European Commission

ROADMAP ON ADVANCED MATERIALS FOR BATTERIES

Prepared by Working Group 3

#BatteriesEurope

Energy

Disclaimer

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List of Acronomys

DoD	Depth of discharge, the fraction or percentage of the capacity which has been removed from the fully charged battery.
CtP	Cell to pack technology, in which the cells are integrated directly into the battery pack without the intermediate step of modules
SEI	Solid electrolyte interphase
SSB	Solid state batteries
LFMP	High voltage lithium iron manganese phosphate cathode material
LMNO	High voltage lithium manganese nickel oxide cathode material
NMC	Range of nickel manganese cobalt oxide cathode materials
LiPF6	Lithium hexafluorophosphate, inorganic salt in the electrolyte
CCS	Combined charging system
DCFC	Direct-current fast charger
CHAdeMO	Trade name of fast charging methods for battery electric vehicles

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Executive Summary

With 50 to 70% of the cost of a battery cell being the cost of the cathode, anode, separator and electrolyte materials, advanced materials are key to further cost reduction and market uptake. R&I in advanced materials enables the development of more cost-efficient, better performing, safer and more sustainable battery cells. R&I in battery materials focuses mostly on increasing the energy density of battery cells for better performance and cost-competitiveness for specific applications. Various battery chemistries exist and are being further developed. Battery chemistries may differ depending on the application (mobility or stationary). In the mobility sector, the focus is on Li-ion battery chemistries, with R&I primarily on liquid-state batteries (generation 3) with a drive towards solid-state batteries (generation 4), in addition to a longer-term perspective in which R&I is conducted on generation 5 battery chemistries. In R&I for stationary storage applications, next to Li-ion batteries, there are numerous developments focusing on Na-ion batteries, innovative redox-flow batteries, and rechargeable metal-air batteries. For all these battery chemistries, further R&I is needed to develop the most appropriate advanced materials. This roadmap will solely focus on R&I needs in Advanced Materials needed to enable key improvements expected in Li-ion battery technologies. Indeed, Li-ion battery technology is expected to stay the technology of choice for many years to come, especially in the electric mobility sector while battery solutions for stationary storage applications are more flexible due to a large variation in requirements for differing use cases.

In this roadmap, we have identified 5 Strategic Topics, later detailed in terms of state of the art, challenges to tackle, research & innovation needs and expected impact. Below, the reader will find a short summary.

Strategic Topic #1 – Generation 3 materials for Li-ion batteries for mobility

Challenge: Develop advanced materials enabling higher energy / power density due to higher capacity and/ or operating at higher voltage. Focus is on adapting the cathode materials (nickel-rich NMCs for high capacity, spinels / Li-rich Mn NMCs for voltage), optimization of low cost and high safety phosphate based materials e.g. LFP, LFMP… development of the anode materials (graphite containing Si(Ox), the electrolytes (stabilized formulations for both electrodes), the binders … and their interplay.

Impact (KPIs): Gravimetric, volume energy density at cell level of 350-400 Wh/kg, 750-1000 Wh/l respectively. For high voltage application, operation at 4.7+ Volt. 3000+ and 2000+ deep cycles for high capacity and high voltage applications respectively. Cost at pack level 100 euro/kWh

Time to market: 2025(+)

Strategic Topic #2 – Generation 4 materials for Li-ion batteries for mobility

Challenge: Develop solid state electrolytes, cathode materials and anode materials with higher thermal and electrochemical stability while targeting higher energy / power densities, fast charging, cyclability and improved safety. Developments range from using conventional materials to Li metal-based anode with or without high voltage cathode materials.

Impact (KPIs): Gravimetric, volumetric energy density at cell level of 400+ Wh/kg, 800+ Wh/l (Generation 4a) to 500+ Wh/kg, 1000+ Wh/l respectively (Generation 4b & 4c). Cycle life up to 3000 cycles (at 80% DoD (depth of discharge)) and ability to operate at charging rate of 3-5C. Cost at pack level down to below 75 euro/kWh. Time to market: 2030(+)

Strategic Topic #3 – Materials for Li-ion batteries for stationary storage applications

Challenge: Develop materials systems (cathode, anode, electrolyte, binders …) to enable stationary Li-ion batteries to be used in various utility scale applications. For applications greater than > 100 MW, a Power to Energy ratio P/E < 1/3 and for commercial high-power applications < 100 MW a Power to Energy ratio of P/E > 4. Material strategies range from improving conductivity, energy density and lifetime in the case of utility-scale applications, while focus is on improving conductivity and capacity for high-power specific applications.

Impact (KPIs): For utility-scale applications - Volumetric energy density of 500+ Wh/l, lifetime of 12000+ cycle (equivalent full cycle at 60-80% of DoD), cost <0.05€/kWh/cycle . For commercial high-power applications C&I - Volumetric energy density of 500+ Wh/l, lifetime of 6000-10000 cycles, rate capability of 2-5 C.

Time to market: 2030

Strategic Topic #4 – Advanced materials to reduce weight of EV batteries

Challenge: Develop lightweight materials based on e.g. glass fibers, carbon fibers, new plastics, high-strength steels, etc and demonstrating high strength-to-weight ratio suitable for structural and functional battery packaging parts

Impact (KPIs): Increase durability by >15% at a cost < 5€/kg of weight saved. Achieve >90% recyclability. Potential weight reduction up to 70% in battery packaging, with light materials and alternative designs (e.g. CtP), meeting EUCAR safety criteria HL4 based on right use of active and structural materials Time to market: 2025(+)

Strategic Topic #5 – Advanced materials to enable ultra-fast charging

Challenge: Developing and optimizing the materials systems (e.g. doping, suitable particles layer to improve electron conductivity and reduce leaching) to enable user-friendly, safe and reliable ultra-fast charging stations with power transfer capability exceeding 350 kW

Impact (KPIs): Charging time < 10 minutes, power transfer capability at 350+ kW and low energy losses due to ohmic resistances during charging process, energy loss < 2%

