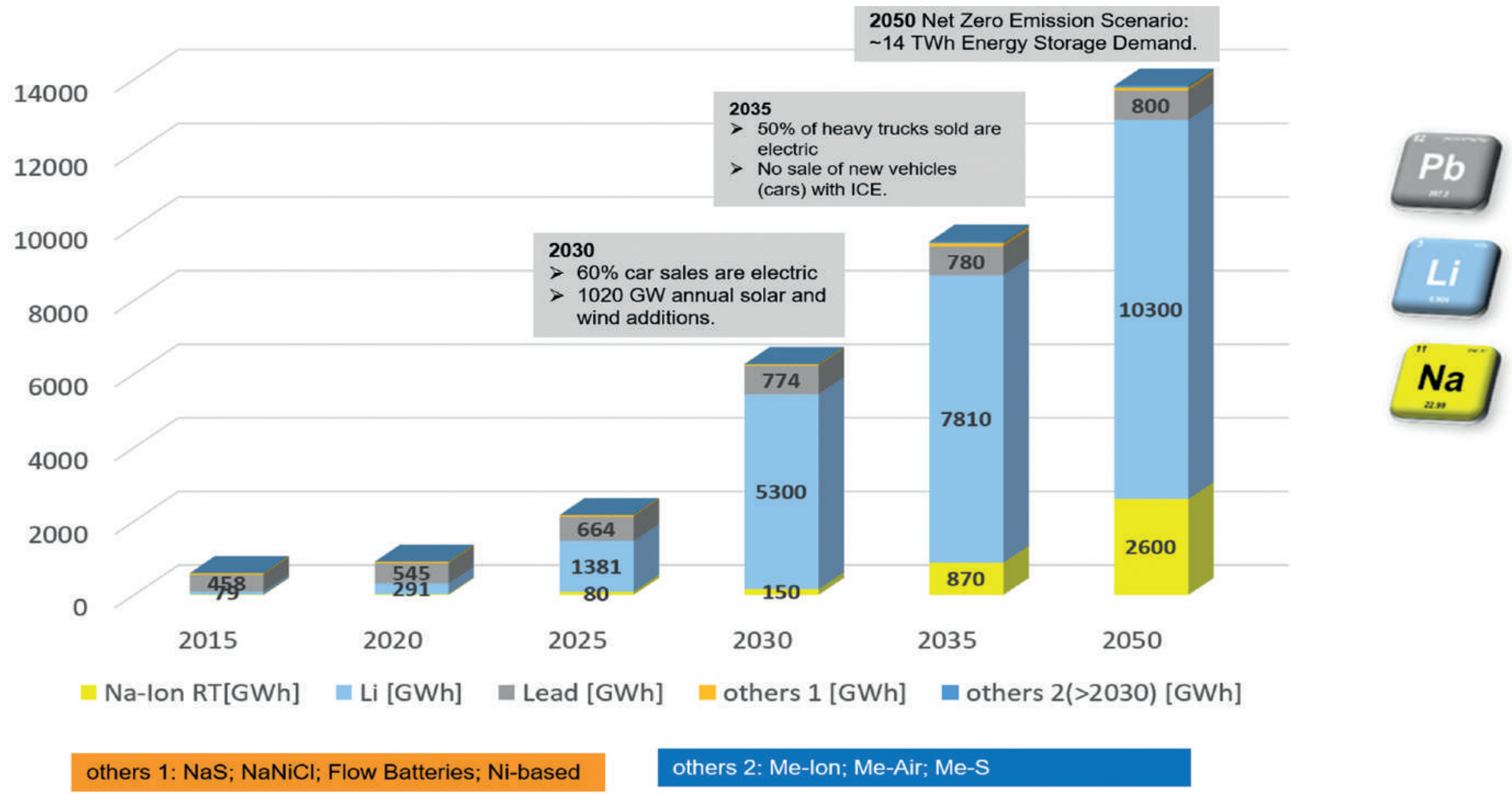
- **The RePowerEU Initiative**, was launched around the time we published Roadmap V2.0 in June 2022, with the objective of making Europe energy independent from fossil fuels. It includes short and medium-term measures to be enacted by 2027, utilizing Innovation Funds to boost demand for clean technologies, with battery energy storage identified as a strong contributor.

- **The Green Deal Industrial Plan**, which came into force in March 2023, includes three initiatives impacting the battery business: (1) the Net Zero Industrial Act (NZIA) to increase clean tech industrial capacity, (2) the Critical Raw Materials Act (CRMA) to enhance collection and recycling of waste products to lower supply disruption risks, and (3) the new Electricity Market Design, creating new opportunities for battery energy storage in Europe's electricity grid, such as in the BTM and FTM segments.

