ROADMAP MATERIALS FOR BATTERY TECHNOLOGY
(March 2024)

BATTERIES FOR MOBILITY automotive, motorcycle, bike, step, drone, maritime, aviation, space		BATTERIES FOR STATIONARY APPLICATIONS home, district, utility
High performance	**Balanced performance**	**Storage**
Materials and processes for high performance Gen 3, Gen 4 and Gen 5 Li-ion batteries with increased safety, higher energy density, longer driving range, faster charging rate and lighter weight.	*Materials and processes for balanced performance and cost for Gen 3 and Gen 4 Li-ion and Na-ion batteries with increased safety but an acceptable driving range, charging rate and weight.*	*Materials and processes for stationary storage batteries with balanced cost and performance with focus on Gen 3 and Gen 4 Li-ion or Na-ion batteries or innovations in redox flow batteries to increase safety, reduce the system footprint, increase energy density, and limit dependency on critical raw materials.*

ENABLERS & ACCELERATORS	
Sustainability	*Development and refinement of tools and models evaluating the technical properties/quality/durability of materials and/or products or evaluating the sustainability/circularity (energy, CO_2/H_2O footprint, emissions, ...) of batteries and related materials and processes as well as the accessibility of data.*
Digitalization and safety	*Development, improvement and validations of various digital solutions (e.g. integrated sensors, adaptive battery management systems, material passports, robotization, IoT, AI applications, Industry 5.0 and digital twins) to support the overall "safe and sustainable by design" goals of future batteries.*
Reuse, refurbish, repurpose, recycling, and reduced critical raw materials dependency	*Second life options for batteries and end-of-life recycling of materials and components to meet current and future regulation and to ensure optimal use of materials in a circular economy as well as solutions to reduce critical raw materials dependency (e.g. by local sourcing or extraction from side streams).*

Figure 1 Diagram Roadmap Battery technology

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Application domain	Focus domain	Battery generation	Reference and targets at cell level (*)			Funding instr. 2024-2027		Funding instr. 2028-2030	
			Ref 2023	Target 2027	Target 2030	SBO	ICON	SBO	ICON
Batteries for Mobility: automotive, motocycle, bike, step, drone, aviation, space	High performance batteries: higher energy, longer driving range, faster charging, lighter	High performance Gen3 Li-ion: HV cathode materials, liquid electrolyte, Si-containing or Li-metal anode	275 Wh/kg 700 Wh/L 1000 cycles 3C charge >150 €/kWh	330 Wh/kg 850 Wh/L 2000 cycles 4C charge <100 €/kWh	350 Wh/kg 1000 Wh/L 3000 cycles 5C charge <75 €/kWh				
		High performance Gen4 Solid State: HV cathode materials, solid electrolyte, Li-metal anode	250 Wh/kg 380 Wh/L 500 cycles 0,2C charge >150 €/kWh	350 Wh/kg 800 Wh/L 1000 cycles 2C charge <100 €/kWh	500 Wh/kg 1000 Wh/L 2000 cycles 3C charge <100 €/kWh				
		High performance Gen5 batteries: lightweight, high power, fast charging, limited cycle life (Li-S, Li-air, Zn-air)	400 Wh/kg 450 Wh/L 250 cycles	500 Wh/kg 650 Wh/L 350 cycles	600 Wh/kg 800 Wh/L 500 cycles				
	Balanced performance batteries: lower cost, average driving range, average charging rate, acceptable weight	Balanced performance Gen3 Li-ion: MV cathode materials, liquid electrolyte, non-Si anode, lower production cost	200 Wh/kg 525 Wh/L 5000 cycles 2C charging >150 €/kWh	250 Wh/kg 550 Wh/L 5000 cycles 3C charging <75 €/kWh	250 Wh/kg 550 Wh/L 5000 cycles 5C charging 50 €/kWh				
		Balanced performance Gen3 Na-ion: liquid electrolyte; hard carbon or tin-based anode	160 Wh/kg 200 Wh/L 2000 cycles	160 Wh/kg 300 Wh/L 3000 cycles	170 Wh/kg 400 Wh/L 4000 cycles				
		Balanced performance Gen 4 Solid State: HV/MV cathode materials, solid electrolyte, Si-containing anode	250 Wh/kg 500 Wh/L <2000 cycles 2C charge >150 €/kWh	300 Wh/kg 600 Wh/L 2000 cycles 3C charge <100 €/kWh	350 Wh/kg 800 Wh/L >2000 cycles 5C charge <100 €/kWh				
		Balanced performance Gen4 Na-ion: solid state electrolyte; normal or Na-metal anode	No data available	No data available	>100 Wh/kg >250 Wh/L >1000 cycles				
Batteries for stationary applications: home, district, utility	Storage: reducted footprint, high energy, high power, low self discharge, increased safety	Balanced performance Gen3 Li-ion: MV cathode materials, liquid electrolyte, non-Si anode, lower production cost	300 Wh/L 2000 cycles 1C charge >250 €/kWh	400 Wh/L 4000 cycles 2C charge >150 kWh	500 Wh/L 6000 cycles >3 charge <150 kWh				
		Redox flow batteries: alternative redox chemistry; improved membrane performance	35 Wh/kg 35 Wh/L 3000 cycles	38 Wh/kg 40 Wh/L 15000 cycles	40 Wh/kg 45 Wh/L 20000 cycles				
		Balanced performance Gen3 Na-ion: liquid electrolyte; hard carbon or tin-based anode	160 Wh/kg 200 Wh/L 2000 cycles	160 Wh/kg 300 Wh/L 3000 cycles	170 Wh/kg 400 Wh/L 4000 cycles				
		Balanced performance Gen4 Solid State: MV cathode materials, solid electrolyte, Si-containing anode	250 Wh/kg 500 Wh/L <2000 cycles 2C charge >150 €/kWh	300 Wh/kg 600 Wh/L 2000 cycles 3C charge <100 €/kWh	350 Wh/kg 800 Wh/L >2000 cycles 5C charge <100 €/kWh				