Time to market: 2025

WG3

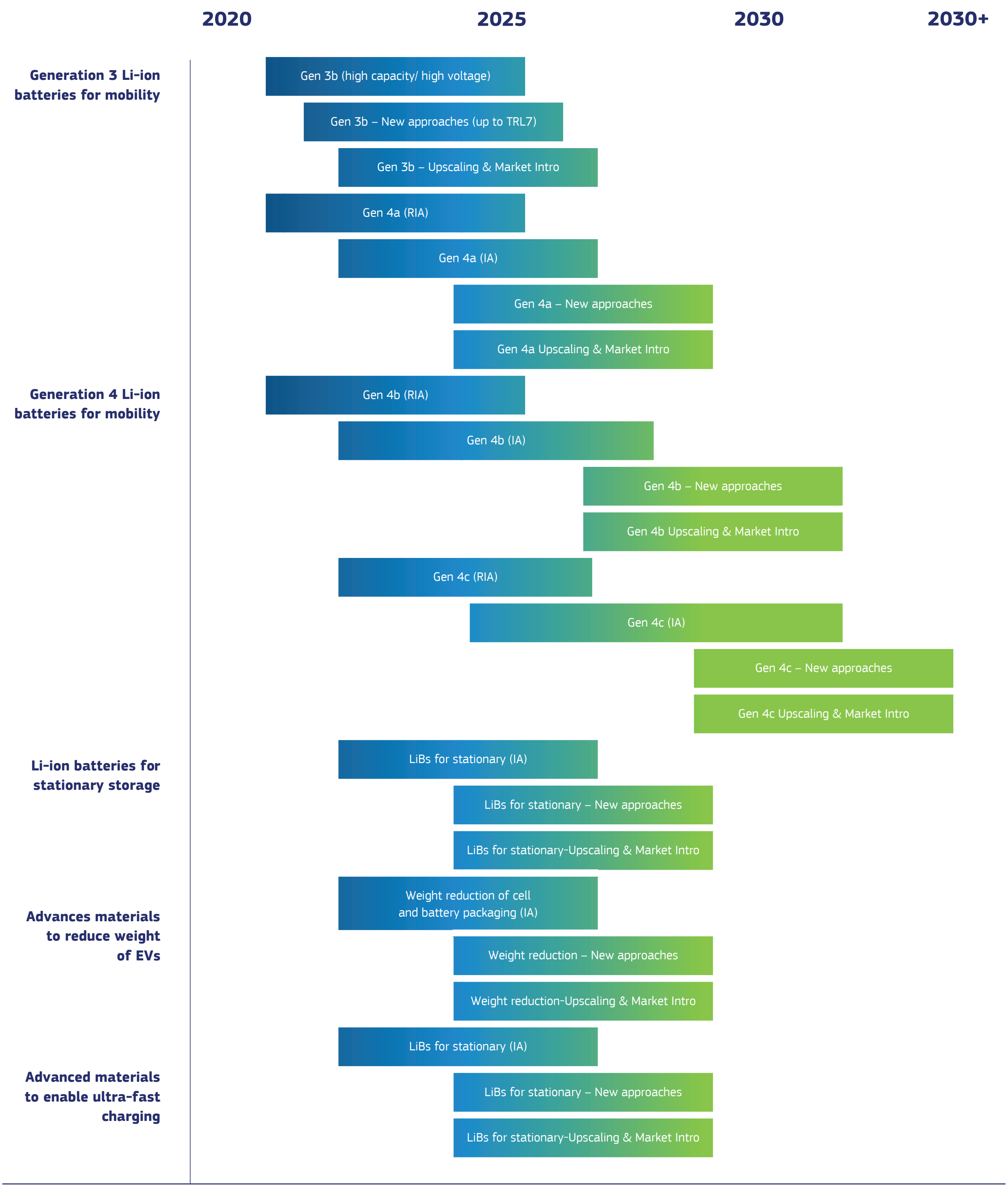


Figure A: Graphical representation of the strategic topics for advanced materials in the period 2020-2030+, developed by Batteries Europe WG3

Vision

Advanced materials are the key performance enablers of batteries while also being a key element determining the cost structure and the environmental impact and recyclability of battery cells. As the manufacturing of battery cells is further upscaled, improved and automated, advanced materials may in the future account for an even larger portion of the total cost of battery production.

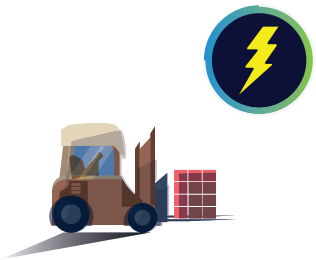
Having access to the best advanced materials and integrating these in an effective and efficient way to manufacture cells will be a key success factor for European players to compete in the development of cost-competitive, high-performance and sustainable battery cells manufactured in Europe.

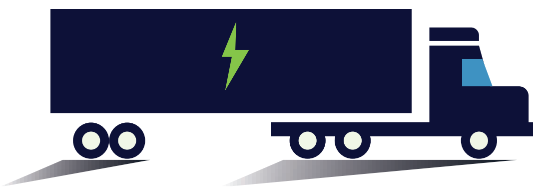
Moreover, advanced materials and their production are key to reducing the CO2 footprint of battery cells. Thanks to developing high-tech advanced materials imparting higher performance while innovating in the way these advanced materials are produced, the European based battery cell makers will be in a position to manufacture batteries with a better environmental footprint.

Our vision is to focus on a limited set of battery chemistries which will dominate the battery chemistry landscape well into the 2030s+. This vision is of course very well complemented with the insights generated by the WG1 on Emerging Technologies whose contribution is key to prepare the long-term future and ensure innovation continuity over various applications relying upon batteries.

Our vision is built on 5 dimensions, which we call Strategic Topics and for which the European battery value chain must build technology leadership as a basis for industrial leadership:

- Strategic Topic #1 – Generation 3[1] materials for Li-ion batteries for mobility;
- Strategic Topic #2 – Generation 4 materials for Li-ion batteries for mobility;
- Strategic Topic #3 – Li-ion batteries materials for stationary storage;
- Strategic Topic #4 – Advanced materials to reduce the weight of EV batteries;
- Strategic Topic #5 – Advanced materials to enable ultra-fast charging.





