European Commission

ROADMAP ON MOBILE APPLICATIONS OF BATTERIES

Prepared by Working Group 5

#BatteriesEurope

Energy

Disclaimer

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The following Writing Teams were involved for writing the different roadmap chapters:

- Road transport:
  - Writing team leader: Denise Tapler (AVL)
  - Contributors: Aitor Apraiz (Mondragon Assembly), Thilo Bein (Fraunhofer LBF), Jeroen Buscher (VITO), Daniela Chrenko (Femto-ST), Pierre-Olivier Cimon (Rimac Automobili), David Francken (Accumalux), Franz Geyer (BMW), Stéphane Henriot (IFPEN), Vincenzo Mulone (University of Roma), Roberto Pacios (CIC energiGUNE), Marlena Volck (AVL)
- Air transport:
  - Writing team leader: Michele De Gennaro (AIT)
  - Contributors: Francesco Salvato (Leonardo), Tine Tomažič (Pipistrel), Blaž Močan (Pipistrel), Jure Tomažič (Pipistrel), Guillaume Cherouvrier (Safran), Jean-Marc Thevenoud (Saft), Helmut Kühnelt (AIT), Andreas Hutter (CSEM), Ana Maria Madrigal (CSEM), Aitor Apraiz (Mondragon Assembly), Thilo Bein (Fraunhofer LBF)
- Waterborne transport (chapter prepared by Waterborne TP):
  - Writing team leaders: Paolo Guglia (Fincantieri), Sara Braida (Fincantieri), Chiara Notaro (Cetena)
  - Contributors: Alessandro Boveri (Cetena), Ashish Kamat (ABB), Inkeri Huttu (ABB), Hermann-Josef Mammes (Meyer Werft)
- Rail transport:
  - Writing team leaders: Pierre Prenleloup (Saft) and Bogdan Vulturescu (SNCF)
  - Contributors: Aitor Apraiz (Mondragon Assembly), Bernhard Fäßler (Stadler Rail), Juyeon Park (National Physical Laboratory, UK), PINTA3 members (Shift^{2}Rail project led by Pascal Mannevy)
- Non-road mobile machinery:
  - Writing team leader: Mikko Pihlatie (VTT)
  - Contributors: Jenni Pippuri-Mäkeläinen (VTT), Marius Baranauskas (VTT), Ari Hentunen (VTT)

List of Acronomys

AGV	Automated Guided Vehicle
AI	Artificial Intelligence
BEPA	Batteries European Partnership Association
BEMU	Battery Electrical Multiple Unit
BEV	Battery Electric Vehicle
BMS	Battery management systems
BTMS	Battery Thermal Management system
EBA	European Battery Alliance
EGVIA	European Green Vehicles Initiative Association
EiS	Entry into Service
ESS	Energy Storage System
ESU	Energy Storage Unit
EU	European Union
EUCAR	European Council for Automotive Research and Development
FAA	Federal Aviation Administration
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HEMU	Hybrid Electric Multiple Unit
IEC	International Electrotechnical Commission
Li/O_2	Lithium–oxygen
LiS	Lithium–sulfur

List of Acronomys

LTO	Lithium-titanate-oxide
LFP	Lithium iron phosphate
KPI	Key Performance Indicators
NASA	National Aeronautics and Space Administration
NMC	Lithium nickel manganese cobalt oxide
PHEV	Plug-in Hybrid Electric Vehicle
PPM	Parts Per Million
R&D	Research and Development
NRMM	Non-road mobile machinery
NOx	Nitrogen Oxide
SoX	State of everything
s-LCA	Social Life Cycle Assessment
TRL	Technical Readiness Level
V2G	Vehicle to grid

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Executive Summary

Decarbonizing the transport sector, which represents around one fourth of the total CO2 emissions in the European Union (EU), will require a combination of several complementary technologies, including batteries, hydrogen, synthetic fuels and sustainable biofuels, supported by innovative approaches for overall energy efficiency improvement. In this context, batteries have a key role to play, since they can enable a full or partial electrification of the different transport modes (road, air, waterborne, rail) as well as non-road mobile machinery. It is crucial to intensify efforts on research and innovation in the field of batteries for transport applications, to make the EU a leader in the transition towards a carbon neutral transport sector. The present document identifies the following key recommendations:

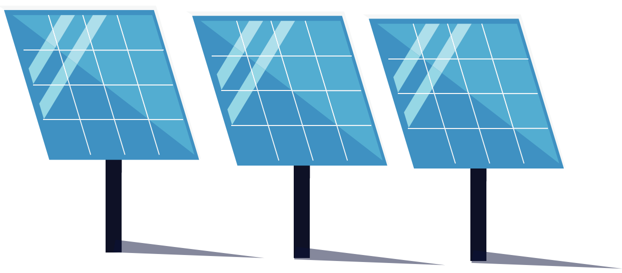
Table A: Key recommendations

Number	R&I Priority
1.	R&D is needed along the full battery value chain (from raw materials to advanced materials, cells, systems and end-of-life management) in order to meet the requirements of transport applications (in terms of battery performances, weight, cost, safety, fast charging capabilities and environmental sustainability).
2.	Strong synergies between the different transport application sectors such as road, airborne, waterborne, rail, non-road mobile machinery, etc.,) can be developed at the battery material and battery cell levels.
3.	At the battery system level, R&D activities should address: - Battery system design and related manufacturing processes (considering mechanical, electrical and thermal aspects); - Battery management (knowledge and data-based battery management, considering algorithms, software and hardware, and including topics related to sensor integration, standardization, interoperability with systems inside and outside the vehicle, smart charging and vehicle-to-grid (V2G)); - Digital twins (for battery design, manufacturing, and battery management in the field); - New methods and tools for assessment of battery performance and safety (new approaches, including the combination of physical and virtual testing, for a faster and more accurate assessment of battery lifetime, reliability and safety).
4.	At relatively low technological readiness levels (TRLs), R&D activities on battery systems can simultaneously address several transport applications, by developing enabling technologies for the benefit of several transport applications sectors such as road, airborne, waterborne, rail, non-road mobile machinery, etc. However, when moving towards higher TRLs, R&D activities should be focused on a specific application sector, since the battery key performance indicators can strongly vary from one application sector to the other.

Vision

Transport represents around one fourth of the total CO2 emissions in the EU[1]. Furthermore, as transport demand continues to grow, the EU transport emissions have increased by around 20% compared to 1990 levels, while the EU total emissions have decreased by around 20% in the same period. On 14 July 2021 the Commission adopted the 'Fit-for-55' package[2], presenting an ambitious set of policy proposals to make the EU's climate, transport, energy, land use, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Notably, the package includes stronger CO2 emissions standards for cars and vans that will accelerate the transition to zero-emission mobility by requiring average emissions of new cars to come down by 55% from 2030 and 100% from 2035 compared to 2021 levels[3]. As a result, it is proposed that all new cars registered as of 2035 will be zero-emission. Moreover, to ensure that drivers are able to charge or fuel their vehicles at a reliable network across Europe, the Commission is proposing a new Regulation on alternative fuels infrastructure[4] that will require Member States to expand charging capacity in line with zero-emission car sales, and to install recharging and refueling points at regular intervals on major highways: every 60 kilometres for electric charging and every 150 kilometres for hydrogen refueling.

In this context, there is an urgent need to materialize the decarbonization of the transport sector. For that, several complementary technologies will be needed, including batteries, hydrogen, synthetic fuels and sustainable biofuels, next to measures for overall efficiency improvement.



[1] European Commission, EU energy in figures – statistical pocket book (2019).
[2] https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541
[3] https://ec.europa.eu/info/files/amendment-regulation-setting-co2-emission-standards-cars-and-vans_en
[4] https://ec.europa.eu/info/files/revision-directive-deployment-alternative-fuels-infrastructure_en

WG5

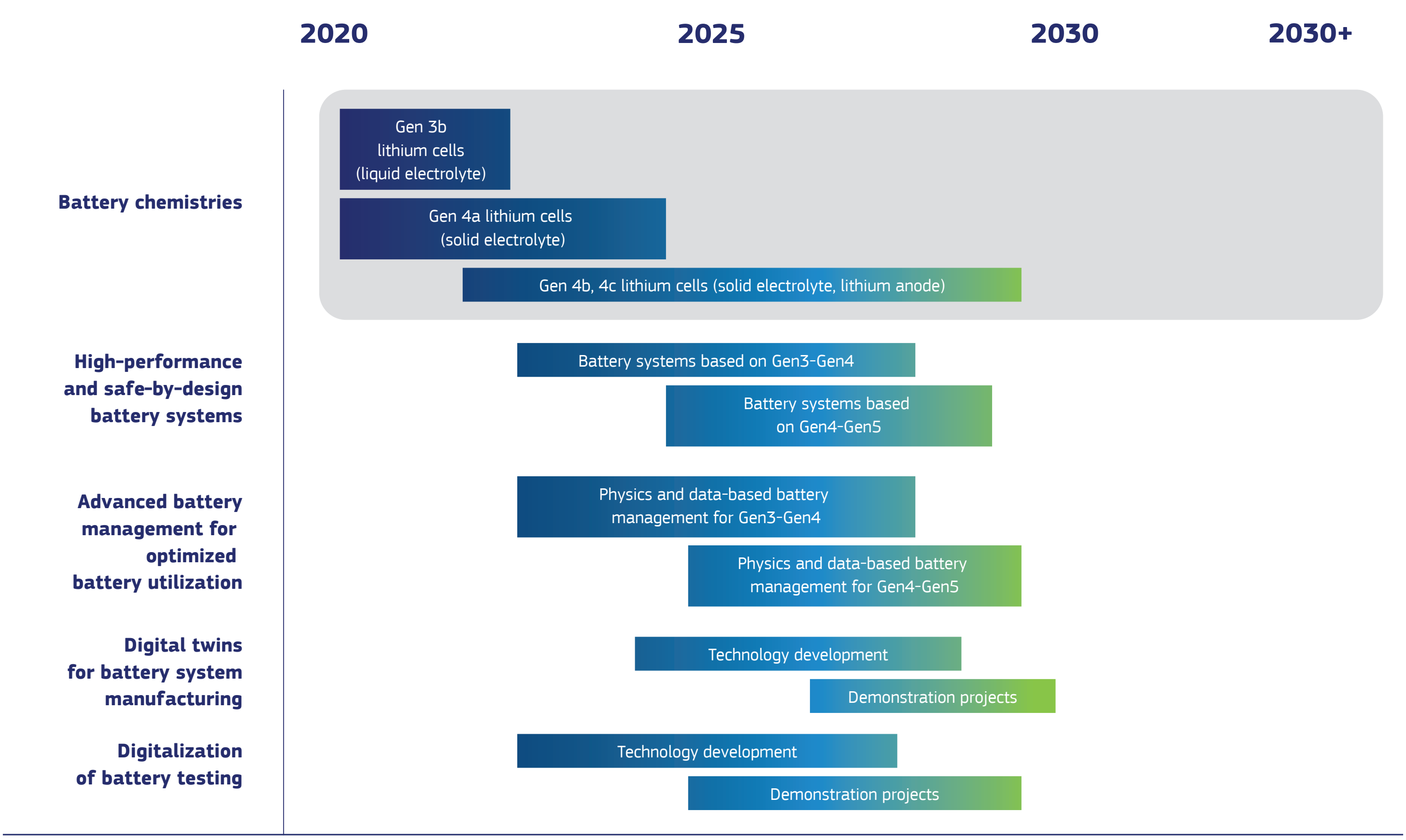


Figure A: Graphical representation of the strategic topics for mobile battery applications in the period 2020-2030+, developed by Batteries Europe WG5

Scope and objectives

This roadmap deals with research and innovation in the field of batteries for the electrification of transport. The different transport modes are addressed (road, air, waterborne, rail), as well as non-road mobile machinery. For each of those segments, the document describes the state of the art, and the research and innovation needs in the short, medium and long terms.