(*) Gravimetric Energy Density
Volumetric Energy Density
Cycle Life
Charging Rate
Cost At Pack level

Too early, insuficient industrial interest
Relevant instrument
Revevant instrument but timing is becoming critical
Too late to start development

Enablers & Accelerators	Focus area	Topic	Reference and targets			Funding instr. 2024-2027		Funding instr. 2028-2030	
			Ref 2023	Target 2027	Target 2030	SBO	ICON	SBO	ICON
Sustainability	Sustainability assessments	Development and refinement of tools to evaluate sustainability and accessability of data	Actual SotA	Refinement for Gen3 and Gen4 batteries	Refinement for Gen 5 batteries				
	Legislation and regulations	Policy advice to support regulation on batteries	Actual SotA	Depending on EU-level	Depending on EU-level				
Digitalization and safety	Smart battery, battery passport, digital twin, adaptive battery management systems	Integration of sensors in battery to log composition, use and performance over entire lifecycle	Concept (TRL 1)	Lab testing (TRL 2-4)	Ind. demo (TRL 4-6)				
	AI supported developments	AI based optimization of battery material composition and manufactoring conditions	Ref	10% improvement	25% improvement				
	Safety	Applications specific battery safety standards	Only available for automotive	Safety standards for stationary batteries	Safety standards for aviation and space				
Reuse, refurbish, repurpose, recycle, and reduced critical raw materials dependency	Second life battery applications	Evaluation of the SoH of battery cells (e.g. X-ray based) in pack or module for use in second life applications	Cell level	Module level	Pack level				
		Robotized or robot assisted technologies for safe and fast disassembly of battery packs or modules	Manual dismantling	Semi automated	Fully automated				
		Redesign for new applications and re-assembly technologies	Manual re-assembly	Semi automated	Fully automated				
	Decreased dependency on CRM	Technologies for improved recycling or extraction of Li	Conventional sourced Li e.g. salts or ores	Recycled Li e.g. EoL batteries or waste	Low Li sources e.g. geothermal brines				
		Technologies for improved recycling or extraction of non-Li battery materials	Mainly high value metals e.g. Co, Ni	Recycling of low Co and low Ni batteries	Recycling of Na-ion batteries				

Figure 2 Roadmap Battery Technology- Detailed Diagram (a) Application areas and (b) Enablers and Accelerators

1. What is the importance of the roadmap?

MateriNex's main objective is to support Flemish companies active in materials research, taking into account the **EU research agenda** and **the Flemish government's policy priorities**. A survey has shown that these **needs** are situated in the area of **high-risk long-term research**.