[1] See Appendix.

Objectives

Within the scope of the WG3 contribution to the roadmap (see 1. Vision) presented by Batteries Europe, and for each of the 5 Strategic Topics, our objective is to provide the reader with insights on the following important elements:

- Global state of the art (what are the solutions existing today and what are their limits?).
- Challenges (what are the technical issues lying ahead and to be tackled?).
- Needed research & innovation activities (where do we need to focus to solve the challenges & which are the advanced materials best suited to solve the challenges?).
- Expected impact (in case of innovation success, what can we expect in terms of technological, economical, and environmental impacts?).
- KPIs to guide innovation (which innovation related KPIs need to be reached at cell level in ideal laboratory conditions?).

Methodology

The initial focus of the WG3 is to provide insights regarding innovation in Advanced Materials for different battery chemistries, both for stationary and for mobility applications.

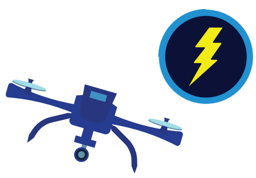
The Strategic Topics herein described deal with Advanced Materials from their development, to their production and to their integration into battery cells. These topics do not cover emerging technologies at low TRL – Emerging technologies are covered by WG1's activities.

The activities of WG3 did not start from scratch. We used indeed a very strong basis which is the EMIRI association's roadmap on advanced materials for low carbon energy and mobility applications[2]. The EMIRI roadmap was established with a broad spectrum of its members coming both from industry and from leading research & technology organizations/ universities while involving EU Commission's representatives for tips and comments. The EMIRI roadmap contains a strong selection of R&I topics for batteries spread over various chemistries and various applications.

Following various meetings late 2019 and over 2020, the scope of WG3 was defined as covering 5 Strategic Topics which are herein described:

- Strategic Topic #1 – Generation 3 materials for Li-ion batteries for mobility;
- Strategic Topic #2 – Generation 4 materials for Li-ion batteries for mobility;
- Strategic Topic #3 – Li-ion batteries materials for stationary storage.
- Strategic Topic #4 – Advanced materials to reduce the weight of EV batteries;
- Strategic Topic #5 – Advanced materials to enable ultra-fast charging.

Late 2020, the work started and was continued over the Q1 2021 based on a limited number of topic (co) leaders and contributors to generate a first iteration in line with the state of the art, the challenges identified and the R&D activities to be tackled to deliver on ambitious KPIs over the years to come. The first iteration was later checked out and amended by the broad community within the WG3 consisting of many experts coming from industry, universities and research organizations and representing various R&D approaches in battery materials.



[2] See Appendix.

1. STRATEGIC TOPIC 1 – GENERATION 3 LI-ION BATTERIES FOR MOBILITY

1.1 DESCRIPTION

High-performance advanced materials are at the core of the technological innovations needed to reach a sustainable and climate-neutral economy and society. Electromobility has become the preferred solution for decarbonisation in the transportation sector with BEVs projected to reach ca 120 million worldwide by 2030[3]. Advanced materials used in cathode, anode, separator and electrolyte make up 50 to 70% of the cost of Li-ion battery cells used to power these vehicles. The requirements for lower cost batteries still guaranteeing high energy density, long cycle life and rapid charging capability need sustainable R&I in advanced battery materials to continuously solve these challenges. Besides the technical R&I challenges of cost, energy and power density, cycle life and safety, other factors like sustainability and criticality of the battery raw materials are becoming more and more pronounced. A solution is needed to enable and sustain EU's competitiveness in the battery industry where Li-ion is expected to remain the dominant storage technology in EV batteries in next future and beyond 2030.

1.2 GLOBAL STATE OF THE ART

On the anode side, graphite is the most common used material, providing good capacities but storing also significant amounts of Li in the solid-electrolyte-interface (SEI). Addition of silicon to graphite is the main trend of new anode development. Premature cell aging and slow charge rates with increased Si-amount limit the maximum usable Si-fraction to 8 wt.%.

Cathode materials of Generation 3 include Nickel-Manganese-Cobalt-Oxides (NMC) of varying Ni content, with the maximum reaching more than 90 wt.% Ni, and lower cost materials with strong chemical bonds based on phosphates. They can be used pure or as a blend. The aim is to reduce Co content, to reduce cations' leaching, to increase performance and in general to decrease critical raw material content. In addition, high-voltage materials such as LMNO (Lithium Manganese Nickel Oxide) spinels and others are available technologies.

For the passive materials the trend

[3] IEA – Global Energy Review 2021.

leads towards a reduction in the number of inactive materials to achieve higher energy densities on cell level. Thinner substrate films and separators are more and more common in cells. The electrolyte that usually consists of organic solvents, additives and a conductive salt like LiPF6 is specifically adapted via additives.

1.3 CHALLENGES

Lithium-ion batteries with liquid electrolytes can be considered the champions of electrochemical energy storage. Key performance indicators for electric mobility like the energy and power density (plus 30 % to 50 %) and costs (minus 50 %) drastically improved compared to 2015 making battery electric vehicles viable alternatives already today. Still, for a wider public acceptance and broader field of applications, substantial improvements in the battery chemistry towards the 2030 targets are required.

Table A: Challenges of Generation 3 Li-ion batteries for mobility

Challenge	Short description	Relevance
Cost	Improve cost competitiveness of battery active and passive materials	+++
Fast charging	3-5C fast charging in 10 min to 80 % SOC	+++
Sustainability	Reduce ecological and social footprint, ensure transparent value chain (battery passport)	+++
Energy density	High energy anodes with high loading and stable capacities of 1.200 mAh/g - High energy cathodes with high loading and stable capacities up to 300 mAh/g	++
Resilient sourcing of battery materials	Increase security of supply by enabling alternatives to Co-rich battery materials	++
Increase lifetime and cycle life	Improve cycle life of high voltage (2000+) and high-capacity batteries (3000+) to allow for viable 2nd life applications	+

1.4 RESEARCH & INNOVATION NEEDS

Short-term needs (by 2025)

- Stable cathodes and electrolytes for high voltage batteries (4.8 V, ≥ 500 cycles).
- Stable cycling of Li- and Ni-rich, low-Co cathode materials (≥ 500 cycles).
- Optimization of low cost and high safety phosphate-based materials e.g. LFP, LFMP.
- Advanced Si/C materials, additives, and electrolytes to enable up to 20 wt% Si (~1000mAh/g) with fast charge and reasonable cycling by reducing cell degradation caused by volume expansion and excessive Li-consumption in the SEI layer.