The The EU Battery Regulation 2023/1542, approved in July 2023, is another cornerstone of the European Green Deal. It aims to improve the circular economy, resource use efficiency, and the life cycle of batteries in terms of climate neutrality and environmental protection. This regulation represents the first holistic approach to a circular economy for electrochemical energy storage systems. The technology-agnostic approach calls for the sustainability of electrochemical storage systems and treats all technologies equally. It aims to ensure that batteries, as key components of sustainable energy storage, will contribute to climate neutrality and environmental protection throughout their life cycle, with low carbon footprints, minimal hazardous substances, and fewer raw materials sourced from non-EU countries. This supports the shift to a circular economy and increases security of supply, enhancing the EU's strategic autonomy.

As we operate on a global level playing field, the roadmap considers both global and European contexts to assess the market and its evolution across battery technologies. We have considered recent data sources from IHS, Roland Berger, Fraunhofer, Bloomberg, McKinsey, ILA/CBI KPMG study, EUROBAT/Avicenne report, and information from IEA and EIT InnoEnergy, resulting in the following best estimates to predict the markets in 2025, 2030, 2035, and up to 2050. The graph is on the next page.

Global Battery market evolutions across battery technologies up to horizon 2050 (1)



In conclusion

By 2035 we expect the total market to reach 9.4 TWh of which

- Lead: stable market at 780 GWh with 60% BEV car sales, 12V SLI OEM market decreasing
- Lithium: increases to 7,810 GWh due to BEV role-out and further BESS uptake, mainly BTM
- Na-ion RT: enters the market with 870 GWh (10%), competing Pb & Li in specific applications (ex. BESS, L-type vehicle propulsion, SLI application)

By 2050: Net Zero Emission Scenario expect the total Storage Demand to reach 14 TWh

- Lead: stable market at 800 GWh, due to 100% BEV sales, 12V SLI OEM & AM dissepearing but compensated by growth in industrial applications
- Lithum: continue to ramp up to 10,300 GWh, mainly due to BEV and BESS increase sales
- Na-ion RT: Market uptake to 2,600 GWh, competing with lithium and lead in certain applications

By 2050, many battery technologies in the market to serve niche markets

- Initially NaS, NaNiCl, Flow Batteries and Ni-based, later also Metal-Ion, Metal-Air and Metal-S entering the market,
- These technologies, while representing a fraction of the total market, are necessary for niche markets

By 2030, ESS has the highest CAGR with roughly 44%, totaling to 850 GWh in 2030 globally

- In North America, ESS will become the second biggest segment beyond BEV with 240 GWh capacity in 2030 – accounts for 5 Giga factories.
- In European ESS demand is likely to be lower, estimated at 130 GWh in 2030, still accounting for three gigafactories
- Countries where the TCO plays a big role such as China, India and Brazile: Current market growth in Pb worldwide market up to +40%, reaching 774 GWh should be further observed.

Most promising technologies, both in BEV and BESS application upcoming in near future

- With highest TRLs, Sodium-Ion and LFP (with LMFP) are closest to enter the market
- Both technologies currently dominate production facilities in Asia
- Increasing opportunities for domestic players in North America and Europe
- Need to build local value chains to serve these technologies
- Continuous innovation in mainstream and new technologies drives down costs

The diversity of technologies making the Batttery supply chains more resilience

Although lithium-ion remains the preferred technology for BES and utility-scale applications, potential global lithium shortages and increased EV demand may lead to material availability constraints. Therefore, further investment in mainstream and emerging technologies is crucial to diversify supply chains.

Total market expected to grow to 9.4 TWh in 2035 up to 14 TWh by 2050, mainly by 3 dominant technologies:

- ***Lithium-based****: to grow from 7.800 GWh to 10.300 GWh. Major causes is the EV role out, however, cuts in policy incentives and tax credits may slow growth prior to 2035, but BESS extension is critical to meeting net-zero targets.*
- ***Sodium RT****: to grow to 870 GWh to 2.600 GWh, due to increasing competing with lead and lithium technologies for different applications*
- ***Lead-based****: stable market up to 780 GWh by 2035 and 800 GWh by 2050 due further incremental performance increases and resilient raw material supply chain, no critical raw materials and with full established circular economy*

4. Drivers for battery innovation

Battery innovation has historically been driven by market needs, particularly by end-user applications, which explains the very broad spectrum of battery products, sizes, technologies, and chemistries on the market.

European industry has long excelled in catering to both mass and niche markets. It has achieved this by spearheading national and international standardization efforts and by contributing innovative products that support the development of a wide range of applications. This robust and adaptable approach has helped maintain Europe's leading position in the global battery industry.