For each MateriNex **innovation theme**, a roadmap with horizon 2030 has been drawn up that establishes the priorities related to basic and applied research for the coming years and the funding instruments to be considered such as strategic basic research (SBO) and/or interdisciplinary cooperative research (ICON).

The roadmap will be used to organize calls for project proposals and to evaluate the submitted project proposals. However, it is a dynamic tool and will be adjusted as needed based on consultation with a broad group of stakeholders (Common Interest Group (CIG)).

2. What is this roadmap based on?

This roadmap is largely based on a draft version of the BEPA roadmap exercise underway at the EU level. The **Batteries European Partnership Association** (BEPA) is the international association representing the private part of the **BATT4EU** partnership. BEPA unites the European battery community that wants to contribute to the ambitious Research & Innovation Batteries Partnership under Horizon Europe. BATT4EU is a public-private coordinated partnership established under Horizon Europe - the European Union's Framework Program for Research and Innovation - which aims to create a competitive and sustainable European industrial value chain for e-mobility and stationary battery applications. (https://bepassociation.eu/about/bepa/)

3. What does this roadmap focus on?

This roadmap starts from the two main **application domains** for batteries namely batteries for mobility resp. stationary energy storage. For mobile applications, there are **two focus domains** (“high performance” and “balanced performance” respectively), while for stationary applications the focus is on “energy storage”. In each focus domain there are **subdomains** (**battery generation**), each of which pursues specific objectives (targets) for similar criteria within a certain period of the 2030 horizon.

For each subdomain, an estimate of the supporting grant instruments considered necessary to achieve the objectives within the time frame has been made. This uses a simple color code where green represents relevant instruments. Blue, too early and currently limited industrial interest, and orange, relevant but critical with respect to timing, can in principle also be funded provided a good argument is made. A red color indicates that the instrument is too late to start up.

In addition, the roadmap has another part that can be described as enablers & accelerators. These are important cross-cutting challenges. Some of these challenges can be the subject of projects. For example, because they are very specific to the innovation theme for which the roadmap was drawn up and because in Flanders a substantial number of companies are active in this field and in some cases even play a pioneering role. See also part 5 “What cross cutting challenges should be considered (enablers)”?

4. What core activities are included in this roadmap?

Materials, especially advanced materials, are the backbone and source of prosperity of an industrial society. In the context of the radical changes and transformations of the 21st century, including climate change, energy transition, sustainability, circularity and digitalization, advanced materials will play a key role. Key recent roadmaps and reports on materials research highlight the importance of materials-based and carbon-neutral innovations as key catalysts for solving the technological challenges.

The Flemish research and industrial community wishes to be an integral part of the EU and global materials innovation ecosystem and to contribute to a green and sustainable future. Important research objectives for the Flemish research and industrial community are related to energy transition and mobility. The intention of MateriNex is to support materials research and development that does not overlap or complement the already subsidized research in Flanders. With the battery technology roadmap, MateriNex opts for the **development of materials and processes for new types of batteries for mobility and for stationary energy storage**. But space is also given to the development, refinement and validation of enablers and accelerators in terms of **sustainability, digitalization and circularity** including reducing **dependence on critical raw materials**.

Battery technology is a key technology for mobility and energy storage and will see immense growth in the coming years (see Figure 3). Moreover, Europe wants to increase its independence in this field, as well as make the technology more reliable and safer.