Mid-term needs (beyond 2025)

- Stable cathodes and electrolytes for high voltage batteries (≥ 1.000 cycles at 4.8 V).
- Decrease specific amount of critical materials (Natural Graphite, Co, Li) per kWh stored energy in line with EU battery regulation considering recycling.
- Large cycle life in low voltage, high-capacity anodes ≥1000 mAh/g, e. g. Si/C composites with above 20 wt.% Si.
- Chemistries enabling cost-effective regeneration, rejuvenation, upgrade of battery materials in the market. E. g. Co-rich NCM to Ni-rich NCM.

Long-term needs (by 2030)

- Cathode materials capacities beyond 300 mAh/g at voltages <4.4 V.
- Anodes utilizing the full potential of Si as anode material. 30 % anode composition, CE > 99%, ≥ 1.000 cycles, and capacities of ≥1200 mAh/g.
- Lithium-ion battery with reduced use of critical materials (other than Lithium).

1.5 EXPECTED IMPACT

Technological impact

- Following the roadmap on generation 3b, Lithium-ion battery materials will pave the way towards their fundamental limits by 2030 leveraging a broad adoption of electrically driven off- and on-road mobile applications by land, sea and air.

Economic impact

- Innovative materials are needed to decrease the dependency of importing raw materials and components from outside the EU, but also to strengthen European suppliers and producers to develop mature technologies and the skills required in Europe.

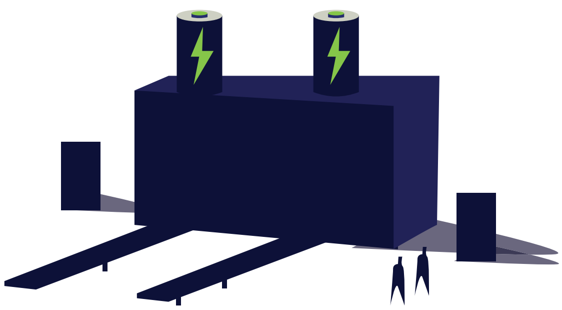
- As Generation 3b materials will dominate the automotive market, progresses in advanced materials will have impact on most relevant industries particularly on international competition.

Environmental impact

- The proposed measures will have a direct environmental impact by keeping the materials in the value chain (closed material loop approaches, increased energy density and lifetime of the battery materials) as well as by fostering sustainable alternatives to critical raw materials and considering recyclability already in the development phase.

Table B: KPIs guiding innovation

KPI	Unit	High Voltage	High Capacity
Cathode capacity	mAh/g	160-180	250-300
Cathode charge time	min to 80 % SOC	10	12
Anode capacity	mAh/g	1000 – 1200	1000 – 1200
Anode charge time	min to 80 % SOC	10	12
Stability window electrolyte	V vs. Li/Li+	4.8	Up to 4.5



2. STRATEGIC TOPIC 2 – GENERATION 4 LI-ION BATTERIES FOR MOBILITY

2.1 DESCRIPTION

With a rapid implementation of electrification of transport, deployment of battery electric vehicles (xEV) is predicted to soar, corresponding with estimated ca. 1800 GWh capacity by 2030 (Credit Suisse Nov. 2020). Improved Li Ion batteries are expected to remain the technology of choice for coming decades. New chemistries, materials and production technologies must however be developed to strengthen the European industrial backbone. Solid State Li-ion batteries (SSB) are considered as a major step in all OEM's roadmaps as they enable doubling of the driving distance due to their higher energy density. Additionally, they provide enhanced intrinsic safety, but still suffer from lower cyclic performance and high interface resistance especially on the cathode side. Advanced Materials activities should develop SSB technology beyond current state-of the art to target maximum performance.

Solid state technology is known to be classified in 3 consequent generations:

- Generation 4a with conventional Li-ion materials (NMC cathode vs. C/Si anode);
- Generation 4b with Li-metal as anode;
- Generation 4c with Li- metal as anode and high voltage cathode (≥ 4.75 V) combining a solid electrolyte with newly developed stable high voltage, high capacity and high rate capability cathode materials such as Li-rich NMCs or spinels.

2.2 GLOBAL STATE OF THE ART

Different solid electrolyte compositions are in development by battery and materials producers, including in Europe. They are based on polymer, inorganic and inorganic/polymer composites. Organic solid electrolytes are covering dry, plasticized polymers, composite, hybrid, heterophasic and single ion conducting electrolytes. Inorganic solid electrolytes belong to following classes: Sulfide Glass Ceramics (ThioLISICON, Argyrodite), Oxide Glass Ceramics (NASICON, Perovskite, Garnet, Anti-Perovskites), Hydrides, LiFT, LiFI and others.

[3] Committee for Mineral Reserves International Reporting Standards.

[4] See Appendix.

2.3 CHALLENGES

Developing solid state electrolytes, cathode materials and anode materials, enabling higher thermal and electrochemical stability while targeting higher energy / power density, fast charging, high rate capability, cyclability and improved safety. Attention on raw material availability and recycling / environmental / safety impact must be considered.