The different application segments share some common key challenges, including battery performances and cost, weight, battery safety, fast charging, and environmental sustainability. To tackle those challenges, research and innovation is needed along the whole battery value chain (from raw materials to advanced materials, cells, systems and end-of-life management). The present document focuses on the battery system level, the other parts of the value chain being addressed elsewhere. In particular, this document addresses battery system design and battery system manufacturing, as well as battery management systems. Issues related to battery materials, battery cell design and manufacturing, and battery recycling are tackled by the other Batteries Europe working groups.

Methodology

This document was prepared under the coordination of the Batteries Europe Working Group 5 (Application and integration – mobile), thanks to the key contributions from dedicated writing teams, each of them focused on a specific transport mode (see Acknowledgements). The writing teams were established by gathering experts from Batteries Europe Working Group 5, except the writing team on waterborne transport which was led by experts from the Waterborne TP association. In the case of road transport, the roadmap relies on the work performed by European organizations such as EUCAR, which has published in 2019 a document summarizing battery requirements for future automotive applications[5], which serves as baseline for the KPI tables in the Appendix.

[5] Battery requirements for future automotive applications, EUCAR, 2019

1. STRATEGIC TOPIC 1: ROAD TRANSPORT

1.1 DESCRIPTION

Road transport is an important part of mobility that needs to be efficient, safe, secure, smart, environmentally friendly, and sustainable. According to studies performed by the European Environment Agency[6], road transport is responsible for about 20% of the total CO2 emissions in Europe. The use of batteries in electrified road transport is one key element to make road transport more sustainable and reduce CO2 emissions.

State of the art

The electrified vehicle concept has drastically evolved within the last decade. Different batteries technologies, starting from lead-acid, NiCd, NiMH, and culminating in the massively adopted Li-ion chemistry nowadays, have allowed electric vehicles to progress from mild and full-hybrid to plug-in hybrid models and, finally, reach the full electric battery assisted vehicle, BEV. A battery for electrified vehicles is a compromise between high-power performance, high energy storage capability, low weight, small volume, long lifetime and low cost, when in addition safety, recyclability and environmental sustainability are also rising new concerns.

The current state of the art Li-ion technology offers energy densities above 250 Wh/kg at cell level and 175 Wh/kg at pack level, at costs between 100 €/kWh and 150 €/kWh at pack level (2020 data from BNEF[7]). For passenger cars, this provides a driving range of around 400 km for a relatively large heavy battery, with an expected lifetime of more than 150,000 km. This is clearly not enough for all classes of vehicles; heavy-duty applications like trucks demand larger batteries with higher energy densities while other applications may need smaller / lighter batteries. Improvements must be achieved with next generation[8] cell chemistries to reach energy densities of around 450 Wh/kg at cell level.

Beyond battery cell performance indicators, a suitable battery system design and integration into the powertrain are essential for the overall performance, security, energy efficiency and environmental sustainability of the vehicle. Battery management systems (BMS) also play a crucial role to optimize battery performances, lifetime, reliability, and ensure safety. In addition, BMS play a key role in the

[6] https://www.eea.europa.eu/
[7] https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/
[8] See Appendix.

future integration of electric vehicles with the recharging infrastructure, opening the door for smart and bidirectional recharging services.

This roadmap relies on the work performed by European organizations such as EUCAR, which has published in 2019 a document summarizing battery requirements for future automotive applications[9], which serves as baseline for the KPI tables (see Appendix A). Other key organizations at the European level on the research or industrial sides include the European Battery Alliance (EBA), EGVIA and the Batteries European Partnership Association (BEPA), and on academic side the Battery 2030+ community. Within the new European research framework programme Horizon Europe, Cluster 5 will be instrumental for the development of batteries and electrified road transport.

The purpose of the KPI tables (see Appendix A) in this roadmap is to provide a perspective on requirement targets for traction batteries in BEVs and Plug-in Hybrid Electric Vehicle (PHEVs) from a road transport point of view, which can be achieved by 2030 compared to the state of the art. The list of KPIs presented in the tables covers typical characteristics on cell as well as pack level such as costs, lifetime, power and energy density, and hazard levels, which are used in the automotive sector to evaluate the technologies. Since for road transport these values might differ due to a large variety of vehicle size and applications, three cases are covered within this roadmap, namely light-duty BEV (Table), light-duty PHEV (Table) as well as medium- and heavy-duty BEV (Table) being distinguished according to their typical battery size.

In parallel with the battery specific KPIs, a very important factor for the success of the battery industry in Europe is the development of all the tools required for a cutting-edge manufacturing technology, not only at cell level, but also at cell-to-module and module-to-pack levels. This competitive advantage should allow very flexible production (i.e. different modules types, for several applications, in the same production line, using different cell types in the same production line, etc.) while at the same time achieving very high levels of automation so to reduce cost, improve throughput and minimize low quality products. An example of quantitative indicator for 2030 of such manufacturing readiness level should target the development of flexible lines, able to handle prismatic and pouch cells in the same production line, performing cell-to-module process at a 2 second/cell throughput, including complete traceability of the production parameters, with a CAPEX lower than 6M€.

[9] Battery requirements for future automotive applications, EUCAR, 2019.

1.2 KEY CHALLENGES

Improved Battery performances and lower costs (see KPI tables)

Improved battery performances in terms of reliability, cycle and calendar lifetime, high energy density (gravimetric and volumetric energy densities), wider operating temperature range and safety are still challenges to be overcome. Additionally, costs must still be largely lowered for the electrified transport to reduce the total cost of ownership in comparison to fossil-fuel alternatives.

Manufacturing of battery systems

Currently, manufacturing technology is one of the main bottlenecks for European battery industry. Low levels of automation and low production volumes currently hinder European competitiveness in the industry. Europe has a strong background in engineering, robotics and automation, key pillars which need to be applied to the development of a competitive cell-to-module and module-to-pack manufacturing infrastructure. To minimize the carbon footprint and the cost Europe needs to develop its own module/pack technology and production models with a remarkable extra added value and a significant degree of differentiation with respect to the state of the art.

Infrastructure and Charging

From an end-users' perspective, there are but a few important constraints for electric vehicle ownership which including driving range and charging anxiety. The Commission proposal for a Regulation on alternative fuels infrastructure will support the development of a European-wide recharging infrastructure network that will help, together with increasing vehicle offer, to increase customer acceptance. Furthermore, fast and normal charging infrastructure have to coexist as a synergic combination to satisfy all user needs and vehicle applications. Additionally, charging strategies such as smart and bidirectional (V2G) charging must be further tested in order to increase the battery lifetime and optimise the use of grid resources towards more sustainable mobility concepts.

Reuse and recycling

Europe needs a complete ecosystem for battery reuse and recycling that can manage the vast amount of battery reaching its end of life in the next decades, and that can also ensure an environmentally sustainable manufacturing.

Sustainability

The European industry of the future has to have a battery business model, whilst implementing diligence obligations with regard to human and labour rights, as well as environmental protection throughout its supply chain. Life cycle assessment should be used to evaluate the sustainability of business models in three perspectives: economic, social, and environmental.

1.3 RESEARCH NEEDS AND RESOURCES REQUIRED

1.3.1 SHORT TO MEDIUM TERM 2020 - 2030

Road transport challenges in Europe are paired with the needed further developments at battery system level. In order to overcome the above-mentioned key challenges, the following research needs have been identified on the short and medium term:

Advances in the design of multipurpose novel Battery Management System (BMS): Battery monitoring, diagnostics, electrical and thermal management as well as cell balancing are typical functions of such systems in order to provide the vehicle control unit with information on how to operate the battery to achieve the longest possible lifetime. New concepts have to include predictive SoX diagnostics based on sensing at cell level, in order to accurately predict EoL, and connectivity and data storage in order to optimize the use of the BEV. Sensing at cell level will also allow full traceability of production variables and to facilitate the implementation of the battery passport concept and digital twinning of manufacturing and battery management. The advanced use of physics-based, data-driven or hybrid models in general, considering for example Artificial Intelligence (AI) with machine learning algorithms, model training and self-adaptive functions will lead to scalable, fully automatized and optimized solution in terms of efficiency and costs. It will also ease the integration into the power train with the rest of the components: inverter, driver and electrical motor towards higher performance and higher vehicle efficiency.

New devices and concepts for thermal management and cooling systems: The adoption of combined standard and fast charging possibilities will require new cooling systems at cell and module level. Faster responding monitoring alternatives based on non-intrusive sensors will be needed to prematurely detect eventual thermal runaway processes. In addition, new thermal characterization techniques will be demanded to avoid safety issues. The use of advanced and predictive models will be key to both support the design activities and define smart control strategies. These will be implemented into the Battery Thermal Management system (BTMS), and integrated with the BEV to maximize performance, vehicle energy efficiency and battery durability. Novel thermal storage technologies may also be key to increase vehicle energy efficiency and help increase the durability of the battery system by achieving more accurate temperature control.

Reuse, dismantling and recycling plants and infrastructures: Battery manufacturers need to interact with reuse, dismantling and recycling experts as early as possible to ensure a low effort reuse and recycling technology. This is the concept of "Design for reuse" and "Design for recycling". The potential reuse and recycling should be considered as early as possible on material, cell and battery level. Decisions on design in low TRLs will influence reusability and recyclability as much as costs, safety and manufacturability. Design for reuse and recycling is a systematic approach allowing the manufacture of batteries with the lowest possible environmental footprint. Distributed smart reuse and recovery infrastructures as well as automated dismantling and recycling processes and facilities should also be developed. Moreover, key indicators will be required to assess the reusability or end-of-life of batteries and allow to trace a cell with regard to critical use situations from cradle to grave.

Improved battery system manufacturing processes: Real time in-line inspection techniques, coupled with self-learning algorithms and automated process controls are required to continuously optimize manufacturing techniques, minimizing resource consumption as well a scrap ratios. In parallel, full traceability technologies and digital twins of the manufacturing lines and processes will be required in order to continuously train and improve the learning algorithms. Improvements and research in automation processes will needed at single process/equipment level, at complete line level in order to optimize holistically the flexible production and finally at whole plant level. Additionally, investigations on new innovative materials/compounds for advanced solutions on lightweight housing integration with reduced cost and enhanced processing efficiency and recyclability are necessary.

Sustainable Business Models and Social Life Cycle Assessment (s-LCA): New tools and comprehensive methodologies must be developed to create business models and to perform environmental and Social Life Cycle Assessment (s-LCA) from a holistic perspective to quantify social responsibility and sustainability of batteries manufacturing including reusability, recyclability and social impact criteria into the design phase of a battery. Sustainable business models driven by life cycle studies must considered including questions of services and ownership options with the aim of providing customers the best option.

Increased integration level: By increasing the integration level of the battery pack with the other powertrain components and the vehicle, it is technically possible to reduce the cost and the weight of the system at the same time as increasing the durability, performance and safety. Approaching the BEV in a holistic manner offers opportunities at many levels. Thermal, electrical, chemical, structural and more aspects must be considered as a whole. Specifically, the main foreseen areas for improvement involve cell-to-pack topology, structural battery pack, the integration of power electronics components within the battery pack as well as hybridised energy storage systems and its variants. The ease of recovery of the batteries and recycling challenges must also be considered in this regard.