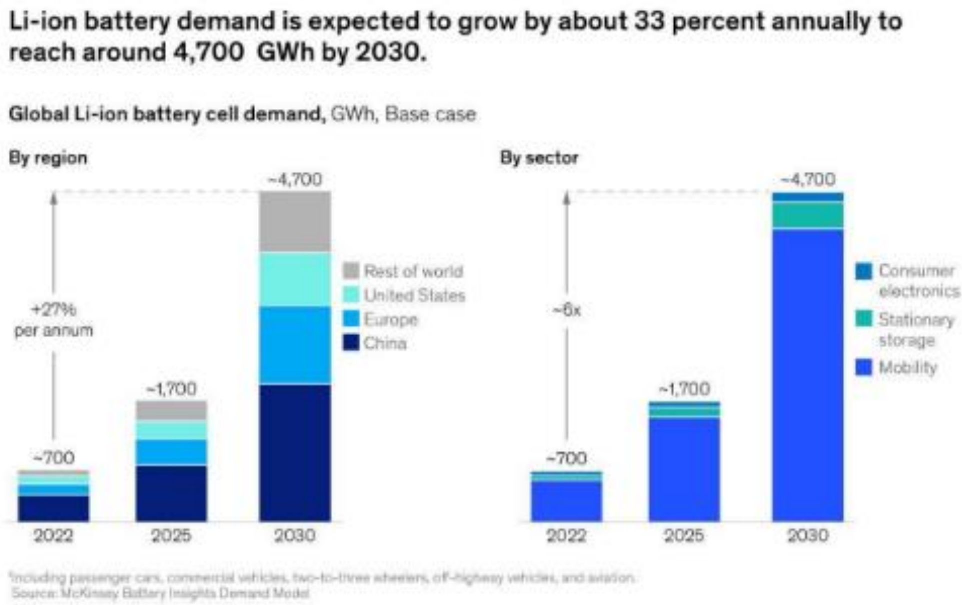

Figure 3 Expected growth in the global Li-ion battery demand by region (left) and by sector (right) (Ref: Battery 2030+ roadmap; https://battery2030.eu/research/roadmap/)

Important elements in the evolution of battery technology are **energy density, lifetime/cycles**, **safety**, **availability** of required **raw materials** and acceptable **cost**. Energy density is an important factor in development and is highly dependent on the battery chemistry used as illustrated on Figure 4 below.

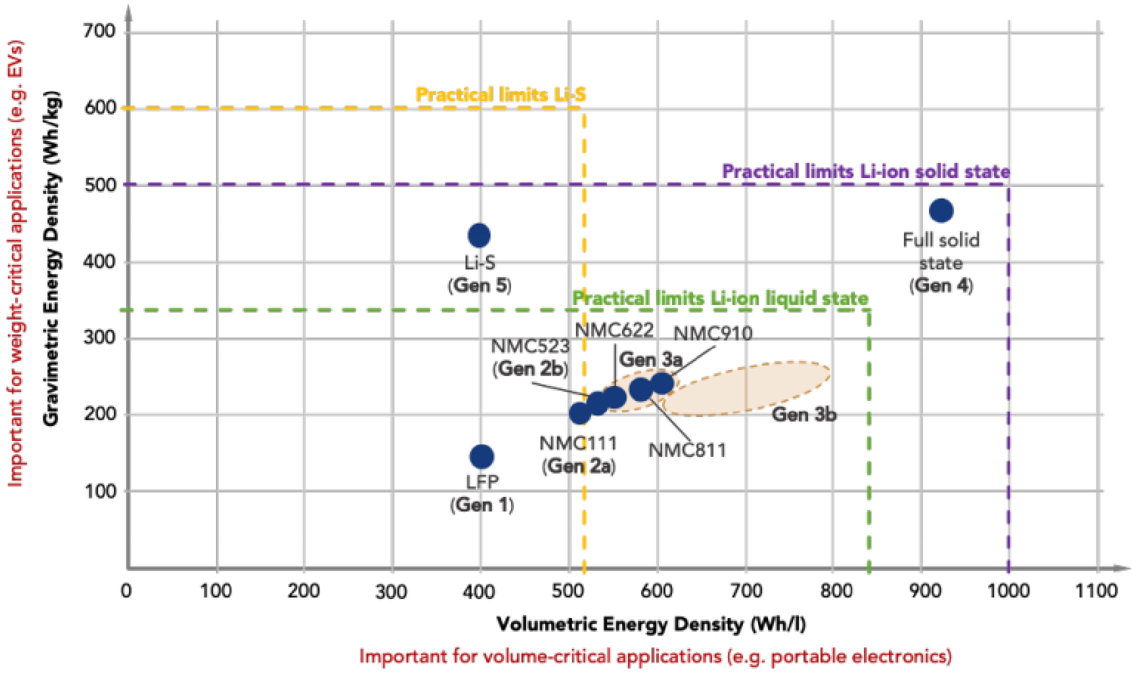

Figure 4 Practical limits for the different types of batteries
(Source: EMIRI roadmap; https://emiri.eu/)