Today, research and Development on batteries are strongly driven by distinctive policy initiatives, with the objective to

- further electrify the mobility and electricity sectors, as well as many other sectors (chapter 4.1)
- to make Europe sustainable and to develop a circular economy (chapter 4.2)
- to take competitive advantages of implementing the Digital Product Passport (chapter 4.3)

Innovation across the entire battery value chain is therefore necessary; at the level of the raw and active materials (e.g. low cobalt, high nickel cathodes, silicon or sodium-ion anodes, coating technologies…), at the level of the cells and modules design and production (solid state, digital twins), or at system level to optimize the integration of the battery In the application (e.g. aviation, FTM and BTM BESS).

4.1 End-user market demand and policy initiatives to further electrify all sectors

Transportation, Industrial automation, residential and commercial buildings, RES integration, and last but not least, the Information and Communication technologies (ICT) are various sectors that will contribute to increase the energy demand in the coming years.

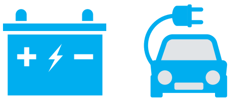
To make electrification in all sectors a success, batteries and a competitive and sustainable European Battery Industry is indispensable. Europe therefore requires a regulatory landscape that treats all battery technologies equally with the objective to

- built further upon existing EU battery manufacturing expertise and capacity (all technologies)
- foster innovation to produce / invest in clean-tech in line with carbon-neutral goals (clean-tech)
- foster innovation and enhance sustainability and the circular economy, making EU greener and independent as well as to make the EU Manufacturing Battery Value Chain more resilient.

End-user market demand for electrification is on the rise as consumers increasingly prioritize sustainable solutions and governments implement policies to combat climate change. In response to this growing demand, various industries are accelerating their transition towards electrification across sectors such as transportation, energy and manufacturing.

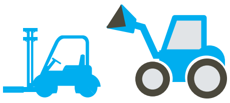
The convergence of market demand and policy support is driving R&D on batteries in different sectors. Promising markets are Battery Electric Vehicles and Electrical Energy Storage, however the uprise is also significant in many other sectors. Part II in the Technical Annex describes 15 different critical applications identified in support to meet the EU objectives, selected from 4 areas, namely:

Area 1: Automotive Mobility Applications



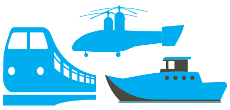
- 12V Auxiliary Batteries
- 12V Start-Lighting-Ignition Batteries (SLI batteries)
- Heavy Commercial Stand-by Batteries (HCV Stand-by batteries)
- Mild and Full Hybrid Vehicle Batteries (HEV batteries)
- Battery Electric Vehicles (BEV batteries)

Area 2: Motive Power Material Handling and Logistics Applications



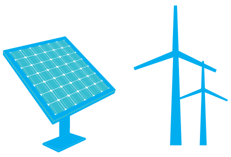
- Motive Power Batteries in all kinds of material handling and logistics machinery

Area 3: Motive Off-road Transportation applications



- Motive Power Batteries in all kinds of Industrial Vehicles
- Motive Power Batteries in railway
- Motive Power Batteries in Marine
- Motive Power Batteries in Aviation

Area 4: Stationary Energy Storage Applications



- 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 (developing countries, weak grids or small islands)

Each chapter describes the integration aspect, the battery KPIs and the innovation priority areas for the different mainstream battery technologies used in the respective application. The selection of the key battery performance indicators (KPIs) for the innovation (such as gravimetric and volumetric energy and power densities, fast recharge time, energy throughput, calendar life and recycling rates) is strongly dependent on the application requirements in which the batteries will be integrated in.

4.2 Sustainability and circularity aspects of the new Battery Regulation

The new **Battery Regulation 2023/1542 is a main driver for R&D on batteries** to further reduce the environmental and societal lifecycle impact of batteries. As not all mainstream battery technologies are at the same maturity, tailored R&D is required on each technology.

The new Battery Regulation, addressing environmental topics - such as sustainable sourcing of raw materials, improving recycling rates, the carbon footprint and reducing other environmental impacts of batteries throughout their lifecycle-, **has recently triggered new R&D challenges on all the mainstream battery technologies.**

As not all mainstream technologies lead, lithium, nickel & sodium-based- are at the same level of maturity, **each technology will need different R&D needs to make progress on different aspects of the circular economy.**

To continue to expedite targeted research and innovation in all mainstream technologies is therefore essential, as well as to investigate in high-TRL most promising technologies to diversify the supply chain for raw materials. These efforts will effectively contribute

- to help meet the Green Deal decarbonization goals and reduce EU's dependency on fossil fuels
- to transition to a sustainable and safe circular economy through the entire life cycle of the batteries
- to address EU's strategic autonomy on primary and secondary battery materials

The **concerns surrounding environmental and health impacts of batteries, affects to a certain extend all battery types in one way or another as all have active components**. Instead of aiming solely to eliminate certain hazardous substances -which is challenging due to the lack of equally effective alternatives-, **further R&D should focus on reducing such substances and to further develop technologies that properly manage environmental and health risks throughout the entire life cycle of the batteries** from mining to production, into the use phase and recycling.