1.3.2 LONG TERM UP TO 2050

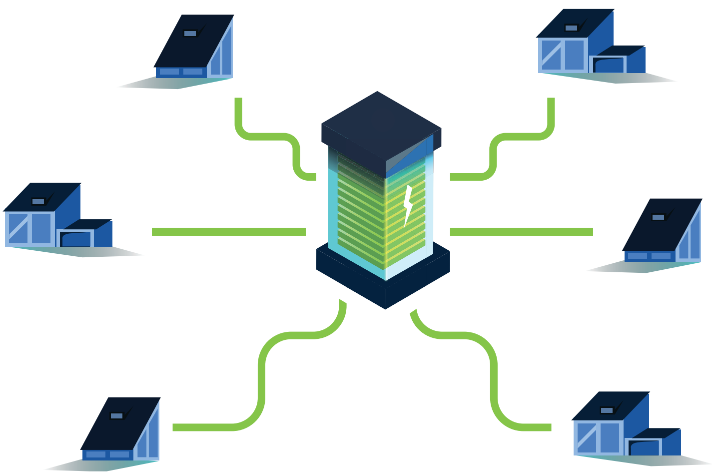
Beyond 2030, the development of new generations of batteries that are sustainable, safe and ultrahigh performing to support the European Green Deal will be still ongoing. Performances and costs, charging, recycling and sustainability of newly developed battery technologies will be still central points on the way to achieve a climate neutral society by 2050.

Road transportation must become fully sustainable with no CO2 emissions and 100% components recycling. Technological aspects will include new charging technologies, effective integration with renewable energy production and optimized synergic combinations of batteries with other power sources (super and metal ion caps, fuel cells, etc). Batteries themselves must become lighter, safer, and fully recyclable using new technologies including hybrid approaches. These evolutions will also modify indicators (costs, weight, energy density, ...) and possibly with an impact on legislation.

1.4 IMPACT

The electrification of road transport will reduce the environmental impacts of transport, lowering CO2 emissions and improving air quality. Road transport is currently responsible for around 20% of the total CO2 emissions in the EU. Switching from fossil fuel vehicles to electric vehicles will lead to a significant reduction of those CO2 emissions. Already today, electric cars outperform fossil-fuel cars in terms of life-cycle CO2 emissions, even with several carbon-intensive electricity grids around Europe. On average, in the EU, the life-cycle CO2 emissions of an electric car are almost three time lower than the emissions of an equivalent fossil-fuel car. This situation will improve in the future, with the ongoing decarbonization of the EU electricity grid.

The large-scale deployment of electric vehicles will also have important impacts on electricity consumption and on the electricity grid. Regarding electricity consumption, it is estimated that the full decarbonization of light-duty vehicles (cars and vans) using batteries would lead to an increase in electricity consumption of around 20%. The decarbonization of road transport should therefore be supported by an increase of low-carbon electricity generation capacities. Regarding the electricity grid, electric vehicles can have a negative impact on grid stability if charging is not managed appropriately. On the contrary, smart charging strategies and vehicle-to-grid can make electric vehicles become an asset to provide flexibility services to the grid. In particular, vehicle-to-grid has the potential to significantly contribute to the storage of intermittent renewable energy sources.



2. STRATEGIC TOPIC 2: AIR TRANSPORT

2.1 DESCRIPTION

Global air transport has been growing at a steady annual rate above 6%, with almost 4.6 billion passengers boarding on scheduled flights in 2019. Europe accounts for around one fourth of this market, with more than 11 million scheduled flights and more than 21 million flight operations overall. The market is expected to grow by 84% by 2040, at an average **growth rate of 4% per year in the EU**. The COVID-19 pandemic has certainly shocked the sector, generating estimated global losses above 500 billion USD, of which above one-fifth in the EU[12]. However, there is a consensus that the pandemic, although more severe than past crises, will neither fundamentally change the air transport industry[13], nor its long-term growth figures[14]. This growth offers market opportunities for European aviation stakeholders.

In 2020, the European Green Deal set the ambitious goal to achieve carbon neutrality in all sectors of its economy, including air transport, by 2050[15], setting the bar significantly higher than former environmental targets set for aviation[16]. Under the 'Fit-for-55´package the Commission is proposingt ReFuelEU Aviation Regulation in order to oblige fuel suppliers to blend increasing levels of sustainable aviation fuels in jet fuel taken on-board at EU airports, including synthetic low carbon fuels, known as e-fuels. The aeronautic industry has the potential to achieve this ambitious objective through (i) the constructive interaction of emerging energy storage technologies, (ii) the employment of carbon neutral energy carriers, and (iii) the introduction of innovative power and propulsion systems, combined with new aircraft architectures and operational features.

Batteries are part of a technology portfolio to decarbonize air transport, together with sustainable biofuels, hydrogen, synthetic fuels and hybridized solutions (where batteries are integrated together with other clean energy sources). Batteries play a key role across all aerial vehicle categories, i.e. from unmanned aerial vehicles to large aircraft and rotorcraft[17], and for both propulsive and non-propulsive in-vehicle systems. In fact, they have the potential to enable the delivery of the earliest fully climate-neutral aircraft, as early as 2030 for

12 ICAO (2021). Economic Impacts of COVID-19 on Civil Aviation https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx

13 https://www.eib.org/en/stories/coronavirus-impact-air-travel [Retrieved Jan. 2021];

14 http://www.oecd.org/coronavirus/policy-responses/covid-19-and-the-aviation-industry-impact-and-policy-responses-26d521c1/ [Retrieved Jan. 2021].

15 https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

16 European Commission. (2011). Flightpath 2050 - Europe's Vision for Aviation. Publications Office of the European Union. doi:10.2777/50266.

17 Civil air vehicles are classified in several ways. The classification on safety rules (EASA CS) is used here because it sensibly affects battery usage in aviation

smaller air vehicles (e.g. mini-liners), as well as drive forward the electrification of systems and propulsion in larger aircraft. Four critical and interlinked technical factors will impact on the implementation and operation of batteries on aircraft:

1. Aeronautic applications are very sensitive to weight, thus both high volumetric and gravimetric energy density are paramount.
2. Safety is aeronautics' distinctive feature and must address the whole battery system and criticality of usage.
3. Environmental conditions (pressure, temperature, humidity) relevant to the battery operation in air transport are wider, and, in general, more severe than in surface transport applications.
4. The very nature of aeronautics' global reach requires widely accepted standards and strict rules for qualification.

While aeronautics issues a challenging set of targets to the battery community, these are not fundamentally different to those of other markets and applications. This suggests that the aeronautic sector has the potential to exploit constructive synergies with other sectors on topics which require massive investments, such as research, industrialization, logistics and recycling.

2.2 STATE OF THE ART

Li-ion batteries (Gen. 3a and 3b) may be suitable for non-propulsive systems and small aircraft applications, while Solid state batteries (Gen. 4a/b) will fit hybrid electric propulsion applications as shown in table 10 in the appendix shows that As of today, Gen. 5 is not considered a viable candidate for a 2035 EiS scenario, given its low TRL; however, lithium–oxygen (Li/O2), lithium–sulfur (LiS) and post-Li batteries might play a role in the long-term scenario. Specifically, **Mg-based post-Li technologies** may offer a viable alternative in case Gen. 4a/b does not develop as expected. Beyond chemistry, the **cell format** (cylindrical, prismatic, or pouch cell) and the inherent level of integration of the battery pack are relevant topics to be considered for air transport applications. Of special interest, albeit for a longer-term scenario, are **structural batteries**, i.e. battery cells and/or modules capable of withstanding part of the structural load.

Notably, all technical solutions will have to address airworthiness. In this respect, the development process for all battery technologies must carefully consider **aviation certification as a constraint and a cost driver**[18]. This will likely require aircraft-specific technical solutions in the battery design and choice of materials, manufacturing process, maintenance strategy and operational life. These elements,

[18] See CS-25, AMC 25.1309, "System Design and Analysis".

combined with the typical long lifetime of aeronautic components, might create a thorny issue, leading to **technological and normative obsolescence**. These will happen if battery technologies evolve faster than certification norms, hampering the ability of the aeronautic industry to benefit from the latest and most high-performing market-ready technologies. This needs to be carefully addressed to gain the most benefit from upcoming technological development and, in this respect, small aircraft can have an advantage over large passenger aircraft given their shorter lifetimes.

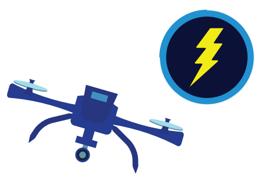
Batteries Partnership of Horizon Europe will be the reference action to develop batteries for airborne applications, leveraging the achievements delivered by Horizon 2020 while constructively interfacing with the **Clean Aviation Partnership**. Synergies are also expected with the European Battery Alliance (EBA) on the industrial side. Looking outside the EU, synergies are expected with the Swiss iBAT Association, as well as with transatlantic initiatives (e.g. NASA/FAA) and cooperation actions with Far-Eastern countries (e.g. China, Korea and Japan).

KPIs

Key Performance Indicators (KPIs) identified for Air Transport Batteries are shown in Table 4 (in the appendix).

The KPIs are organised across five main aircraft categories and according to their reference certification rules: (i) e-taxis (CS-23 and/or CS-VTOL), (ii) general aviation aircraft (CS-23), (iii) commuters (CS-23), (iv) regional aircraft (CS-25) and, (v) large passenger aircraft (CS-25) including short-and-medium range segment (e.g. A320) and long range (e.g. A350).

These categories are further divided into **non-propulsive applications** (i.e. electrification of all on-board systems except propulsion), **hybrid electric propulsion** (at 30-to-50% of degree of hybridisation), and fully electric propulsion. Rotorcraft and convertiplanes (CS-27/29) are not explicitly reported here since their requirements can be covered under the categories (i) to (iv) depending on their power/energy demand. Drones below 150 kg are also not explicitly included since battery development is not considered a critical constraint for them. Notably **all KPIs consider the battery at pack level** (i.e. including battery specific hardware and software systems, excluding interfaces with other aircraft systems) to ensure **comparability**. An exception is the “Global market size”, which ranges from 2030+ to 2050+, given differences in time-to-market for the different applications.



2.3 RESEARCH NEEDS AND RESOURCES REQUIRED

The key research challenges for airborne applications' batteries are geared towards the achievements of the KPIs in Table . These are further elaborated hereunder, according to medium term (2020-2035) and long-term vision (up to 2050).

2.3.1 SHORT-TO-MEDIUM TERM 2020-2035

1. Active materials, electrodes, cell format and battery cells of Gen. 3b, 4a and 4b capable of meeting Table gravimetric energy density, exploiting as many synergies as possible with other sectors.
2. Airworthy battery modules and packs (including cooling systems, BMS, in/on-cell sensors, ancillary items) tailored to specific aircraft application and capable of a battery pack-to-cell energy density ratio above 80%, while fulfilling aviation rules[19]. The development of methods and tools (e.g. new manufacturing, digital twins, etc.) is included here.
3. Integration of battery packs within hybrid and/or full electric aircraft power architectures.
4. Enable battery calendar and cycle life as per KPIs from Table .
5. Enable charge/discharge cycles and C-rates compatible with aircraft usage profiles, including on-ground procedures and infrastructures;
6. Develop adequate battery check, maintenance and/or refurbishment procedures synchronised with the aircraft maintenance schedule while mitigating obsolesce.
7. Develop a sustainable, long-term vision for a circular economy of batteries for airborne applications (including material sourcing, manufacturing, dismantling and recycling).

2.3.2 LONG TERM UP TO 2050

1. Push the boundaries of research and development for items (i) to (v).
2. Explore disruptive integrations of batteries within structural elements and with alternative energy conversion systems.
3. Explore Gen. 5 Li/O2, LiS, and Mg-based post-Li materials and cells.

[19] For instance, CS-25.1309 and related AMC material for safety, DO-178 and DO 160 for hardware and software qualification.