Different applications require different battery specifications and currently there is already a wide range of battery types. A distinction is made based on the **battery chemistry** (e.g., LFP, LMFP, NMC, HLM, ...), **liquid or solid electrolyte** (SSB or Solid State Battery) and the **type of anode** (graphite, Li-metal, ...). On this basis, a distinction can be made between different battery generations. The state-of-the-art (SotA) is different for different battery generations and within the same generation for different battery types. As a benchmark the performance of the different battery types in 2023, as included in the BEPA roadmap exercise, is taken and the specifications for development of new materials for the different battery types are expected to be in line with these for 2027 and 2030.

The innovation timeline to 2030 was split into two periods: 2024-2027 and 2028-2030. This distinction was made in order to better target the co-financing instruments for basic research. The innovation landscape includes many international players and evolves very quickly. The roadmap takes into account the timely deployment of certain basic developments (SBO) and industrial leadership in developments (ICON) that are closer to the market.

5. What cross cutting challenges should be considered (enablers)?

The development of **appropriate methods and tools for sustainability** evaluation based on (social) life cycle assessments ((s)LCA), techno-economic assessments (TEA), natural and geopolitical **availability** (critical raw materials), **toxicological evaluations**, but also **the cost** and **energy requirements** of the production process are essential and guiding the choice and development of new battery materials and their life cycle. **Safety** for use but also with respect to **environment and health** are extremely important. Existing and future **laws and regulations** in this area, such as the recently amended European legislation on batteries and waste batteries, should also be taken into account and sufficient attention should be paid to **policy support initiatives**. Making **data available** for this purpose, such as the carbon footprint of materials and processes, is essential. When developing new technologies, this is often a separate exercise. First and foremost, this will be needed at an academic level, with subsequent testing of industrial practice.

Digitalization plays an important role in battery materials research, in terms of **data management**, **sharing and storage**, and the use of digital analytical methods such as modeling, machine learning and artificial intelligence (AI), typically using high performance computing (fast computing clusters). Some possibilities:

- Material selection: using **high throughput** methods, a multitude of compounds can be screened in a short period of time to identify candidates for further experimental testing.
- Modeling: extensive digital modeling using measurements and data collected from physical systems is often named by the term **digital twin**, and is a digital representation of a real system, such as a battery. The behavior of the physical system can be studied quickly, easily and efficiently in that digital twin.
- Predicting battery performance: with advanced data analysis techniques such as **machine learning**, data can be used to predict the performance of certain batteries, such as **state-of-charge** and **state-of-health**. In this way, performance can be simulated under different conditions and in different environments. It is also possible in this way to optimize usage to extend service life, for example. Systems for this purpose are known as Battery Management Systems (BMS).
- **Data management**: in general, it is important to organize data management well to enable applications such as those described here. It is about making data FAIR (FAIR = Findable, Accessible, Interoperable, Reusable). In the current context, this mainly involves experimental data, such as design and results of experiments and tests, as well as simulations. This is in line with the European Data Strategy that aims to better use data to increase competitiveness and exploit data as a valuable resource. (https://digital-strategy.ec.europa.eu/en/policies/strategy-data)

Reuse of batteries or battery cells in another application at the end of their first life cycle (**second life**) can contribute significantly to meeting the large and rapidly increasing demand for batteries. This will also provide great economic added value in terms of battery products and services. Developing **new physicochemical analysis technologies**, such as X-ray-based characterizations, to evaluate the reusability of battery cells is very important and complementary to other digital tools. The **safe dismantling** and **controlled (re)assembly** of batteries requires new developments in **automation and robot-assisted manufacturing** (Industry 5.0).

To **minimize the dependence on critical raw materials**, efforts should be made to replace certain materials such as cobalt but also to optimize the recovery and reuse of battery materials at the end of their life (end-of-life recycling). A first important challenge is to better sort collected batteries according to their material composition (NMC, NCA, HLM, LTO, LFP, LMFP, Na-ion, ...). **New recycling processes** need to be developed to not only recycle the more valuable materials such as cobalt, nickel and copper but to enable reuse of most of the materials (preferably 80% and more) in new batteries including e.g. electrolyte, polymeric binders, separator, graphite, phosphorus and manganese. The challenge in this area is greatest for cheaper battery types such as LFP, Na-ion and Li-S. For these, the development of regeneration processes aimed at direct material recycling is the most obvious option. Exploring **alternative sources for critical materials** should also be investigated such as industrial by-products, historical waste heaps and/or primary raw materials such as certain minerals or geothermal brines for lithium.