The industry recognizes the need for further innovation in order to align with the implementing measures and impact assessmentsto elaborate further on the new Batteries Regulation. The implementing measures should ensure more harmonized legislation and harmonized standards to be developed by the industry under the CEN/CENELEC mandate M/579 to support the initiatives. R&D areas identified are:

- **The design**: To reduce hazardous substances at the basis, to increase the energy throughput during the use phase, to increase recycling rates at end-of-life, to ensure safety when extending life-time by repair and re-use (2nd life)

- **The production:** To reduce the carbon footprint by using energy from RES, less water consumption, water treatment, increase use of recycled content in batteries

- **Information provision:** Carbon footprint, recyclability, recycled content declaration, minimum information requirement with regards to performance and durability, Supply chain due diligence (working conditions, governance)

With regards to information provision, the setting up of a **battery passport scheme**, as a **key instrument** in which the battery industry is **committed to further investigate on opportunities and threats when used in all the phases of the product life cycle** (chapter 4.3.)

Addressing the different aspects in the Battery Regulation comprehensively, these efforts will **strengthen EU's strategic autonomy** in battery materials as well as to make the **domestic manufacturing industry more resilient** with stable and diverse material supply chains on battery materials used in BEVs, BESS and various other applications. With this in mind the EU should continue to

- Invest in Innovation to **diversify the supply chain** for raw materials in all mainstream battery technologies.
- Encourage **domestic manufacturing facilities** to expand horizontal and vertical in the value chain.
- Ensure that the Battery Regulation **treats** all mainstream and future battery technologies **equally**.
- Recognize the **role of standards in providing a cohesive framework to enforce the regulatory measures** (CEB/CENELEC/Mandate M/579)
- While striving for autonomy, engaging in **collaboration with international standardization** partners
- Investing in **education and training** programs focused on battery manufacturing, battery products, and battery integration skilled to cultivate the right workforces within EU.

In this context the chapter 5 of the roadmap gives the reader information on the state-of-the-art of each mainstream and most promising technology identified and analysis how each can support the transition to a circular economy. At the same time the chapter demonstrate the complementary of technologies.

The European Battery **Industry is strongly committed to sustainability and safety aspects laid down in the Battery Regulation**, targeting the entire value chain. More than ever, the recycling and recovery of battery materials is a high priority for meeting the new environmental requirement,

4.3 Digitalization and implementation of the Battery Passport

With the growing battery market, driven primarily by the rise in BEVs and BESS, the introduction of the Battery Passport enables detailed **tracking** of origins and life cycle of each battery, from material sourcing through manufacturing, use and recycling, this transparency aims to ensuring that materials are sourced ethically and that manufacturing processes adhere to environmental regulations. Other aspects to consider are:

- The digital product passport, if well implemented by taken into account the corporate concerns of the Battery Manufacturing Industry, should include the right level of detailed information about the chemistry, structure and health status of the battery, making it more efficient for recycling companies to recover valuable materials as well as for repurposing in less-demanding applications (2nd life), **thus facilitating a circular economy**.

- As governments worldwide implement stricter regulations on battery production and disposal, a Battery Passport, should help manufacturers **demonstrate compliance with these regulations** by providing accessible, verifiable data on the entire lifecycle of the battery.

- If the right level of access right attributed, the Battery Passport will **enhance consumer confidence** and business partners **allowing to differentiate their products** based on sustainable credentials.

- Also, **detailed life cycle data will drive innovation in battery design, manufacturing and recycling processes**, as access to comprehensive and degradation data will help developers improve battery technologies and extend their lifespan.

- Implementing standardized Battery Passport will also help set **industry-wide benchmarking for quality and performance**, ensuring that batteries meet certain minimum criteria before they are placed on the market.

The implementation of the Battery Passport system will require collaboration across the entire management battery supply chain, from raw material suppliers to manufacturers and end-users, as well as integration with international standards and regulatory frameworks. This will also pose technical challenges, including developing a blockchain or similar encrypting technologies to secure interoperable within the digital platforms to manage and share data throughout the entire battery life cycle.

Developing the battery Passport is a challenge but there are also threats. With the digital transformation, further R&D will be needed on the battery management system (BMS) and the battery system design and the integration in the application. This should be industry-driven to ensure that the Battery Passport is applicable worldwide. It is also for that reason that EUROBAT is members of the Global Battery Alliance (GBA) to take into account the international dimensions, such as securing access to raw materials for batteries, standards and skills development.

5. R&D areas and potentials per battery technology

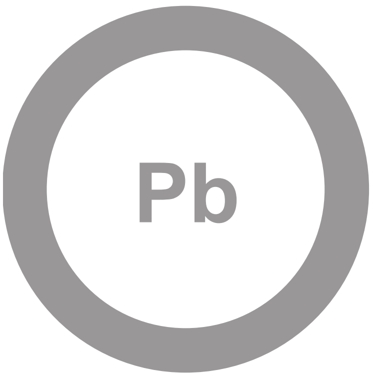
Demand for batteries has continuously grown, and the performance of batteries improved, due to **increased electrification** across a multitude of applications. With the aim to achieve climate neutrality, further electrification of the most carbon-intensive sectors – transport and energy – is **pushing the boundaries of the mainstream battery technologies even further**.