2.4 IMPACT

Aviation plays a key strategic and economic role in modern society[20]. The aeronautic sector supports 87.7 million jobs worldwide (pre-COVID-19 data) for a value of 3.5 trillion USD (4.1 % of global GDP), with 2.7 million jobs and 991 billion USD turnover in Europe. Aeronautical jobs are, more than others, opening new market possibilities, enabling knowledge transfer, and igniting catalytic effects, generating indirect benefits in several business sectors. On the environmental side, the air transport sector reduced its CO2 emissions per seat kilometer by more than 80% since the introduction of the jet engine in the 1950s. However, it is still a fuel-hungry sector; in 2019 civil aviation accounted for 8% of global liquid fuel consumption, equivalent to 363 billion liters, for a value of 188 billion USD, or 23.7% of air operators' expenses. In the same year, air transport emissions amounted to 914 million tonnes of CO2, i.e. 2.1% of global anthropogenic CO2 emissions, and they are expected to significantly increase by 2050.

The EU is the global technological leader in the aeronautic sector, from general aviation to commuters, from regional single-aisle to long-range passenger aircraft, across **all types of air vehicles** (rotorcraft, propeller aircraft, jets), and applications (commercial passenger and freight transport, private and public services, and defense). Based on this supremacy, the renewed push towards achieving the objectives of the New Green Deal and benefitting from the momentum given by the post-COVID-19 pandemic recovery plan, **the European aeronautic industry has the potential to lead the global transition to carbon-neutral air transport**. This is an **unprecedented opportunity** for the aeronautic and battery value chain to leverage their best resources finding synergies and to offer global breakthrough products.

[20] ATAG publication repository, https://www.atag.org/our-publications/latest-publications.html [Retrieved Jan. 2021].

3. STRATEGIC TOPIC 3: WATERBORNE TRANSPORT

3.1 DESCRIPTION

Achieving a zero-emission waterborne transport before 2050 is the main priority embraced by the European waterborne sector. Current electrified vessels only represent a small percentage of the global fleet, hence there is great interest in integrating batteries onboard. The key challenges to achieve waterborne electrification regard safety and lifetime requirements along with cost reduction and improvements regarding batteries' charging, performance (incl. volume and weight) and sustainability-related issues. Future solutions should be applicable to all types of vessels and range from hybridisation up to full electrification, including different batteries use cases. The expansion of the waterborne battery market will foster European competitiveness and employment.

3.2 STATE OF THE ART

Marine electrification has been primarily driven by battery supported architectures to reduce emissions and improve operational efficiency. In 2020, more than 200 vessels are in operation with battery systems and over 170 vessels are under construction, see Figure 1 in the appendix.

Most of the batteries are built in to passenger and car ferries as well as offshore supply vessels and growing in other sectors of coastal and short distance shipping. Long distance shipping is utilising hybrid systems with batteries for improving fuel efficiency as well as reducing redundancy to keep fuel engine generators online. However, according to the Marine Battery Forum[21], vessels with batteries represent only 0.5% of the world fleet. As regards, the entire maritime battery market at present, in MWh, constitutes less than 1% of the lithium-ion batteries produced globally per year, yet it is an expanding market segment.

Waterborne battery technology is driven by two key requirements: safety and lifetime. Compared to road transport and stationary ESS standards, marine safety regulations are much more stringent. Most European marine battery suppliers source cells from suppliers in Asia and develop their own modules and systems to comply with marine requirements. The most used battery chemistries are lithium

[21] The MBF Battery Market Update, Andrea Aarseth Langli – Maritime Battery Forum, WATTS UP 2020.

nickel manganese cobalt oxide (NMC) (111 or 532) or Lithium iron phosphate (LFP) types, today which provides a good balance between safety, specific energy, energy density and cycle life. NMC and LFP cell chemistries have some inherent differences that may impose some different design solutions (i.e., increased levels of energy efficiency and safety, according to specific applications), on a module and system level.

Hybrid and high-power applications along with very high cycling needs, use the same Li-ion cells but utilise a smaller capacity window to ensure the high cycle life or power demand. Other option for high cycle life and high-power needs is the lithium-titanate-oxide (LTO) battery chemistry.

Cost of marine batteries is evaluated on the total installed energy needed for the specified operation and the design life, and it comprises also the auxiliaries systems required by classification societies, depending on the different technical solutions adopted. Battery cell cost reduction in €/kWh alone is not necessarily an indication of reduced ESS cost for marine applications.

The R&D for the maritime are not focused on the battery technology itself, but mostly on the system integration of the different battery applications into the ships or offshore structures and the safety aspects of this installation. An overview of ongoing and finalized R&D projects over the past years, is provided Table in the appendix. Battery topic in maritime R&D projects is only one part of the development for a complete electrical ship design.

Key performance indicators (KPIs) for waterborne transport are to be found in Table and Table (in the appendix). In both, with reference to "ship lifetime" target, it is to be noted that the average age of a seagoing ship is around 20-25 years, while the average lifetime of inland vessels is even longer (40-60 years). In those tables, the specifications have been divided between so-called "energy batteries" (where batteries are typically the main energy carrier onboard) and "power batteries" (where batteries typically complement another energy carrier, for example for managing power peaks).

3.3 KEY CHALLENGES

Batteries can contribute to the decarbonization of the waterborne transport sector. **Key challenges** to be addressed include:

- Improved battery energy and power performances along with reduced costs;
- Improved battery safety;
- Fast charging, is a key enabler

for improving usability of certain electrified waterborne transport modes. This also opens the way to develop a vehicle-to-grid technology, where large batteries used onboard ships could provide services to the electric grid thus improving the integration of renewable resources;

- Environmental sustainability.

3.3.1 SHORT TO MEDIUM TERM 2020 - 2030

Battery performances

Battery performances (energy density Wh/kg and Wh/L, power density W/kg and W/L, cycle and calendar lifetime, reliability, as stated in §5.4) have to be improved along with safety requirements (especially on a battery room level) achieved. Cost (in €/kWh) should be reduced around 2 times the cost of the mass market battery systems. Better understanding of calendar and cycle life, aging models of these low-cost, high-energy batteries should enable optimal sizing of waterborne battery installations and reduce the overall costs.

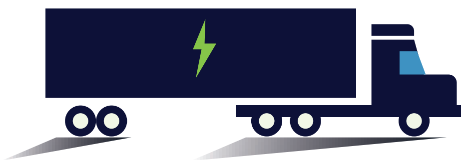
The above-mentioned research needs can be partially achieved in the medium term through optimization of existing technologies (chemical batteries, configurations, systems and management) and the development of hybrid storage systems, combining different technologies to improve the overall system performance. Meanwhile, Innovation Actions and demonstration projects are needed to provide documented experience in new waterborne specific battery safety concepts on module, system and battery room level. Such concepts should cover novel materials that can both contain heat transfers from cell to cell and eliminate the escape of explosive gases in case of cell damage, or module to module to prevent catastrophic thermal runaway situations. Such containment can also explore possibilities to handle venting gases from Li-ion cells that mitigate the flammability and explosivity of such gases. In case of fire, new extinguishing systems are needed to handle battery room fires.

Fast charging is another key enabler for improving the usability of all electrified transport modes. For medium and short range naval applications it is a solution that will allow the complete electrification of goods and people transport systems (ferries, tugs, fishing, etc.), while also giving the possibility of partially electrifying other types of ships for some operational scenarios of interest (cruise ships, supply vessels, etc.)

Battery cycle life and second/end-life policies and technologies

Designing of MWh systems for waterborne application for over 20 operational years needs excellent understanding of both calendar life and cyclic aging. For multiple segments of waterborne sector, this is a challenge in long-term perspective that may be tackled in the short term[22] considering the new generation of Li-ion cells developed in the mass market EV businesses. Cycle operation as well as cycle numbers from EV operation differ substantially from that of marine operation. Cell supplier testing do not cover the needs of the waterborne industry, thus there is a real need for better aging models and test data that can cater to specific waterborne needs. Cycle tests need to be performed, at shallow DoD (Depth of Discharge) at different cell voltage regions and all within a very narrow temperature range of 10 to 45 °C. The development of a European standard for assessing and comparing cell lifecycle could help identify the most promising battery technologies for each application.

In parallel, battery second life and end-life policies and technologies for protecting our environment, reducing the European dependency on raw material imports are a key priority. Better environmental sustainability can be reached by applying circular economy principles. As stated by the European Green Deal, the current figure of 45% collection rate should rise to 65 % in 2025 and 70% in 2030 so that the materials of batteries are not lost for the economy.



3.3.2 LONG TERM UP TO 2050

Safety, lifetime and cost improvements must be addressed from the Waterborne market standpoint with the research and innovation actions which have a long-term perspective.

Safety

Safety of the Waterborne battery systems should ideally focus on inherently safe cell chemistries that minimize the level of catastrophic damage in case of battery failures and exposure to high temperatures. A dramatic improvement in cell safety can be achieved through improvements in intrinsic safety of cells (with improvements in the chemical technology used, as promised by solid-state batteries for example) and with improvements in cell control and management systems and their operational safety. Safety design aspects on system level should focus on the high voltage and MWh energy management that can ensure operational safety.

Lifecycle

Maximizing battery calendar and cycle life would have to go hand in hand with

[22] See also Table 2 and Table 3 in Appendix A, where "Operating lifetime expectation" KPIs are put closer to ship's lifetime, by 2030.

the specific vessel lifetime. Enabling an increase in battery life (up to decades) will improve the sustainability of such systems in waterborne vessels, reduce the needs for midlife battery replacement and increase financial viability of electrified waterborne systems (allowing a shorter payback horizon of the initial investment). Batteries will need to be designed for the ease of recycling and second-life applications to be in line both with the larger European battery ecosystem and the future circular economic related to batteries.

Costs

Long term cost parity would mean that waterborne battery costs would cost the same as the mass market battery systems. Inherently safe cell chemistry is a prerequisite for this to happen, which would enable mass market standardized cells, modules and thus systems that can be simply carried over for waterborne integration. Standardization of safety requirements across industries will be needed to enable simplification in regulations, at the same time taking in account the different risk assessment perspectives.

3.4 IMPACT

The European Green Deal aims to ensure that Europe will be the first climate-neutral continent. Batteries Europe collaboration with the Waterborne sector will drive the transformation towards more sustainable and circular solutions for zero emission power sources. Future solutions will be applicable to all main ship types and needed services and will bring impact on European society by:

- offering sustainable alternative power source solutions for the waterborne industry;
- enabling decarbonization and other emission reduction in waterborne transport;
- creating need for sustainable European raw materials / forcing to find more sustainable raw materials in Europe;
- creating jobs on battery related waterborne manufacturing on retrofits and new builds;
- increasing European competitiveness on providing safe, reliable, low-cost, circular and sustainable battery solutions for waterborne transport.

There are some policy considerations needed to facilitate the electrification and the implementation of different battery solutions across all segments of the waterborne sector. Future-proof design and retrofittable technologies with upcoming innovations will need large investments and will have to meet long-term policy objectives. The dialogue between battery and waterborne industry stakeholders and policymakers will aim at fostering:

- a reliable framework of regulations, applicable world-wide, to facilitate the transition to a zero-emission mode of transport;
- The establishment of a long-term governance, closely linking private and public stakeholders.

For a list of further reading please see in the appendix.

4. STRATEGIC TOPIC 4: RAIL TRANSPORT

4.1 DESCRIPTION

In order to achieve the vast decarbonisation and zero-pollution ambition envisaged in the EU Green Deal, where 55% CO_2 reduction (compared to 1990) is targeted by 2030 and carbon neutrality by 2050[23], European railways would exploit alternative fuels and powertrains. Today, diesel accounts for around 20% of EU rail traction. European railways are committed to gradually phase out rail diesel traction by 2050. Shorter timeline commitments have been taken by some major operators (SNCF around 2030-35; DB 2035)[24]. The railway sector should be considered as the backbone of the future mobility strategy which should result in an increase of its market share, with a modal shift from road and air[25].