Table B: KPIs guiding innovation

CHALLENGE	High energy	High power
Creating stable solid electrolyte chemical interfaces	+++	+++
Improve ionic conductivity of solid electrolyte	+++	+++
Improve processability of solid electrolyte	+++	+++
Improve stability of solid electrolyte towards mechanical stress	++	++
Enhance thermal operation window	++	++
High Li-ion transference number (tLi+ up to 1)	++	++
Reduce costs for raw material, cell manufacturing and recycling	++	++
Increase gravimetric and volumetric energy density on cell level	+++	
Increase power density of battery cells		+++
Improve anode towards homogeneous Li deposition		++
Reduce Li-metal anode thickness for lower material cost and higher volumetric/gravimetric energy density	++	++
Reduce the ecological footprint in production and recycling	+	+

2.4 RESEARCH & INNOVATION NEEDS

Short-term needs (2025) for Generation 4a/4b:

- Active materials incl. coatings for reduced interfacial resistance to electrolyte & catholyte;
- Reducing thickness of the anode;
- Developing thin solid electrolyte (e.g. multilayer and composite electrolytes) with high ionic conductivity over a wide range of temperatures and a transference number up to 1;
- Manufacturing of new solid electrolyte interlayers;
- Solutions for manufacturing and handling Li metal sheet in dry atmosphere;
- Improved interface design to ensure efficient charge-transfer and electrochemical stability and improved cell mechanical stability;
- Development of coating strategies for current collectors.

Mid-term (2025-2030) & long-term needs (>2030) for Generation 4c:

- New materials and/or chemistries at higher voltage;
- Coating for these materials to stabilize the electrode and electrolyte interface;
- Novel solutions for low cost manufacturing strategies such as solvent-free electrode manufacturing and solid electrolyte deposition;
- Important targets of development are the reduction of interface resistance to solid electrolyte and avoidance of dendrite formation at high C-rates;
- New cell design compatible with the developed components.

2.5 EXPECTED IMPACT

Technological impact

- Solid state batteries to be the most promising technology for use in EV's for the next decades.

Economic impact

- As the share of advanced materials represents a dominant share of the battery cell cost structure, innovation on advanced materials for solid state batteries will be a powerful lever for European competitiveness and a cornerstone for the future of its Giga Factories.

Environmental impact

- Developments will enable a carbon-neutral and circular approach of mobility;

- Developments should cover life cycle analysis, as well as reuse and recycling.

KPIs guiding innovation

KPIs to be reached by 2030

- Gravimetric, volumetric energy density at cell level respectively of 400+ Wh/kg, 800+ Wh/l (Generation 4a) to 500+ Wh/kg, 1000+ Wh/l (Generation 4b & 4c);
- Cycle life up to 3000, operate at charging rate > 3C, operating temperature up to 80°C;
- Cost at pack level down to below 75 €/kWh.

At the level of materials, it could mean the following

- Cathode nominal capacity of 250-300 mAh/g and operating at 3.8-4.3 V (Gen. 4a and 4b) and at 3.8-4.8 V (Gen. 4c);
- Anode operating at 0-0.3 V and nominal capacity of 1000 mAh/g (Gen. 4a), operating at 0-0.1 V and nominal capacity of 4000 mAh/g (Gen. 4b and 4c);
- Electrolyte with a Li-ion transference number of up to 1 by 2030 and ionic conductivity > 1x10-3 S/cm - Catholyte (electrolyte used in the cathode) with ionic conductivity >5x10-3 S/cm.

3. STRATEGIC TOPIC 3 – LI-ION BATTERY MATERIALS FOR STATIONARY STORAGE

3.1 DESCRIPTION

Utility-scale applications (> 100 MW)

Electricity storage will play a crucial role in enabling the next phase of the energy transition, together with solar and wind power generation, it will allow sharp decarbonisation in key segments of the energy market. Wind and solar generation both experience intermittency, a combination of non-controllable variability and partial unpredictability. Utility-scale storage solutions are therefore needed to tackle these situations.

Commercial high-power applications (< 100 MW)

Existing power grids are expected to reach their limits in coping with situations of temporary high loads caused by fast charging of electric vehicles. In order to promote the use of electric vehicles by consumers, fast charging stations have to be distributed across the road network, including areas with limited grid power capacities. This challenge can be met by fitting fast charging stations with suitable Li-ion battery systems capable of balancing those loads.

3.2 GLOBAL STATE OF THE ART

Utility-scale applications

Large scale utility Li ion energy storage may assist renewable energy integration in several ways. These uses include matching generation to loads, balancing the grid through ancillary services, load-levelling, managing uncertainty in renewable energy generation through back-up storage and smoothing output from individual plants. As the cost of Li Ion technologies decreases continuously, storage will become increasingly competitive, and the range of provided economical services will increase. Plant capacities increased in the multi MW/MWh size and grew to dimensions never seen before requiring energy storage for longer periods (time constants around 5hrs). Evidence is growing that large Li ion plants can replace gas peakers to provide power on high demand days.

Commercial high-power applications (C&I)

In order to minimize impact of EV charging on the existing power grid or to avoid deterring costs of additional grid infrastructure, deploying stand-alone distributed charging stations is seen as an optimal solution. Stand-alone stations with RES are usually not capable of producing uninterruptable electrical power due to the intermittency of renewable sources. Energy storage is thus the solution to enable EV charging in these areas and/or these conditions.

Other C&I applications may include for example load shifting, compensating in areas where the grid infrastructure is inadequate or integration with intermittent renewable energy.

3.3 CHALLENGES

Utility-scale applications

To fully exploit potential of Li-ion batteries, cycle cost has further to be decreased to < 0,05€/kWh/cycle meaning further drastic improvements in cycle and calendar life whilst at the same time optimizing reliability and safety by developing advanced materials. Also, storage time in these utility large scale applications is close to 3-4 hours, to fully store the energy from one day of sun. Power is a less critical criterion than energy and cost per cycle.

Commercial high-power applications

To fully exploit potential of Li-ion batteries, CAPEX has to come down by 2030 in the range of 100 – 200 €/kWh with an OPEX target below 0.05 € /kWh/cycle. Lifetime should be demonstrated at 6000+ cycles. On the energy performance side, a volumetric energy density beyond 500 Wh/l is desired. A specific target is also rate capability of 2 to 5 C. Optimizing reliability and safety by the development of advanced materials is also a challenge.