In addition, to remain competitive and catch up in niche, mass-market and emerging areas, Europe published the new Battery Regulation to remain competitive and catch up in niche, mass-market, and emerging areas, which puts **environmental sustainability** at the heart of European battery production while also addressing the ambitions of the green energy transition, **including securing access to raw materials for batteries.**

Besides the mainstream technologies currently on the market, lead-, lithium-, nickel- and sodium-based (chapter 5.1), the EUROBAT TF Innovation industry experts made also a selection of the most promising high-TRL upcoming battery technologies, based on their current innovation potential and technology readiness level (chapter 5.2).

5.1 Mainstream Battery technologies available in the market

5.1.1. Lead-based batteries



Lead-based batteries have been on the market since over a century because they are affordable, safe and sustainable. Occupational exposure to lead is under control because the battery industry has proactively taken measures to limit the exposure of its employees to blood lead contamination during the manufacturing process.

Europe should allow the market to drive innovation and recent progress on lead battery research should not be discounted. The further development of lead batteries in a variety of enhanced technologies will serve applications that can contribute to the achievement of the zero-carbon targets in the European Green Deal.

The collection and recycling of lead batteries are well-established and ensure a minimum impact.The EU has a mature process of collection and recycling that is both efficient and cost-effective and operates within an established infrastructure that ensures a circular economy.

Batteries are collected by recognised companies and recycled within specialised recycling facilities (secondary lead smelters) in a closed-loop system that operates under strict environmental regulations. From an end-of-life perspective, this process reduces the need to produce additional virgin materials, such as primary lead and plastics, which have the biggest environmental impact in the lifecycle of the product.

Currently, an astonishing 99% of end-of-life lead batteries are collected and recycled. This is because lead battery recycling generates since long a net-income across the entire value chain.

Recycling targets for lead batteries will be maintained at a very high level in

2030, with 90% efficiency and recycling of active materials at 99%, achieving a circular economy and benefiting the whole value chain.

In order to achieve or to exceed the secondary lead targets, the usage of secondary lead could be further increased. Further R&D should be carried to better refine in order to remove more impurities during the recycling process. For more detailed information, please consult the Technical Annex.

5.1.2. Lithium-based batteries

Li-ion technologies have a high energy density and low weight. The technologies considered in this Roadmap consist of a combination of specific anode and cathode materials.

Recycling is undertaken through pyrometallurgy or hydrometallurgy, and more recently, by direct recycling and some newly installed capacities are currently under development. End-of-life cells and modules, as well as production scraps, are not crushed but treated directly. Valuable metals are recovered for conversion into active cathode materials for the production of new batteries. Lithium represents a small fraction of what is recovered and is not currently reused in the battery value chain.

Production processes, recycling processes and transportation have been identified as challenges to recycling. 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 85% by **2035.** The recovery of nickel, cobalt and lithium will also be fully commercially viable in future.

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, the Lithium-ion market progression is slower as lead acid batteries are predominate 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 be also 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 different available anode and cathode materials, which are described in the Technical Annex.

For more detailed information on the state-of-the-art status and the improvement potential of lithium-based batteries, please consult the Technical Annex.

5.1.3 Nickel-based batteries

Ni

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),** renowned for their very long life and unmatched sturdiness, as well as their progressive aging which can be monitored, hence allowing preventive maintenance.
- **Nickel-metal hydride batteries (Ni-MH):** offering a higher energy density, generally well suited for high-current-drain applications. The Ni-MH technology however requires a BMS for its proper operation, hence introducing an element of vulnerability.

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.

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.

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.

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.

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.

For more detailed information on Nickel-based batteries please consult the Technical Annex.