The hybridization of diesel trains will bring at least 20% reduction in diesel consumption and a considerable reduction in Greenhouse Gas (GHG), Nitrous Oxide (NOx) and PPM. Their replacement by battery or hydrogen trains will take regional transport even further, towards zero emissions[26] to improve air quality and reduce noise.

Development of the existing electrified railway activities. To reach the climate goals of the Paris Climate Agreement, Rail transport has already an undeniable green competitive advantage and, as such, may substantially contribute to the objectives of the Green Deal.

Storing large amounts of energy in a clean form on board trains opens a wide range of possibilities for rail transport. On-board and on-ground storage make it possible to **optimize the electrification infrastructure** by using it in areas that are difficult to electrify or at high cost like tunnel or bridges (see Wales & Borders operation) but also depots/sorting, to smooth out the power supply with a control of peak

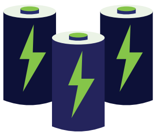
[23] COM (2021) 550
[24] Community of European Railway (CER) Compendium, Alternative fuels and powertrains (September 2020)
[25] European Union Agency for Railways, 2020, Report ERA1234, "FOSTERING THE RAILWAY SECTOR THROUGH THE EUROPEAN GREEN DEAL"
[26] VDE Alternativen zu Dieseltriebzügen im SPNV - Einschätzung der systemischen Potenziale (July 2019)

load consumption, to offer a reliable operation in case of power supply failure like energy autonomy for the comfort of passengers or for traction to a nearby station, to simplify the freight exploitation especially for last mile operation.

4.2 STATE OF THE ART

4.2.1 EXISTING BATTERY OR HYBRID TRAINS (DIESEL OR FUEL CELL)[27]

Despite the early development of the battery electric train (and especially Battery Electrical Multiple Unit: BEMU), the technology is mostly in a testing phase in the EU with limited commercial operation. Elsewhere, in Asia there are several examples in passenger commercial service already. An overview of the main existing battery electric trains is to be found in Appendix B3. There are fewer examples of hybrid Hydrogen (H2) trains demonstrations today compared to battery electric trains. All Hydrogen fuel cell systems utilise an energy storage system hybrid powertrain, where a lithium-ion battery storage system compensates for the low power rate of the fuel cell. The lithium-ion battery of the hydrogen fuel cell trains in service is in range of 200 kWh. An overview of current hybrid Hydrogen fuel cell demonstration trains is also provided in Appendix B3.



4.2.2 EXISTING BATTERIES PERFORMANCES

Nowadays, two main lithium technologies are used within railway applications: NMC (Bombardier Nanjing tramway and BEMU demonstrator, iLint fuel cell train) and LTO (Siemens Desiro, CAF, Stadler Flirt). Battery trains expected performances are about 80 to 120 km autonomy, 7 to 10 years lifetime and maximum peak power 3 MW traction power. Translated to storage level, the useful energy is around 500 kWh (installed is up to 800 kWh

[27] A battery train is a dual-mode train, powered by batteries on non-electrified lines and by catenary under electrified lines. A hybrid train mixes simultaneously two energy sources, like diesel engine and battery, or fuel cell and battery.

depending on the technology). The battery storages currently installed in existing train platforms are constrained by the available space onboard (mass and volume) and by their performances (efficiency, lifetime). New rolling stock should consider a limited energy and power provided by the onboard energy sources and improve not only the batteries technologies but also the train subsystems (comfort auxiliary's consumption, energy efficiency, tones per axel). An overview of key projects for Battery and Hybrid trains is provided in Appendix B3.

R&D is necessary to ensure batteries and hybrid solutions which are fit for purpose are created to serve the rail industry. This requires extensive collaboration efforts. Many European or national R&D initiatives could contribute directly or indirectly to Batteries developments or test on trains, some examples include:

European Partnership on Clean Hydrogen in Horizon Europe, including potential test of hybrid H2 trains (like CAF's dual mode HEMU demonstrator);

European Partnership on Transforming Europe's Rail System in Horizon Europe where new solutions for decarbonised railway are developed and tested.

National H2 plans in France (7B€) and Germany (9B€) could fund potential hybrid H2 trains demonstrations or commercial deployment[28].

Key Performance indicators for the rails sector zero emission drive trains are developed and revised in an EU Horizon2020 project called PINTA3[29] in connection with the Shift2Rail partnership. In particular two KPIs are examined and revised annually:

- Local to train CO2 emissions: ie. the CO2 emitted by the train itself when operating;
- CO2 emissions for fuel production for hybrid trains and/or for local electricity production for BEMU or catenary part, depending on the national energy mix.

In addition, KPI related to the impact of train decommissioning at battery level could be explored, with assessment at train level of potential re-use or re-purpose of traction batteries after the end of their initial life.

Key Performance indicator tables specifically related to batteries for rail applications are to be found in Appendix A.4. Two types of batteries are considered depending upon the train integration: energy traction battery (mainly for BEMU), or power traction battery (mainly for hybrid trains or like in Siemens MireoPlus battery train). The KPIs for energy traction are included in Table 8 and considers batteries from 600 kWh to 1000 kWh. The KPIs for power traction batteries considers batteries between 100 kWh and 600 kWh, see Table 9. KPI

[28] Roland Berger from STUDY ON THE USE OF FUEL CELLS AND HYDROGEN IN THE RAILWAY ENVIRONMENT, Shift2Rail H2 study, 2019

[29] https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA3

are expressed at ESU level for railway application (ESU: Energy Storage Unit, see IEC 62928), and estimation at cell level is provided. Full ESU is including rack, gas exhaust system, BTMS, BMS, and related to cell performances (e.g. high-power cell might require lower cooling unit at system level or allow smaller battery sizing depending on the use case).

4.3 RESEARCH NEEDS AND RESOURCES REQUIRED

R&I needed to reach next level depends on the requirements defined in the European roadmaps on railway technologies. Under Shift²Rail initiative (PINTA3, started December 1st, 2020), a synthesis of requirements for batteries to meet those routes will be established (at system level). This will be finalized under 18 months from start, a first evaluation will be available for Autumn 2021.

4.3.1 SHORT TO MEDIUM TERM 2020 - 2030

Several European reports[30] underline the needs to research:

- **Increased energy density:** Improve technical performances (Energy density, at system level) leading to higher train autonomy;
- **Fast recharge:** Allow fast recharge without degrading the lifetime of the battery, at system level including requested cooling systems;
- **Cheaper, on LCC basis at system level:** Develop intrinsically cheaper technologies, on LCC basis at system level. It covers initial investment cost, maintenance cost, energy efficiency, simplification of electrotechnics and cooling devices;
- **Explore use of harmonized standards:** Where possible for railway rolling stocks, harmonise the standards applicable to trains and buses at the EU level. This should be done through unified technology standards, unified vehicle interfaces for electricity supply and unified data protocols;
- Standardise where possible batteries technical solutions, safety requirements, and recharge systems to support interoperability across Europe, reduce costs thanks to scale effect on serial products;
- Standardise virtual certification, simplify the validation and train certification process to reduce cost and duration of certification across Europe;
- **Battery Cycling characteristics** Develop accurate lifetime modelling taking into account micro-cycles (1 to 2% for energy cells and 4 to 5% for power cells) DoD and the power charge during the recovery laps of time;

[30] Battery Electric and Fuel Cell Trains Maturity of Technology and Market Status; Rebecca Thorne Astrid H. Amundsen Ingrid Sundvor; Institute of Transport Economics/ Norwegian Center for Transports Research (May 2020); UK rail industry decarbonisation taskforce, final report to the Minister for rail (July 2019)

- Synthetic railway mission profile(s) to provide information about the cycling characteristics at operational usage performance as requested at battery level (similar to EN 50591 or according to its update with hybrid usage);
- **Battery Cooling system** development to reduce weight, volume, size, noise and energy consumption / efficiency. Cell internal resistance could also contribute to this goal;
- **Battery Packaging safety** improvements in order to avoid explosion, gassing and intoxication.

4.4 IMPACT

Extrapolating from France to European main fleets (over 1000 trains) gives between 9 GWh and 16 GWh necessary for European railway industry, see Table in the appendix. Consequently, the hypothesis is that there will be a 1 GWh request for batteries for railway transportation in Europe until 2035.

Apart from pure technical topics, it is needed to align public policies and public funding, public procurement to favour, support and help the deployment of low-carbon railway solutions as an alternative to Diesel traction. These developments must be monitored and encouraged by the technicians who work on their own on the technical side.

CO2 taxes on oil-based fuels, transient incentives to support the first years of potentially non profitable new low carbon solutions, EU Taxonomy/ EU Green Bonds and Sustainable Finance, MEAT (Most Economically Advantageous Tender) procurement rules are in the scope of such "business rules" scope of work.

Please see Table 14 in the appendix for a list of references.

5. STRATEGIC TOPIC 5: NON-ROAD MOBILE MACHINERY

5.1 DESCRIPTION

Non-road mobile machinery (NRMM) electrification developments are heavily dependent on application specific requirements. For instance, many purely electric powertrains require the largest possible batteries for maximum operational flexibility, while regenerative hybrids' requirements are much smaller. The following sections overview the NRMM electrification and the requirements for battery technology from the perspective of the most energy-hungry industrial sectors – mining, forestry and agriculture, construction and port (cargo handling).

5.2 STATE OF THE ART

The specificity of NRMM applications and working conditions affect the electrification potential significantly. The major differentiators of NRMMs are their mobility and rated power. According to IDTechEx research[31], all main NRMM application sectors show positive tendencies for electrification. In 10 years' time, the number of electric NRMMs is predicted to increase one hundred-fold in the agriculture, twenty-fold in mining and three-fold in the construction sector. The mining sector features the most powerful yet least numerous vehicles. The agriculture sector, on the other hand, tends to employ less powerful but more numerous and more varied NRMMs.

7.2.1 Electrification of non-road mobile machinery

Mining sector features the most powerful NRMMs, some of which require great manoeuvrability like hauling or trucking procedures. Thus, the mining sector exemplifies the maximum capabilities and limitations of battery electrification. The mobility requirements with respect to power are inversely proportional to the electrification potential i.e. the electrification potential decreases with increasing mobility requirements. The exception is the highest mobility NRMMs (trucks) because they are the largest energy consumers of this sector. For these machineries, the electrification options vary from full battery electric to trolley assist[32] and to

[31] Electric Vehicles 2020-2030: 2nd Edition. Markets, technology, manufacturers, opportunities. Land, water, air: unique detail. Dr Peter Harrop, Dr Richard Collins, Luke Gear, Dr Na Jiao, Dr David Wyatt and Dr James Edmondson

[32] Trolley Assist connects diesel-powered haul trucks to an electrical cable system for some segments of the journey. When connected to the cable, the truck would be powered by electricity, reducing the use of diesel fuel and related emissions.

various hybrids with smaller batteries for fuel consumption efficiency. The mining sector electrification can be hindered by the remoteness of mine location and poor access to the electricity grid.

Currently, the largest battery operates in a fully electric mining truck called eDumper[33], which is designed for downhill usage with an estimated energy-negative operation cycle. Its operation depends on the road topology of the mine - it requires the dumping grounds to be at lower altitude than loading grounds ie. mountain-top mining. The NMC battery used has 710 kWh capacity and weighs 8 tonnes. The next breakthrough might be Anglo American Fuel Cell Electric Vehicle (FCEV)[34] hybrid truck pilot project with a 1000 kWh battery which will provide insight into hybrid solution performance.

Forestry and agricultural sector NRMMs differ from mining equipment significantly as they are very mobile, less powerful, and can require flexible operability in varying terrains. Further, the power rating tends to be much lower, as the productivity is usually improved by increasing the fleet size rather than utilising larger machinery. Full battery electrification is viable for lower power machines, as well as for the most mobile machines such as logging trucks. Hybridisation is also a viable strategy for better efficiency for all NRMMs. Both forestry and agriculture lean towards multifunctional and automated NRMMs, which indicates a great perspective for battery technology.