3.4 RESEARCH & INNOVATION NEEDS

Utility-scale applications

- Develop new intercalation compounds with low cycling strain and fatigue for Li-ion batteries aim for 12000+ cycles (equivalent full cycle at 60-80% depth of discharge);
- Improve cycle lifetime & calendar lifetime to develop reliable, cost-effective products;
- Develop fast-charging Li-ion anode materials other than lithium titanate;
- Develop high-energy-density electrodes with high ionic and electronic conductivity;
- Develop a highly ionic-conductive solid electrolyte for solid-state Li-ion batteries for safety;
- Characterisation of the interfaces needed to address system lifetime

and performance by using predictive models to understand performance and degradation;
- Decrease content of critical raw materials in used cathode chemistries;
- Decrease Balance of System cost & improve management, protection functions.

Commercial high-power applications

- Improve conductivity to increase power by e.g. incorporating structured carbons such as Graphene as conductive additive into electrodes or conductive 3D-structures into electrodes and by the development of power optimized materials and architectures;
- Develop high capacity Li-based technologies by incorporating silicon into negative electrode and developing safe high energy density cathode materials;
- Develop high capacity Li-based technologies with reduced Li-consumption in SEI on the anode side and higher utilization of Li stored in the cathode;
- Develop high capacity Li-based technologies with stable SEI on anode and cathode side;
- Decrease cathode's Co content improving structural stability by composition adjustment;
- Develop coatings for cathode materials with high energy density for lower interfacial resistance (stable SEI);
- Develop innovative separators improving safety & reducing use of organic solvents;
- Incorporate shutdown mechanisms into separator materials or separator design and improve structural resilience of separators through new materials, designs or coatings.

3.5 EXPECTED IMPACT

Technology impact

- Large energy Li-ion battery systems above 100 MW with P/E ratio < 1/3 and delivering on performance, cost and safety (utility-scale);
- Solutions enabling Li-ion battery systems (below 100 MW) with P/E ratio > 4 and delivering increased lifetime, lower OPEX and CAPEX (commercial high-power).

Economic impact

- Commercial success of European battery material and cell producers developing Li-ion battery solutions (utility-scale & commercial high-power);
- Availability of EU-based supply of Li-ion batteries to support decarbonization of grid utilities (utility-scale) & to develop off-grid recharging (commercial high-power).

Environmental impact

- Contribution to potential partial replacement of Gas Peaker Plants (utility-scale);
- Accelerated uptake of renewable electricity into the grid and decarbonization of the industry through green & cost-competitive electricity (utility-scale).

KPIs guiding innovation

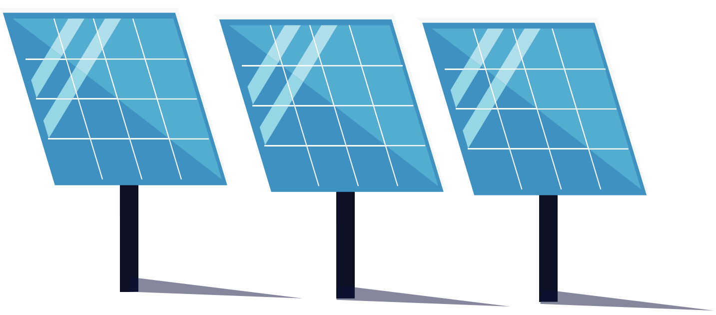
Material strategies are diverse, such as improving conductivity, energy density, lifetime in utility-scale applications, while improving conductivity & capacity in high-power applications.

For utility-scale applications (> 100 MW, P/E < 1/3) (by 2030):

- Volumetric energy density of 500+ Wh/l;
- Lifetime of 12000+ cycles (equivalent full cycle at 60-80% of depth of discharge);
- Calendar life of 20+ years, cost < 0.05 euro/kWh/cycle;
- Compliance with high safety standards;
- Increased operating temperature (up to 80°C) without additional cooling;
- For commercial high-power applications (< 100 MW, P/E > 4) (by 2030):

Volumetric energy density of 500+ Wh/l

- Lifetime 6000 - 10000 cycles, calendar life of 20+ years, cost at pack level <75 euro/kWh;
- Rate capability of 2-5 C (back up charging stations);
- Compliance with high safety standards;
- Increased operating temperature (up to 80°C) without additional cooling.



4. STRATEGIC TOPIC 4 – ADVANCED MATERIALS TO REDUCE WEIGHT OF EV BATTERIES

4.1 DESCRIPTION

International developments towards less air pollution and lower CO2 footprint are pushing towards electrification of transport. To optimize EV's for the Original Equipment Manufacturers (OEM's) and consumers, lightweight measures and materials are needed in the components of batteries. A high weight may lead to decreased driving dynamics and shorter range. Moreover, advanced lightweight materials when used in the battery packaging will contribute to increase the gravimetric energy density of the battery. Novel lightweight components will further improve vehicles' energy efficiency. For each kg reduced from the total weight, 20 kg of carbon dioxide emissions during the lifecycle of the vehicle are saved.

4.2 STATE OF THE ART

Work is already ongoing to reduce vehicle's battery mass with intensive use of high strength steels (HSS), aluminum alloys, and polymer composites. Carbon fiber composites have a huge additional potential, but manufacturing cost is still high. Alloys need to improve production processes, increase strength/weight ratio and increase the share of recycled materials.

4.3 CHALLENGES

Developing new lightweight materials and processes based on glass/carbon fiber reinforced composite, new thermoplastics, high strength steels, Al alloys and coatings, to optimize the high strength-to-weight ratio suitable for structural and functional battery parts in a cost- effective way and respecting efficiency, performance durability, corrosion resistance, while reducing the lifecycle environmental impact and considering circular economy aspects. A combination of materials and design technologies, such as the Cell to Pack (CtP) for battery packaging can be considered synergically to achieve the objectives.