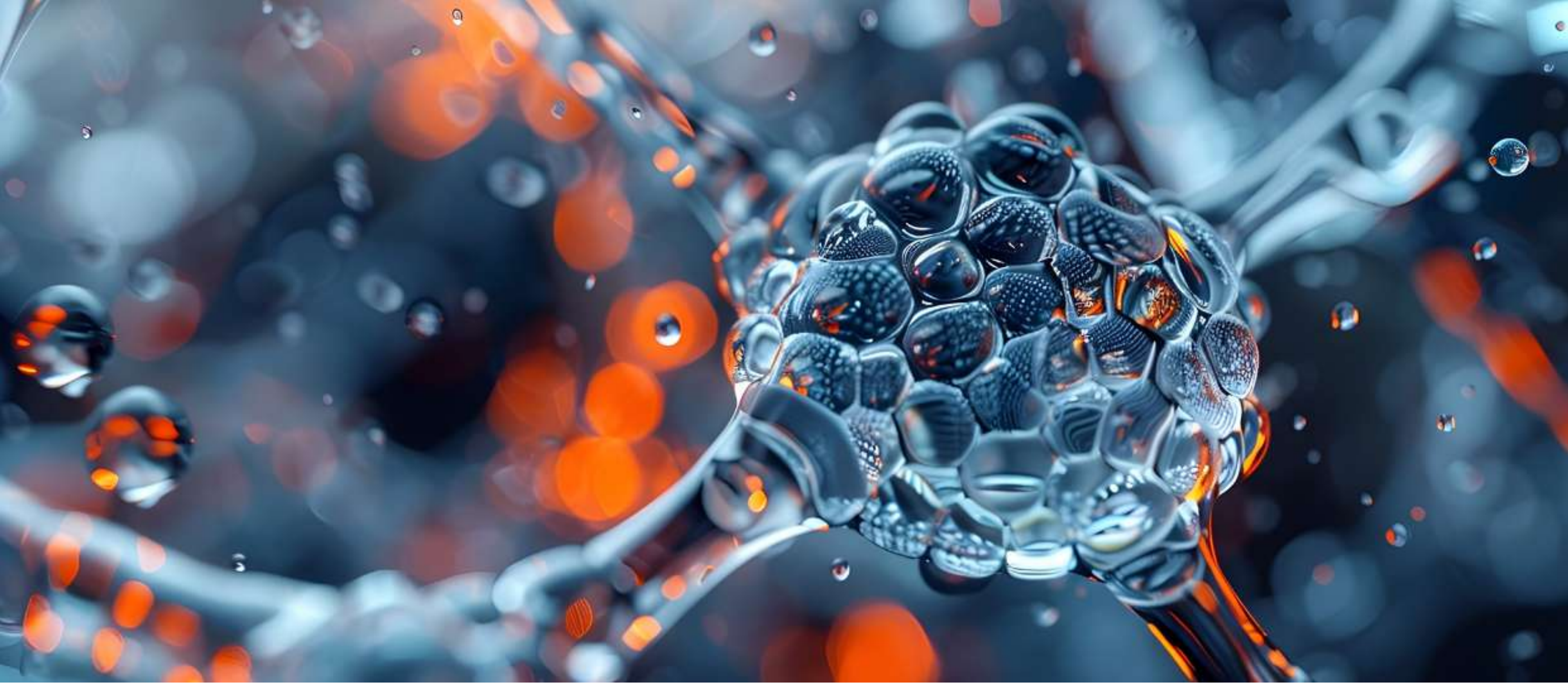
5.1.4 Sodium-based batteries

High-temperature sodium-based batteries offer relatively high energy density and low weight compared to lead-based batteries. Two prominent technologies on the market are:

- **Sodium nickel chloride batteries (NaNiCl)**
- **Sodium-sulfur batteries (NaS).**

The production and operation of NaNiCl batteries is energy-intensive, leading to a higher environmental impact, particularly dependent on the heat source used. Additionally, factors, such as high demand for nickel and complex modular construction contribute to environmental considerations.

While both chemistries can be recycled, they often undergo downcycling. For NaNiCl batteries, nickel recovery for use in the steel industry is feasible.



The ceramics and salt extracted during recycling can find applications in road construction. NaS batteries also contain significant proportions of steel and aluminum, facilitating further recycling to minimize their environmental impact.

More recently, room temperature sodium-ion batteries (SIB or NIB) have been explored as a potentially cheaper, lower energy alternative to lithium-ion batteries (LIB). It is expected that limited capital investment will be required to adapt LIB cell/pack manufacturing equipment to produce SIB.

Interest in this chemistry increased in 2020-2021, when Li-ion raw materials commodity prices increased, and on the back of several announcements by Asian LIB manufacturers, who committed to scale-up and create a value chain for this battery chemistry.

Sodium batteries have a potential specifically for cost-sensitive automotive and grid applications, especially when gravimetric or volumetric energy requirements are less stringent.

For more detailed information on sodium-based batteries, please consult the Technical Annex.

5.2 Most Promising Future 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 of raw materials.

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

In pursuit of enhancing battery performance across real-life applications, and driven by imperatives of durability, safety, sustainability, and affordability, industry experts have converged on promising future technologies for inclusion in the current roadmap. Sustainability stands as a paramount driver, aiming to produce batteries with minimal environmental impact, obtained in adherence to social and ecological standards, ensuring longevity, safety, and the potential for repair, reuse, or repurposing. As such, the essential electrochemical storage systems identified are listed hereunder. More detailed information on those most promising future technologies is in the Technical Annex.