Cargo handling section. Ports and harbours are usually located in industrialised areas with strong grid connections and geographically limited area of operation with repeating routes and tracks in closed proximity. These features aid the NRMMs electrification progress. Increasing shore power and cold ironing of marine vessels may also provide improved access to power systems, bring synergies and facilitating electrification of the port NRMM fleets. Most port NRMMs, such as straddle and shuttle carriers, rubber tyred gantries, terminal tractors, and AGV’s, will be electrified within the next 10 years. In addition, many port NRMMs are largely immobile such as crawler and gantry cranes and powered by cable reels.

Construction sector electrification is slower than predicted. Globally, the construction industry is responsible for 11% of energy-related carbon emissions and there is little sign of improvement. Tier 4 limits do not restrict the utilisation of ICE and enacting new tiers/stages for emissions are being delayed. Novel electric solutions are available but are not widespread. The reasons are unsurprising – large initial investment, recharging downtime and unreliable on-site power supply.

[32] https://insideevs.com/news/362547/edumper-8-ton-battery-pack/

[33] https://www.internationales-verkehrswesen.de/wae-and-anglo-american-develop-worlds-largest-fcev-mining-truck/

7.2.2 Battery requirement for non-road mobile machinery

Battery requirements depend strongly on the application and the operation strategy, e.g., the choice between overnight charging and opportunity charging during the workday. Many applications must operate at cold or hot ambient temperatures, and also have charging capability at subzero temperatures. For applications with continuous power-intensive use in harsh conditions, such as mining loaders, the cycle life, safety, and power density are important, whereas energy density, calendar life, and cost per kWh are less critical. Applications with opportunity charging typically require batteries with high-rate charging capability.

Typical requirements for non-road machinery include long cycle life, high peak power capability, and wide ambient temperature range combined with less demanding requirements for energy density and specific energy.

7.2.3 Typical battery chemistries in non-road mobile machinery

Most NRMM batteries utilise Li ion batteries with either NMC or LFP cathode, and graphite or LTO anode. NMC and LFP both have a good balance between energy, power, safety, lifetime, and cost, which makes them strong all-round technologies. NMC is strong for applications with high energy density requirements, whereas LFP is safer and does not contain cobalt. Technologies with graphite anodes suffer from lithium plating at low temperatures and charging rates higher than C/2–1C, resulting in increased rate of degradation. Even though some graphite anode-based batteries specify higher maximum charging rates, it often comes with a compromise in energy density and cycle lifetime. LTO anodes operate at higher potential, leading to lower full cell voltage and energy density. However, they do not suffer from lithium plating at high charging rates or low temperatures, which enables fast charging and long cycle lifetime at wide temperature range. Due to these properties, LTO is common in harsh-use applications that feature mission profiles with high-power peaks, fast charging, high number of work cycles per day, or operation in extreme temperatures.

The development of the NRMMs is guided by the emission standards, Regulation (EU) 2016/1628[35]. The current 'NRMM Regulation' sets limits for the gaseous and particulate pollutant emissions, i.e. carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and particulate matter (PM), and covers all machineries from small to large, including <19 kW and >560 kW engines. Greenhouse gas emissions are not regulated hence it is not straightforward to estimate how significant a driver the current 'NRMM

[35] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1628

Regulation' is for electrification. Having said that, meeting the present emission limits often requires introduction of exhaust after-treatment filters, making the overall system more complex, costly and possibly poorly performing. This in turn may drive the manufacturers towards electric solutions. Further, carbon dioxide (CO_2) limiting legislation has entered for heavy-duty vehicles, and such a regulation may be reality for NRMMs too, in the coming years.

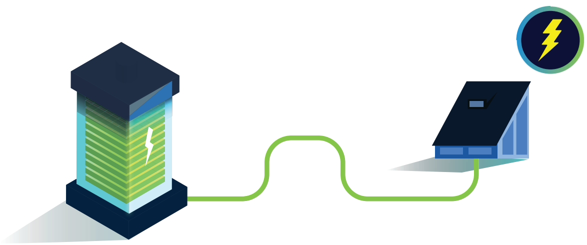
Development and market availability of battery electrified NRMMs have progressed considerably during the last five years. Lower power and/or lower range battery electric machineries are already available and even the biggest machinery, e.g., heavy dump trucks are being piloted.

When it comes to the research and innovation programs and actions, the NRMMs and their technologies are gaining attention. While there were next to no topics related to NRMM electrification in the EU Research and Innovation programme Horizon 2020, Horizon Europe is starting to recognise the importance of more sustainable and cleaner NRMMs.

KPIs for battery packs and cells for NRMM applications are defined in Table 9 in the appendix. As the NRMM segment is very versatile with regards to the applications and requirements, the KPI list is generic and reflects the characteristics of typical heavy-duty applications.

5.3 RESEARCH NEEDS AND RESOURCE REQUIREMENTS

NRMMs are more versatile than automotive or heavy-duty road vehicles. Some NRMM may provide plenty of space for a battery system, whereas for others, the design-critical parameter may be the volume available for the battery. In other words, the design bases for the battery systems vary, and this lifts the importance of battery system design and optimisation. Also, as manufacturing series are smaller, cost reductions through scale benefits is more difficult than in the automotive sector and requires modular and scalable design approaches. Issues related to pre-normative research, standardisation and regulations must be dealt with to support design, manufacture and industrial deployments.



5.3.1 SHORT TO MEDIUM TERM 2020 - 2030

Advances in system integration

Advances including advanced battery cooling/heating solutions and thermal management systems, sensors and BMS, new lightweight materials having equivalent or improved thermomechanical properties. System integration needs to be based on advanced electrical, thermal, and mechanical design tools enabling virtual design cycles, virtual prototyping and an agile systems development cycle. Highly integrated modular and robust battery designs would result in improvements in energy density, power density, thermal management, safety, lifetime, charging rate, and reductions in cost, size and weight.

Advances in battery management

Optimisation of performance and lifetime can be improved using electrochemical and degradation models along with data-driven models for diagnostics and prognostics. Management and lifecycle optimisation will increasingly move in the direction of real-time computation and analytics through digital twins. Other development areas include e.g. robust BMS HW solutions and advanced BMS architectures, e.g. use of data buses or wireless data transfer between cell boards and master BMS, edge computing capability, and cloud interface.

Improvements in safety

Safety aspects are critical in the harsh conditions and high intensity applications typical for NRMM. Safety needs to be handled at three levels: First, the intrinsic safety of the materials and composite layers of the battery cell. Secondly, the battery module geometrical and structural solutions related to electrical, mechanical and thermal stability and controllability. Third, advanced management systems including sensors, data collection and diagnostics, as well as control and management strategies to keep the system in the safe domain.

Sustainability and eco-design

Battery packs shall be designed to be easily repaired, reused, and recycled. For example, modules, subsections or even smaller units in case of large-format cells could be intervened and replaced if needed. Another approach to sustainability is to look at the environmental footprint of the NRMM as a whole. On the one hand, this relates to the manufacturing of the battery system and the entire NRMM, and on the other, the lifecycle environmental impacts from the system-level use of the NRMM.

Reducing price of batteries

The design requirements for batteries used in electric NRMM are stricter than those in the automotive sector thus the price per capacity of the battery system is higher, thus initial investments are still large. There are several cost elements necessary to address including: materials, cell design, cell manufacture, cell technology selection, system design, structural materials, management systems, and vehicle integration. Battery system integration and manufacture needs to be industrialised and automated so as to reach scale and cost benefits.

Improving lifetime of batteries

Maximising the useful lifetime of the batteries is a key factor in the techno-economics of electric NRMM. Lifetime can be improved through cell-level advancements in materials and their tailored microstructures, but equally well through careful management and optimised operation of the battery cells and the entire system. This lifetime and performance optimisation calls for advanced management systems capable of analytics and prognostics, and a vehicle or fleet control that takes into account the productivity and techno-economic cost efficiency optimisation of the entire NRMM system.

5.4 IMPACT

In a study by Risk & Policy Analysts Limited and Arcadis[36], the overall fuel consumption of the NRMMs (including sectors Construction machinery and equipment, Agricultural machinery and equipment, Gardening equipment, Rail, Inland waterway vessels) has been estimated to add up to around 31.4 million tonnes in Europe annually. Furthermore, this consumption has been evaluated to result in roughly 100 million tonnes of CO2 equivalent emissions in the EU27 annually, which corresponds to 2% of the EU27's total greenhouse gas emissions[37]. Hence, the NRMMs have an impact on the environment on a global scale.

Electrification would not only decrease or eliminate the local emissions, but it would also decrease the energy consumption in general. Assuming a tank to wheel efficiency of 25% for a conventional diesel NRMM and a grid to wheel efficiency of 60% for a fully electric alternative, the annual energy consumptions of a 100% diesel and 100% battery electric fleet are 395 TWh and 165 TWh, respectively. These figures were evaluated based on the 31.4 million tonne annual fuel consumption, using an energy content factor of 12.58 MWh per tonne for diesel. If even a moderate part of the

[36] http://publications.europa.eu/resource/cellar/60e67ef3-f68f-42d0-ba3f-afb053704359.0001.02/DOC_1

[37] https://data.consilium.europa.eu/doc/document/ST-13690-2014-ADD-2/en/pdf

NRMM fleet responsible of the 31.4 million tonne annual fuel consumption was electrified, that would result in a notable demand of batteries.

6. PRIORITISATION, KEY RECOMMENDATIONS AND CONCLUSIONS

1. R&D is needed along the full battery value chain (from raw materials to advanced materials, cells, systems and end-of-life management) in order to meet the requirements of transport applications (in terms of battery performances, cost, safety, fast charging capabilities and environmental sustainability).
2. Strong synergies between the different transport application sectors (road transport, airborne transport, waterborne transport, rail transport, non-road mobile machinery …) can be developed at the battery material and battery cell levels.
3. At the battery system level, R&D activities should address:
   a. battery system design and related manufacturing processes (considering mechanical, electrical and thermal aspects);
   b. battery management (knowledge and data-based battery management, considering algorithms, software and hardware, and including topics related to sensor integration, standardization, interoperability with systems inside or outside the vehicle, and vehicle-to-grid);
   c. digital twins (for battery design, manufacturing, and battery management in the field);
   d. new methods and tools for assessment of battery performance and safety (new approaches, including the combination of physical and virtual testing, for a faster and more accurate assessment of battery lifetime, reliability and safety).
4. At relatively low technological readiness levels (TRLs), R&D activities on battery systems can simultaneously address several transport applications, by developing enabling technologies for the benefit of several applications sectors (road transport, airborne transport, waterborne transport, rail transport, non-road mobile machinery, etc.). However, when moving towards higher TRLs, R&D activities should be focused on a specific application sector, since the battery key performance indicators can strongly vary from one application sector to the other.

Appendix

KPI Tables

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.

Road transport

Table 2: Light-duty battery electric vehicles (BEV). Typical battery size: 20-100 kWh (2021), 40-120 kWh (by 2030)

KPI (pack level)	**Conditions**	**2019**	**2030**
Cell/pack weight ratio (%)		70	80
Cell/pack volume ratio (%)		60	75
Operating lifetime expectation	Minimum guaranteed lifetime	150,000 km (vehicle lifetime)	
Cost (€/kWh)		200	85
KPI (cell level)	**Conditions**	**2019**	**2030**
Gravimetric energy density (Wh/kg)	C/3 charge and discharge, 25°C, charging with CC and CV step	250	450
Volumetric energy density (Wh/L)	C/3 charge and discharge, 25°C, charging with CC and CV step	500	1,000
Gravimetric power density (W/kg)*	180s, SOC 100%-10%, 25°C	750	1,000
Volumetric power density (W/L)*	180s, SOC 100%-10%, 25°C	1,500	2,200
Cycle life [80% SOH] (no. of cycles)	80% DOD, 25°C	1,000	2,000
Hazard level	EUCAR cell-level safety performance	<=4	<=4
Cost (€/kWh)		125	70
Market	**Source**	**2017**	**2030**
Typical market size (GWh/year)	Avicenne Energy, 2019; IEA Global EV Outlook,	40	1,000-2,500

Table 3: Light-duty plug-in hybrid electric vehicles (PHEV). Typical battery size: 5-15 kWh (today), up to 25 kWh (in the future).