4.4 RESEARCH & INNOVATION NEEDS

Short/mid-term needs

- Development of low-cost materials with higher strength-to-weight ratio and high-performance coatings to protect against wear and/or corrosion, suitable for structural and functional battery parts;
- Development of effective low cost, low carbon footprint and efficient manufacturing processes including multi-processes for these high strength-to-weight advanced materials;
- Development of recycling technologies, incorporating recycled sources in the design of new materials and components, integrated features, or hybrid solutions where relevant;
- Development of low weight battery case materials, coatings and designs such as CtP with improved electrical resistance, studying safety aspects of active materials.

Mid/Long-term needs

- Development of production processes of carbon or fiber reinforced composites, thermoplastic matrices while increasing strength to weight ratio and cost effectiveness;
- Development of multi material solutions and cost-effective joining of dissimilar lightweight materials including their protection against corrosion and wear;
- Development of easy to recycle strategies by design, using recycled materials, and analyzing their implication in lifecycle cost, social and environmental impact;
- Safety evaluation and lifecycle assessment of the materials, process and design solutions.

4.5 EXPECTED IMPACT

Technological impact

- New advanced materials and coatings and their manufacturing technologies to achieve a higher performance and durability of the battery components while reducing weight.

Economic impact

- New technologies developed for lightweight materials and their manufacturing processes will enhance European EV competitiveness and contribute to business creation. The light- weight solutions (materials and coatings) are not limited to vehicles but can be applied to other market applications;

- Lightweight materials should also contribute to cost reduction (95€ for every excess g/km CO2 emissions per vehicle).

Environmental impact

- The use of lightweight materials is a cost-effective measure to CO2. savings: 100 kg less in car weight represents an 8,5g/km reduction of CO2 emissions. A 10% weight reduction in the vehicle's weight, can be translated into reduction in energy consumption by 7%.

KPIs guiding innovation

- To increase by >15% the durability at a cost < 5€/kg of weight saved
- To achieve >90% recyclability;
- Potential of weight reduction up to 70% in battery packaging, with light materials and alternative designs (e.g CtP), meeting EUCAR safety criteria HL4 based on the right use of active and structural materials.

5. STRATEGIC TOPIC 5 – ADVANCED MATERIALS TO ENABLE ULTRA-FAST CHARGING

5.1 DESCRIPTION

The availability of high-power ultra-fast charging stations enables long-distance electromobility and can support adoption of electric vehicles. High power levels for ultra-fast charging increases the challenges for designing convenient and reliable equipment for transferring energy from charger station to vehicle. Today the Combined Charging System (CCS) defines a standard for cable/plug-based systems for use in charging stations. Concepts for contactless charging and automated charging are available for lower power levels.

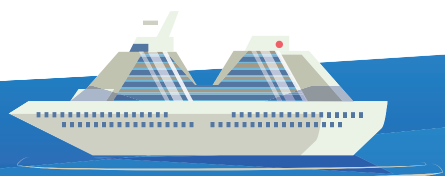
To develop user friendly and reliable ultra-fast charging stations with power transfer capability of 350+kW, innovation in advanced materials is needed. Increased power transfer requirements for 350kW range ultra-fast chargers (level 5: ultra- fast DCFC) will challenge the current system design for charging stations. Due to their weight, cables and plugs will become less easy to handle, large currents may give unacceptable temperature rise in cables and plugs, and consequences of wear and tear, dirt and corrosion will become critical.

5.2 STATE OF THE ART

Today five levels of chargers exist: level 1 (AC 1,4kW), level 2 (AC 6,6-19,2kW), level 3(DC 50kW), level 4 (DC 150kW) and level 5 in development (DC 350kW). State-of-the-art DC fast chargers are installed either as single-stall units or multi-stall charging stations. Single-stall units are typically rated at 50 kW and powered by a dedicated service transformer. Commercial DC fast chargers support one or more of the five existing DC fast-charging systems: CHAdeMO (used globally), CCS Type 1 (in the United States), CCS Type 2 (in the European Union), GB/T (in China), and the Tesla supercharger (used globally). Now large electric vehicle fast-charging station networks in Europe partner to create new integrated alliances and partnerships exist to install networks in EU with ultra-fast DC chargers of 350 kW.

5.3 CHALLENGES

Main challenges are related to safety, cost, weight and volume of the necessary equipment on-board the vehicle. Others are related to possibilities for automation and efficiency, ruggedness against worldwide environmental challenges for the cabling such as high and low temperature, UV protection and resistance to high humidity, salt, dust, snow and ice. It is important to reproduce at laboratory scale the failure mechanisms of the cables (e.g wear, corrosion, tear, in order to find new appropriate materials solutions. The user experience must also be targeted such that comfort and convenience of long range EV travel can reach equivalent or higher levels than for fossil fueled cars. Another significant challenge that needs to be overcome is standardization and certification of the EV charging equipment. Challenges related to grid impact of fast chargers and measures to cope with limitations in grid infrastructure are not within the scope of this topic.



5.4 RESEARCH & INNOVATION NEEDS

Short-term needs (by 2025)

- New material technology (insulation, conductors, cooling) and connection methods for safe, reliable and easy-to-handle 350 kW charging cables and plug connections;
- Solutions for automated plug connections at 350 kW power transfer;
- Components and topologies for low cost and high efficiency ultra-fast charger stations with multiple charging connections (electronics, rectifiers...);
- Demonstration that the charging mode does not impair battery lifetime when being charged in a conventional way (10-20% usage);
- In case of impact of charging conditions on battery integrity and lifetime, develop the material solutions to mitigate the deteriorating effects of ultra-fast charging.

Mid-term (beyond 2025)

Technology for contactless power transfer up to 350kW

- Development of material technology and solutions enabling a low weight of on-board equipment for high power contactless charging;
- Demonstration that the charging mode does not impair battery lifetime when being charged in a conventional way (10-20% usage);
- In case of impact of contactless charging conditions on battery integrity and lifetime, develop the material solutions to mitigate the deteriorating effects of ultra-fast charging.

5.5 EXPECTED IMPACT

Technological impact

Increased acceptance for EVs will be the consequence of improved user experience for EV long range travel. Ultrafast charging will be needed to allow EVs to be charged at a speed comparable with tanking of Internal Combustion Vehicles.