5.2.1 Advance Lead-based battery technologies

Key areas for innovation are improvement of lifetime, higher material utilization, high power density and increase energy density. In general, positive alloy have to be improved. For e.g. pure lead technology is one option to improve performance in all aspects as mentioned before.

Bi-polar lead technologies would give in addition a significant improvement in terms of power and energy density increase. Other areas of innovation are additives to the positive and or negative active material. They can potential delivery improved lifetime and a better mass utilization.

Recycling of lead acid batteries achieved already an excellent level (>85%). The lead material is fully recycled without downsizing. Partly sulfuric acid and housing material without flames retardant additive is recycled in addition. A new part of innovation is the potential recycling of housing material with flames retardant additives.

A new driver for innovation is the battery passport requirement. The new battery regulation requires for industrial batteries > 2kWh a digital twin (a virtual representation to reflect a physical object accurately). It spans the object’s lifecycle, is updated from real-time data and uses simulation, machine learning and reasoning to help make decisions. Li batteries need battery management system (BMS) by definition, so including information functionalities on SOC, SOH and other parameters is easier as lead batteries do not have a BMS. One of the innovation focus areas is to develop a BMS for industrial lead-based batteries to establish a digital twin.

For SLI batteries we will see a merger of the classic SLI function (starting, lightning and ignition) and auxiliary batteries. Those batteries requires prediction algorithm to determine the power capability for functional safety. Means the reliability of battery performance must be improve via design and manufacturing processes. Software have to be improved to project the power capabilities of the battery precisely for functional safety applications.

5.2.2 Sodium-ion Room Temperature battery technologies

Sodium-ion batteries have a similar working principle to Li-ion batteries. As sodium resources are cheap and equally distributed worldwide (2.75% of the earth’s crust is sodium, compared to 0.0065% for lithium), and considering the technological similarities with existing Li-ion batteries, the industrialization process of sodium-ion batteries will be accelerated.

Based on potential application scenarios, higher energy density, longer cycle life and better low temperature performance are the most critical indicators. In total, the cost and safety advantages of sodium batteries will gradually gain in prominence. Therefore, it is likely that sodium-ion batteries will be used in two- and three-wheeled vehicles, in 12V starter applications, in A0 and A00 passenger vehicles, and in certain industrial applications (e.g. stationary) – to effectively supplement Li-ion batteries. Readiness for the mass market is expected end of 2024.

More information on sodium-ion room temperature battery technologies is available in the Technical Annex.

5.2.3 Post Li-ion battery technologies

Inexpensive and environmentally friendly metals, such as sodium and polyvalent light metals, should one day replace the current Li-ion 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.

As there are many Li-ion variations, the Technical Annex includes a tabulation of the categorization of Li-ion technologies, indicating the timeline of **the readiness level for mass-market introduction for the proposed technologies**.

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

Solid-state batteries use an electrolyte made of solid material instead of the usual liquid electrolyte. This technology could bring economic and sustainable benefits. The main advantages of future solid-state batteries are:

- Significant increase in the energy density of the cells
- Significant decrease in fire risk due to the less pronounced flammability of the electrolyte
- Significant reduction of the use of cobalt

Readiness for the mass market of Gen 4b is expected after 2025, while the mass-market readiness level of Gen 4c is expected from 2030.In between, we can expect:

More information on the lithium all-solid-state battery technologies is available in the Technical Annex.

5.2.3.2 Lithium-sulfur battery technologies (LiSB)

The low cost and high abundance of sulfur (i.e. the active cathode material) make LiSB more appealing than Li-ion batteries given the fact that the latter use critical materials, such as cobalt and nickel, in the manufacturing of the cathodes.

The high energy and low cost make LiSB 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 energies. LiSB are promising because of the high energy density, low cost and natural abundance of sulfur. More information on LiSB technologies is available in the Technical Annex.
Readiness for the mass market is expected after 2030.

5.2.3.3 Lithium-air battery technologies (Gen. 5)

Lithium-air batteries possess a great potential for efficient energy storage applications to resolve future energy and environmental issues. The extremely high theoretical energy density is attractive, but there are still various technical limitations to overcome. 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.
More information on lithium-air battery technologies is available in the Technical Annex.
Readiness for the mass market is expected after 2030.

5.2.4 Redox flow battery systems

Redox flow battery system is another electrochemical system for large stationary application like ESS batteries. Vanadium bases system are mature and in small scale production with good results in ESS application.

The battery systems can demonstrate excellent efficiency and good lifetime results. The independent sizing of energy and power of the system is a strong advantage. The Energy density is defined by the size of the external tanks for the liquids. A draw back of the Vandium Redox Flow technology is that vanadium has been categorized as a critical raw material.

More information on Redox flow technologies is available in the Technical Annex.