KPI (pack level)	Conditions	2019	2030
Cell/pack weight ratio (%)		70	75
Cell/pack volume ratio (%)		60	70
Operating lifetime expectation	Minimum guaranteed lifetime	150,000 km (vehicle lifetime)	
Cost (€/kWh)		230	120
KPI (cell level)	**Conditions**	**2019**	**2030**
Gravimetric energy density (Wh/kg)	C/3 charge and discharge, 25°C, charging with CC and CV step	200	350
Volumetric energy density (Wh/L)	C/3 charge and discharge, 25°C, charging with CC and CV step	500	800
Gravimetric power density (W/kg)*	180s, SOC 100%-10%, 25°C	750	1,750
Volumetric power density (W/L)*	180s, SOC 100%-10%, 25°C	1,500	3,850
Cycle life [80% SOH] (no. of cycles)	80% DOD, 25°C		>2,000
Hazard level	EUCAR cell-level safety performance	<=4	<=4
Cost (€/kWh)		145	100
Market	**Source**	**2017**	**2030**
Typical market size (GWh/year)	Avicenne Energy, 2019; IEA Global EV Outlook, 2020	5	100-150

Table 4: Medium- and heavy-duty battery electric vehicles (BEV). Typical battery size: 150-600 kWh (today), up to 1000 kWh (by 2030).

KPI (pack level)	Conditions	2019	2030
Cell/pack weight ratio (%)		70	80
Cell/pack volume ratio (%)		60	75
KPI (cell level)	**Conditions**	**2019**	**2030**
Gravimetric energy density (Wh/kg)	C/3 charge and discharge, 25°C, charging with CC and CV step	250	450
Volumetric energy density (Wh/L)	C/3 charge and discharge, 25°C, charging with CC and CV step	500	1,000
Gravimetric power density (W/kg)*	180s, SOC 100%-10%, 25°C	750	1,000
Volumetric power density (W/L)*	180s, SOC 100%-10%, 25°C	1,500	2,200
Cycle life [80% SOH] (no. of cycles)	80% DOD, 25°C	N/A	6,000
Hazard level	EUCAR cell-level safety performance	<=4	<=4
Market	**Source**	**2017**	**2030**
Typical market size (GWh/year)	Avicenne Energy, 2019; IEA Global EV Outlook, 2020	20	200

*Not specified if the pulse is in charge or discharge mode. The operating conditions give 10%-100% as a SoC range in which the 180s power pulse can be applied; obviously for low SoC starting values the pulse should be applied in charge mode, whereas for high SoC starting values the pulse should be applied in discharge mode.

Air transport

Table 5: Battery pack level KPIs per air vehicle category and per application type (non-propulsive, hybrid and full electric).

	Pax. [#]	Typical mission range [km x 10^3]	Typical mission duration [mins]	Max Power [MW]	Gravimetric energy density [Wh/kg]	Cost [€/kWh]	Life cycles [#]	Global market size [GWh/year]
				Non-propulsive systems				
e-taxis (CS-23, CS-VTOL)	≤6	≤0.2	30	Battery technology development not relevant in these categories				
General aviation (CS-23)		≤0.2						
Commuters (CS-23)	≤19		60					
Regional aircraft (CS-25)	50-100	≤1	80	0.5	>250	n.a.[38]	5,000 +	600+ (year 2030+)
Large aircraft (CS-25)	150-300	1.5-7.0	240+	1-2				1,800+ (year 2030+)
				Hybrid electric propulsion				
e-taxis (CS-23, CS-VTOL)	≤6	≤0.2	30	<0.15	350	250	2,000 +	1 (year 2030+)
General aviation (CS-23)		≤0.2		0.03	250	600		0.02 (year 2030+)
Commuters (CS-23)	≤19		60	0.4	350			0.2 (year 2030+)
Regional aircraft (CS-25)	50-100	≤1	80	2-3	400+	n.a.[32]	10,00 0+	3,000 (year 2040+)
Large aircraft (CS-25)	150-300	1.5-7.0	240+	not applicable in this category				
				Fully electric propulsion				
e-taxis (CS-23, CS-VTOL)	≤6	≤0.2	30	0.2-0.3	350+	200	2,000 +	1-2 (year 2030+)
General aviation (CS-23)		≤0.2						0.05 (year 2030+)
Commuters (CS-23)	≤19		60	1.2	400+			0.5 (year 2030+)
Regional aircraft (CS-25)	50-100	≤1	80	4-6	800-1,000	n.a.[32]	5,000 +	12,000 (year 2050+)
Large aircraft (CS-25)	150-300	1.5-7.0	240+	not applicable in this category				

38 Battery pack cost is not considered a limiting constraint across all CS-25 applications.

WATERBORNE TRANSPORT

Table 6: Battery electric or hybrid electric ship with energy battery (cruise ship, ferry, …)

Typical battery size: 500 kWh – several tens of MWh		*ESU: energy storage unit	
	Source	**2017**	**2030**
Typical market size (GWh/year)	Fincantieri, Saft	~0.2	~4
KPI (ESU* level)	Conditions	State of art	2030
Cell/ESU weight ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	60	70
Cell/ESU volume ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	30	60
Operating lifetime expectation	10 years of operation	~50,000-80,000h	(<ship lifetime)
Cost (€/kWh)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	600-700	250-300
KPI (cell level)	Conditions	State of art	2030
Gravimetric energy density (Wh/kg)	1C charge and 3C discharge, 25°C	~180	350
Volumetric energy density (Wh/L)	1C charge and 3C discharge, 25°C	400-500	800-1,000
Cycle life [80% SOH] (no. of cycles)	70% DOD, 25°C, 1C charge and discharge	5,000-8,000	>10,000
Hazard level	EUCAR cell-level safety performance	<=5	<=2
Cost (€/kWh)		150	75

Table 7: Battery electric or hybrid electric ship with power battery (offshore vessel, drilling vessel, hybrid fuel cell, …)

Typical battery size: 100 kWh – several hundreds of kWh		*ESU:energy storage unitge unit	
	Source	**2017**	**2030**
Typical market size (GWh/year)	Saft	~0	~2,5
KPI (ESU* level)	Conditions	State of art	2030
Cell/ESU weight ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	60	70
Cell/ESU volume ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	30	60
Operating lifetime expectation	10 years of operation	~50,000-80,000h	(<ship lifetime)
Cost (€/kWh)	Full ESU (including rack, gas exhaust system, BTMS, BMS)	1,300	600-700
KPI (cell level)	Conditions	State of art	2030
Gravimetric energy density (Wh/kg)	1C charge and 3C discharge, 25°C	~100	200
Volumetric energy Density (Wh/L)	1C charge and 3C discharge, 25°C	200	400-500
Cycle life [80% SOH] (no. of cycles)	25% DOD, 25°C, 4C charge and discharge	25,000-50,000	>80,000
Hazard level	EUCAR cell-level safety performance	<=5	<=2
Cost (€/kWh)		300	150

Rail transport

Table 8: Energy traction battery. Typical battery size (for 1 train): 600 kWh to less than 1 MWh. 100 km autonomy considered 2020, long term target 2030: x2.

KPI (ESU level)	Conditions	State of art	2030
Cell/ESU weight ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS) 2C charge and 2C discharge capable continuous	45-55%	60%-65%
Cell/ESU volume ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS) 2C charge and 2C discharge capable continuous	18-22%	35%-40%
Operating lifetime expectation	6-10 years of operations (16h/day 350 day/yr)	~30,000-60,000h (<train lifetime)	
KPI (cell level)	**Conditions**	**State of art**	**2030**
Gravimetric energy density (Wh/kg)	2C charge and 2C discharge, 25°C	~150-190	300-380
Volumetric energy density (Wh/L)	2C charge and 2C discharge, 25°C	~350-450	700-900
Cycle life [70% capacity] (no. of cycles)	70% DOD, 25°C, 1C charge and discharge	3,000	> 5,000
Hazard level	EUCAR cell-level safety performance	<=4 except overheat	<=3

Table 9: Power traction battery. Typical battery size (for 1 train): 100 kWh to 600 kWh. If used for long autonomy, then same as for energy traction batteries.

KPI (ESU level)	Conditions	State of art	2030
Cell/ESU weight ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS) 4C charge and 3C discharge capable continuous	45%	60%
Cell/ESU volume ratio (%)	Full ESU (including rack, gas exhaust system, BTMS, BMS) 4C charge and 3C discharge capable continuous	13-22%?	30%
Operating lifetime expectation	10-20 years of operations (16h/day 350 day/yr)	~55,000-110,000h (<train lifetime)	
KPI (cell level)	**Conditions**	**State of art**	**2030**
Gravimetric energy density (Wh/kg)	4C charge and 3C discharge, 25°C	~80-90	120
Volumetric energy density (Wh/L)	4C charge and 3C discharge, 25°C	~160-170	200
Cycle life [70% capacity] (no. of cycles)	70% DOD, 25°C, 2C charge and discharge	20,000	> 30,000
Hazard level	EUCAR cell-level safety performance	<=4 except overheat	<=3

Non-road mobile machinery

Table 10: Non-road mobile machinery (NRMM). Typical battery size: 20-1000 kWh.

KPI (pack level)	**Conditions**	**2019**	**2030**
Cell/pack weight ratio (%)		70	80
Cell/pack volume ratio (%)		60	75
Charging time (min)	80% ΔSOC, minimum impact to lifetime	60-90	20-30
Operating lifetime expectation		20,000 h (vehicle lifetime)	
Cost (€/kWh)		>500	200
KPI (cell level)	**Conditions**	**2019**	**2030**
Gravimetric energy density (Wh/kg)	C/3 charge and discharge, 25°C, charging with CC and CV step	200	350
Volumetric energy density (Wh/L)	C/3 charge and discharge, 25°C, charging with CC and CV step	500	800
Cycle life [80% SOH] (no. of cycles)	80% DOD, 25°C	3,000	6,000
Hazard level	EUCAR cell-level safety performance	<=4	<=4
Cost (€/kWh)		150	80
Market	**Source**	**2017**	**2030**
Typical market size (GWh/year)	Northvolt	1	30

Supplementary information

Air transport

Table 11: Reference battery generations1 against current TRL and fitness for air transport assessment (2035 EiS scenario) of reference battery generations as per current status (Jan. 2021).