6. Complementarity in the Flemish innovation landscape for batteries

Several Flemish companies are active in research and development of (materials for) battery technology. Some of them have already endorsed this roadmap. In the Flemish academic community, almost all universities and the SOCs (Strategic Research Centers) VITO and imec are active in the field.

Notwithstanding MateriNex's focus on high-risk long-term research, the bridge will also be made to higher TRL (Technology Readiness Level) and production.

Alignment regarding complementarity (of research) with other funding organizations such as the spearhead clusters and the SOCs (as far as their ICON program is concerned) will have an important place in the operation of MateriNex. With regard to materials for battery technology, this is initially with Flux 50, Catalisti and The Blue Cluster as far as the spearhead clusters are concerned, and with imec and Flanders Make as far as the SOCs are concerned.

7. Dissemination

Dissemination will be a mandatory part of any project that is approved. This will follow the rules of VLAIO.

Initially, the Common Interest Group Materials for Battery Technology will focus on sharing (public) research results. In terms of “next step” dissemination or dissemination across the value chain, there will be collaboration with spearhead clusters and SOCs that have complementary roadmaps. Specifically for batteries, connection will also be sought with the Battery Accelerator learning network of Flux 50.

In addition, for broad dissemination regarding the thematic priority, the VLAIO network will be used and MateriNex will provide support. In particular, there will be collaboration with the relevant collective research centers in this area.

8. Which project types and how to submit a project proposal?

With financial support from the department of EWI and commissioned by EWI and VLAIO, **VITO,** as an **independent strategic research center**, makes a team available to facilitate the management of the earmarked resources of the Fund for Innovation and Entrepreneurship to support materials research in Flanders. This is done under the name **MateriNex**.

Every year, MateriNex launches a **call** mentioning the date and modalities of the mandatory **pre-application** (for SBO and ICON) as well as the modalities and timeline to submit a full project proposal. Only project proposals that receive a GO from an **independent expert group (composed by the MateriNex team in consultation with VLAIO)** may develop and submit a full project proposal to VLAIO. This GO has a validity of max 1 year. For ICON projects, a “request for partners” facilitated by MateriNex can be used. Feasibility studies can be submitted at any time and have a shorter processing time. **VLAIO is responsible for the evaluation of full proposals for cSBO, ICON and feasibility studies**.

The **modalities for cSBO and ICON** projects as well as feasibility studies are defined in the respective manuals on the VLAIO website. We mention in particular:

A **cSBO** project proposal is submitted by **at least two research groups of at least one Flemish research center** (according to art. II.2 and II.3 of the Codex Higher Education). A Flemish research center is hereby defined as an organization established in the Flemish Region for research and knowledge dissemination (university, university college (“Hogeschool”), (strategic) research center. **Imec, VITO, VIB, Flanders Make, VLIZ and the Flemish scientific institutions with an endowment from the Flemish government**, can only submit a cSBO project proposal in collaboration with at least one other Flemish research center. A **Flemish university college** (“Hogeschool”) always submits a cSBO project proposal in collaboration with or at least after advice from the university within the association with which it is affiliated. Flemish university colleges can only submit a project proposal in cooperation with at least one other Flemish research center.

ICON (Interdisciplinary Cooperative Research) is a project type in which an ad hoc and balanced **consortium of one or more research centers and at least three unrelated companies** develop new knowledge, which can be practically applied and thus contribute to economic and possibly broader social added value in Flanders. An ICON project consists of a business part and a research part. The Flemish industrial partners can appeal for support from the Fund for Innovation and Entrepreneurship.

Feasibility studies are studies at the beginning of an innovation trajectory, where the overall feasibility and relevance of further investments in research, development and innovation must be checked. **Applicants are companies** that have a legal personality (at the latest at the time of signing the agreement). Furthermore, the applicant company must be able to sufficiently (but not exclusively) exploit the results in Flanders. The implementation of the project may also involve cooperation with other companies and with research institutions as subcontractors.