6. Concluding remarks and recommendations

6.1 In conclusion

The future promising technologies presented in this Roadmap **are not all at the same technology readiness level**. We consider **sodium-ion room temperature batteries as 'most promising' in terms of earliest entry into the market.**

Considering the projected timeline for innovations to enter the market, the upscaling of production capabilities, as well as the market projections from different credible sources, **we can conclude that Li-ion and lead-based batteries will remain the dominant technologies in the coming years**

With focus on the time horizon of **2035, both lithium- and lead-based batteries will remain dominant technologies in the European and worldwide markets. However, Na-Ion Room Temperature (RT) will take over a substantial market share in specific markets.**

- Lithium-based: fastest growing market with double digit annual growth
- Lead-based: to remain stable but with the impact of the potential automotive ICE ban in 2035 to consider
- Sodium-ion RT: offering a sustainable alternative, maturing faster with performance competing in specific markets, thanks to further R&D making it 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 digital twins, something that was never done before and likely to generate new opportunities for improvement, also in the integration aspect
-
-

6.2 Recommendations

The European battery industry, represented by EUROBAT, emphasizes the importance of developing all battery technologies to maximize contributions to Europe's decarbonization objectives and strategic autonomy. This Roadmap underscores that the various battery technologies, each with distinct features and developmental potential, are complementary and essential for supporting the EU's Green Deal agenda. **Given the diversity in battery features needed in a multitude of applications, there is not one technology type that fits all**.

Make Europe resilient by opening up technological evolutions in all battery technologies

Policy should not fix the technologies but focus on the objectives, leaving the liberty to the industries to find the best ways to reach those objectives. Deciding on one or another technology today is by definition an act of making a bet, as we can only make that choice based on what we know today.

- As a chain is only as strong as its weakest link, future **EU R&D public funding should be spread more equally** among the different technologies by targeting applications with the best available technologies. **Boosting innovation in all battery technologies** (lead, lithium, nickel, and sodium) to support the transition to a circular economy will make the EU industry more resilient and will contribute to Europe's strategic autonomy in battery materials.

- In addition to continuing R&D on mainstream technologies, R&D on **high-TRL promising technologies** should also be further conducted, such as on sodium room temperature (Na-ion RT), which represents the most promising technology in the near **future in terms of cost, raw material availability, and performance** to support the transition.

- **R&D related to all technologies** to increase recycling, use of recycled content, or to reduce the use of critical substances, will support the objectives of EU's **Critical Raw Materials Act** (CRMA), unveiled in March 2023 in response to escalating demand for raw materials critical to Europe's economic stability.

Strengthening Europe's competitiveness, while ensuring a global level playing field

Europe must ensure a level playing field for all battery technologies, **recognizing their complementary nature and essential role in transforming the EU** into a prosperous society with a resource-efficient and competitive economy aiming for net-zero emissions by 2050. To achieve this goal, a legislative framework that promotes a robust and sustainable European battery supply chain is essential to be further developed.

- The **Net-Zero Industrial Act** (NZIA), unveiled in March 2023, supporting the domestic battery manufacturing industry and deployment of markets in Europe, **should be pursued** to ensure its success
- The **diversity of battery technologies** in Europe's portfolio is **crucial for meeting various and evolving battery uses and applications, while also mitigating risks associated with fluctuations in the cost of raw and active materials.** Overemphasizing one technology poses a strategic risk to Europe's global competitiveness, potentially impacting citizens' purchasing power and eroding industrial knowledge across key markets within the EU.
- Building on the **existing European domestic manufacturing industry capacities and their expertise** will accelerate the transition as it will bring **academic innovation faster into new products** and new products into new production lines to successfully **scale up promising innovations, serving niche and mass markets** to supplement future demands.

To contribute to Europe's transition to achieving a sustainable and circular economy

- With the new **Battery Regulation** in place in 2023, additional environmental challenges need to be overcome to develop a circular economy. In this regard, not all mainstream technologies are at the same level of maturity. **Each technology** will need **different R&D efforts** to make progress on different aspects of the circular economy's key sustainability performance indicators.
- The four **pillars of the Green Deal Industrial Plan**—(1) simplifying permitting, (2) enhancing skills, (3) facilitating open and fair trade, and (4) grants and loans—should be **pursued** to target the entire battery manufacturing industry value chain in order to maximize our contribution to the green transition.
- With the **green transition triggering an exponential battery demand**, Europe should facilitate the further build-up of local production capacity of batteries, to be produced **with less hazardous substances and with the lowest carbon footprint**

Technical Annex

The Technical Annex to the Roadmap 3.0 provides the reader with detailed background information on the mainstream and future battery technologies and their potential for improvement for each application addressed in the roadmap.

While part 1 of the annex focuses entirely on the details of battery technology features, part 2 covers the technical details on a diverse range of end-user battery-powered applications in the areas of automotive mobility, motive power, and stationary applications, with the aim to provide stakeholders with comprehensive insights into the latest developments and opportunities in the battery manufacturing industry.

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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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