Battery Type (Generation)		Current TRL	Fitness for air transport applications (2035 EiS)
3a	Cathode: NMC 622/811 Anode: C + Si (5-10 wt)	8-9	minor applications, non-propulsive systems
3b	Cathode: HE-NMC, HVS Anode: Si/C	5-6	non-propulsive systems / small aircraft propulsion
4a	All-solid-state electrolyte, with composite anode (Graphite or Graphite/Si)	3-4	non-propulsive systems / hybrid propulsion
4b	All-solid-state electrolyte, Li-anode	2-3	non-propulsive systems / hybrid/full-electric propulsion
5	Li/O2, LiS solid	1-2	long term solution for hybrid/full-electric propulsion

Waterborne transport

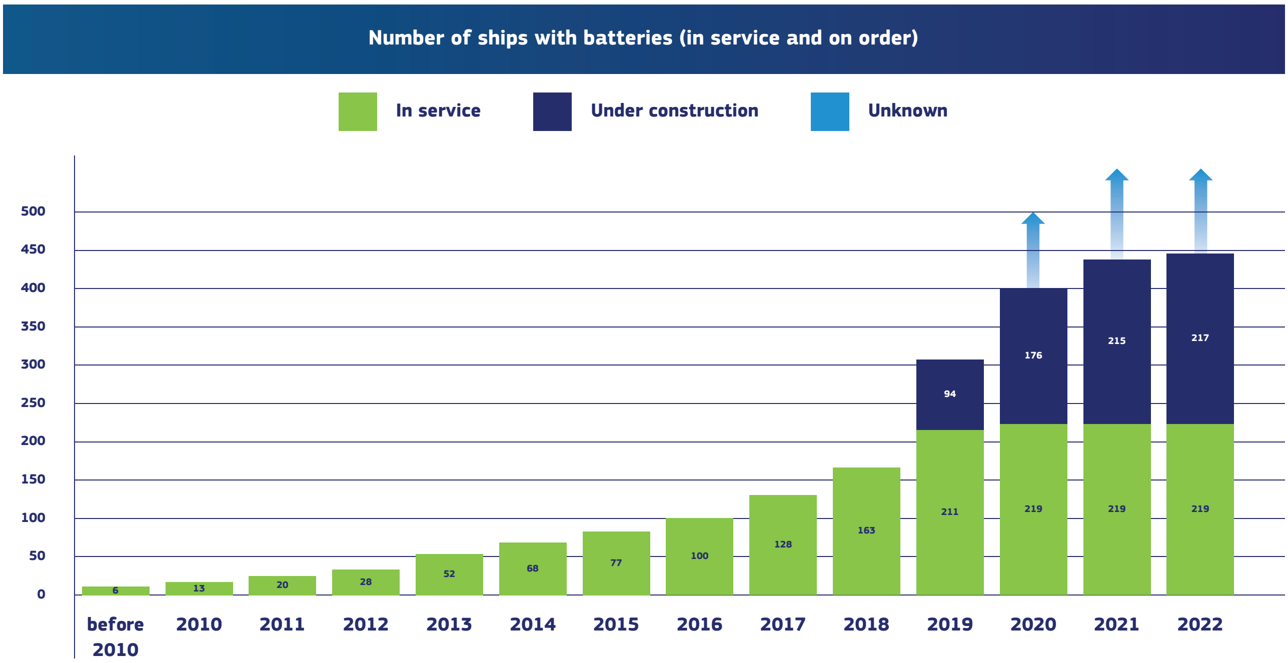


Figure 1 – Number of ships with batteries (in service and on order), cumulative distributions.
The MBF Battery Market Update, Andrea Aarseth Langli – Maritime Battery Forum, WATTS UP 2020.

Table 12: Ongoing or finalized R&D projects over the past 15 years.

PROJECT	SCOPE
FELLOWSHIP	Research collaboration, providing insight into the actual operation of maritime battery system
MF AMPERE	The World's first all-electric car ferry in commercial operation
SUSTAINABLE TRAFFIC MACHINES I AND II	Installation of hybrid propulsion and exhaust gas cleaning systems on two RoPax vessels
ZERO EMISSION	Retrofit of two ROPAX vessels to all-electric powered by batteries
MOTORWAY OF THE SEA LINK RODSTOCK-GEDSER	Retrofit of two RoPax vessels with hybrid propulsion and upgrade of the ports Gedser and Rodstock
E-FERRY	Building of an all-electric ferry
ELEMED	The first cold ironing pilot implementation in the East Mediterranean
YARA BIRKELAND	World's first fully electric and autonomous container ship
PORT-LINER	World's first inland waterway container barges to sail from European ports with full electrical propulsion
SUPERGREEN	Deployment of alternative fuels infrastructure
BB-GREEN	Development and launch of an innovative waterborne transport solution
SAFELILIFE	Evaluation of battery safety properties and interrelation with degradation and ageing
MARITIME BATTERY SAFETY JDP	Testing and analysis of battery safety properties to generate knowledge needed to increase efficiency of regulation
MOZEES	Develop materials for environmentally friendly energy technologies for transportation
HYDRA	Hybrid power-energy electrodes for next generation lithium-ion batteries
TRAM	Transport: Advanced and Modular
SEABAT	Development of a full-electric maritime hybrid concept

Table 13: Further reading

Draft proposal for a European Partnership under Horizon Europe BATTERIES| Towards a competitive European industrial battery value chain for stationary applications and e-mobility, 10 June 2020.
Draft Proposal for a European Partnership under Horizon Europe Zero-Emission Waterborne Transport, Waterborne TP, 5 May 2020.
Strategic Research Agenda for batteries 2020, Batteries Europe, European Technology and Innovation Platform, December 2020.
Strategic Research and Innovation Agenda for the Partnership on Zero-Emission Waterborne Transport, Draft version, Waterborne TP, October 2020.

Rail transport

A large description of existing trains is done in [1]:

- Stadler commissioned in Germany in 2020 55 Flirt Akku battery train (and additional 50 as option), 150km autonomy for about 600kWh battery onboard.
- Bombardier battery train Talent3 (in 2018): 300kWh, 40 km autonomy. Bombardier estimates that total costs of ownership are currently 50% lower than a fuel cell train, and that energy costs are reduced by 35% compared to diesel and fuel cell technologies.
- Siemens Desiro ML Cityjet (528 kWh LTO technology), battery train for ÖBB in operation since September 2019. In Germany's Baden-Württemberg, Mireo Plus B fleet contract for 20 battery electric commuter trains to enter service 2023. Siemens Avenio tramways uses 42kWh lithium batteries, LTO & LFP.
- Alstom battery train contracted 11 Coradia continental BEMU (Fleet) in Saxonia (Leipzig-Chemnitz), operation planned in December 2023.
- CAF tramways commissioned for Birmingham have a 80kWh lithium battery onboard for the new extensions of the existing lines.
- DB Cargo orders 50 hybrid locomotives from Toshiba, DB Cargo is starting the sustainable renewal of its shunting fleet
- Several hybrid shunting or last miles hybrid locomotives (diesel engine and lithium batteries), already in service, use lithium batteries: Gmeinder DE75 BB and Zweiweg International, Aselsan HSL 700, CRRC, TSV600 (maintenance engine) or in project (Vosloch DE18). The onboard energy is between 100 and 400kWh.

Fuel Cell

- Two first of series Coradia iLint fuel cell trains manufactured by Alstom entered regular commercial service in September 2018, with a range of 1000 km. The lithium-ion battery pack is supplied by Akasol (NMC, 222 kWh at 800 V). In Germany 14 (+ 27 trains) will enter commercial operation by the end of 2022. Also 6 (+ 8 option) Coradia Steam H2 trains will enter commercial operation in Italy by the end of 2023.

- Siemens Mobility is developing a H2 train prototype – the Mireo Plus H, for operational tests with new tanking system in 2022 with DB, and passengers' operation in 2024, with range of up to 600 km. A three-car version will have a range of 1000 km.
- Stadler contracted with the Austrian Zillertal Railway 5 fuel cell trains (option for 3 more) with battery onboard.
- There are currently no H2 freight locomotives in operation, but several projects are ongoing (e.g. ÖBB with 1.1 t hydrogen storage (ÖBB 2019), in Poland, a partnership between PESA and the oil refinery group PKN for the development of H2 locomotive has been sign in end 2019).

In Japan, since 2007, JR East has put into commercial service the first hybrid self-propelled train in the world (KiHa E200, 15kWh) and since 2014 the ACCUM self-propelled vehicle (190kWh), dual mode catenary - battery. JR Freight has been using more than 30 HD-300 Toshiba shunting locomotives (68kWh) since 2010, JR Kyushu has been using the DENCHA vehicle in commercial service (430kWh), also a dual mode catenary-battery vehicle since 2013. Tokyo Metro have installed batteries in subways or suburban trains (380kWh) for other functions such as energy recovery during braking or power assistance under 1500V emergency. The Shinkansen N700S, is equipped with a lithium battery (212kWh) allowing it to run autonomously for a few kilometers. A prototype of a regional self-propelled fuel cell (a fuel cell powertrain includes a battery) train will be launched by JR East in 2021 (possible series in 2024, 240kWh).

Battery and Hybrid train projects currently under development:

Alstom is involved in France in a Hybrid Diesel regional train demonstration and a Hybrid H2 regional train. In both applications, the LTO lithium battery capacity is in a range of 100 to 200kWh.

In France, **Bombardier** retrofits diesel engines of a dual mode regional train with an 800 kWh NMC lithium battery, with range of 80km.

CAF leads a European consortium to develop a HEMU dual mode demonstrator able to run with H2 Fuel Cell, LTO batteries and under existing 3 kV DC catenary.

Talgo will develop for 2023 the Vittal-One, HEMU fuel cell prototype (https://www.talgo.com/home-highlights).

Toshiba, in deep cooperation with DB, develops Diesel-Battery Hybrid shunting locomotive for DB Cargo (62 kWh LTO).

Concepts for freight battery trains in Norway are currently evaluated.

Table 14: Rail transport battery market: Rough market estimation of potential quantities based on battery solutions

Rolling stock type	Quantity	Low estimation [MWh]	High estimation [MWh]
Germany (passengers) [40]	16978	2798	5251
Germany (freight) [41]	3863	708	1352
France (passengers)	3584	591	1108
France (freight)	1254	230	438
Czech Republic (passengers)	1191	196	368
Czech Republic (freight)	1413	259	494
Italy (passengers)	963	159	298
Italy (freight)	1575	289	551
Holland (passengers)	4026	664	1245
Romania (passengers)	390	64	121
Romania (freight)	1963	360	687
UK (passengers)	11107	1831	3435
UK (freight)	244	45	85
Switzerland (passengers)	724	119	224
Switzerland (freight)	1130	207	395
Austria (freight)	1019	187	356
Total		***8 706***	***~16 400***

40 Railcars and Multiple Units
41 Locomotives including Light Rail Motortractors

Further reading

[1]Battery Electric and Fuel Cell Trains Maturity of Technology and Market Status; Rebecca Thorne Astrid H. Amundsen Ingrid Sundvor; Institute of Transport Economics/ Norvegian Center for Transports Research (May 2020)

[2]EIB Project Carbon Footprint Methodologies, Methodologies for the Assessment of Project GHG Emissions and Emission Variations (July 2020)

[3]UK rail industry decarbonisation taskforce, final report to the Minister for rail (July 2019)

[4]Community of European Railway (CER) Compendium, Alternative fuels and powertrains (September 2020)

[5]EIB Project Carbon Footprint Methodologies, Methodologies for the Assessment of Project GHG Emissions and Emission Variations (July 2020)

[6]VDE Alternativen zu Dieseltriebzügen im SPNV - Einschätzung der systemischen Potenziale (July 2019)

[7]Roland Berger from STUDY ON THE USE OF FUEL CELLS AND HYDROGEN IN THE RAILWAY ENVIRONMENT, Shift2Rail H2 study, 2019.

[8]Roland Berger – Automotive Competence Center & Forschungsgesellschaft Kraftfahrwesen mbH Aachen "E-mobility Index" 2018

[9]European Union Agency for Railways, 2020, Report ERA1234, "FOSTERING THE RAILWAY SECTOR THROUGH THE EUROPEAN GREEN DEAL"

[10]UIC 2020 Railway Statistics Synopsis https://uic.org/support-activities/statistics/

[11]SNCF Open Data site: https://data.sncf.com/pages/accueil/

[12]Joachim J. Mwambeleko, T. Kulworawanichpong "Battery electric multiple units to replace diesel commuter trains serving short and idle routes" DOI: org/10.1016/j.est.2017.01.004, Journal of Energy Storage, Volume 11, June 2017, Pages 7-15 ?