Economic impact

Ultrafast charging technology will be a key asset for European charging station manufacturers.

Environmental impact

International developments towards less air pollution and CO_2 production are pushing towards a rapid implementation of electrification of transport requiring fast charging.

5.6 KPIs GUIDING INNOVATION

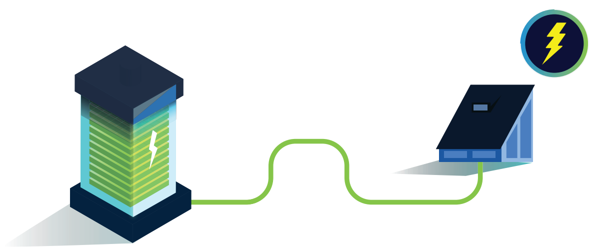
- Charging time below 10 min for a 80% state of charge;
- Power transfer capability at 350 kW or more;
- Low energy losses (<2%) due to ohmic resistances during charging process.

6. PRIORITISATIONS & KEY RECOMMENDATIONS

With about 50-70% of the cost of a battery cell being the cost of the advanced materials, an ambitious R&I programme in advanced materials is key to more cost-efficient, better performing, safer and more sustainable battery cells enabling market uptake of battery technology, while building a strong industrial leadership in Europe and delivering on the EU's Green Deal agenda.

The activities outlined in Figure A cover the typical innovation journey from research & innovation action (or innovation action for more developed technologies) all the way to upscaling & market introduction as well as the integration of a dimension allowing for "new approaches" integrating feedback from the market and new discoveries coming from the research field.

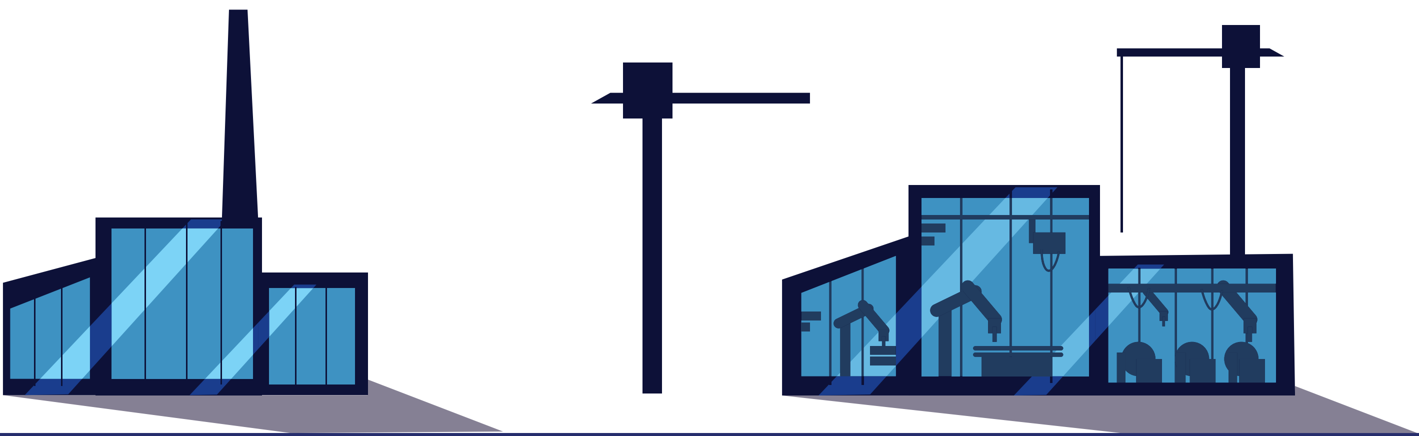
While investing in R&D on Li ion batteries with liquid electrolyte (generation 3b) is still needed, we advocate for a strong and ambitious drive towards solid-state batteries (generations 4a, 4b and 4c) which will be the key technology on which European industry has to invest with the support of public authorities. R&I on generation 5 battery chemistry (Li-air, Li-Sulfur) is also expected with a horizon for industrialization further in time, with possible early-bird applications in specific segments. In the stationary storage space, next to logical R&I support on Li-ion batteries, there are numerous developments focusing on Na-ion batteries, redox-flow batteries and metal-air batteries which also need to be supported.



7. CONCLUSIONS

By 2030, Li-ion technologies (generation 3 and generation 4) will be the globally dominant technology in mobility applications. In the stationary space, next to Li-ion technology, we will see other technologies as well. Provided an ambitious, effective and efficient funding programme is put in place in Europe to support the industrial investments and the research ecosystem, the European battery value chain will demonstrate leadership with sustainable, cost-competitive and high-performance batteries innovated and made in Europe.

Beyond 2030, we expect to see several new chemistries proposed. Novel AI-based tools, physics-aware models and autonomous synthesis robotics will indeed enable researchers and developers to "learn" the interplay between battery materials and interfaces, providing the foundation to improve future battery materials, interfaces, and cells.



Appendix

Table 1: Li-ion batteries Generations

Generation	1	2		3		4			5
		2a	2b	3a	3b	4a	4b	4c	
Type	Current	Current	State-of- The-Art	Advanced Lion HC	Advanced Lion HC	Solid State			Beyond Li-ion
Expected Commercial-isation	Commercial- ised	Commercial- ised		2020	2025	>2025			
Cathode	NMC/NCA LFP LMO	NMC111	NMC424 NMC523	NMC622 NMC811	HE NMC Li-rich NMC HVS	NMC	NMC	HE NMC	
Anode	Modifed Gaphite $Li_4Ti_5O_{12}$	Modified Graphite	Modified Graphite	NMC910 Carbon (Graphite)+Si	Silicon/ Carbon (C/Si)	Silicon/ Carbon (C/Si)	Li metal		Li metal
Electrolyte	Organic LiPF6salts			(5-10%)	Organic+ Additives	Solid electrolyte -Polymer (+Additives) -Inogranic -Hybrid			
Separator	Porous Polymer Membranes								

Source: Nationale Plattform Elektromobilität, Marcel Meeus, JRC.

References

See within text.