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BATTERIES FOR ENERGY STORAGE IN THE EUROPEAN UNION

2022

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS AND MARKETS

Joint Research Centre

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Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Executive Summary

Batteries are needed in the context of Green Deal and the REPowerEU plan to meet our objective for climate neutrality, to reduce dependency on fuel imports as well as to ensure maximum use of renewable electricity and reduce curtailments. Over 50 million electric vehicles are expected on the EU's roads by 2030 (at least 1.5 TWh of batteries) and over 80 GW / 160 GWh of stationary batteries. By 2050 the EU's entire car fleet of 270 million vehicles should be zero-emission (mostly electric). E-mobility is the main driver of demand for batteries; lithium-ion batteries are expected to dominate the market well beyond 2030 but developments in other technologies will be continued in parallel.

General Technology Overview:

The mass produced lithium-ion battery family inter alia includes:

- LFP – cheap, durable, do not contain expensive cobalt and nickel, relatively safe, is gaining market in mobility and stationary applications, will increase in importance in future, even if its energy density is lower compared to NMC and NCA chemistries. Low value for recycling, EU manufacturing very limited
- NMC111 – relatively expensive, contain lots of cobalt and nickel, was important chemistry in mobility, being replaced by lower cobalt chemistries (NMC442, 532 and now 622). High value for recycling, EU manufacturing very limited
- NMC622 – contain less cobalt and more nickel, current leader in mobility applications, good value for recycling, main chemistry produced in EU and used by EU's automotive industry.
- NMC811 – contain even less cobalt and more nickel, future leader in mobility applications, good value for recycling, main developing/future chemistry in EU
- NCA – relatively expensive, contain lots of nickel and cobalt (used by Tesla), competes with NMC and LFP in EV applications, lower durability than NMC and less thermally stable, good value for recycling. EU manufacturing very limited, if any.
- LTO – contain titanium next to other materials, expensive and poorer energy density, but very durable, safe and fast-charge capable, used in elevated temperature or heavy duty applications and when extreme durability is needed, some manufacturing is existing in EU.

The currently dominating chemistry is Li-ion (LFP, NCA and NMC622), in future Li-ion will still dominate (LFP, NMC811+), but the role of sodium-ion, flow batteries and sodium based technologies will significantly increase.

Lithium-ion batteries containing silicone rich or lithium metal anodes, solid state batteries, lithium-sulfur – high energy batteries at different development and commercialisation levels, considerable research is currently done on those.

Lithium-air – future technology at low level of development

Lead-acid battery – cheap, mature and widespread technology, used as starter battery in ICE vehicles or for auxiliary power in EVs, also for backup power and in industrial applications. Well-developed recycling in EU. Lead-acid batteries benefit from marginal increase in sales and can no longer keep market leader position with e-mobility on the rise.

Sodium-ion – potentially cheap, safe technology, just commercialised in China. Do not relay on any critical raw material. Less performing than mainstream lithium-ion chemistries in terms of energy density.

Redox-flow batteries – many chemistries possible, most developed one based on vanadium, but versions working on cheap, non-toxic and non-critical materials available, flexible in power and energy scaling, potentially suitable for seasonal energy storage.

High temperature (molten salt or sodium) batteries – well-established sodium-sulfur and sodium metal halide batteries, combine high energy and power densities, long lifetimes, longer storage duration than li-ion and low-cost materials. Suitable for grid scale storage and from this sector come most of recent deployments.

Technology Deployment

Mobility Applications

Mobility applications of batteries are focused on personal and light duty commercial vehicles. Electric buses are sold much less, heavy trucks and other modes of transport are electrified only marginally.

Despite chip and magnesium supply disruptions, deployment of battery technology in the EU reached historic highs. The market share of electrified (battery and plug-in hybrid) electric vehicles sold in 2021 reached 18%, compared to 3% in 2019 and 10.5% in 2020, and surpassing China with 16%. However, in absolute numbers electrified vehicles sales in 2021 were highest in China reaching 3.3 million units, followed by EU with 1.7

million and US with 0.63 million. The EU vehicles electrification leaders are DE, FR and IT in absolute numbers and SE, DK and FI in market share. National EV sales ranged from 1.3% in Cyprus to 45% in Sweden.

Electric buses sales in 2021 were biggest in China reaching 86 000 units, 2 300 in EU and 1 300 in US. The EU leaders were France (622 units), Germany (613 units) and Denmark (224 units).

Global electric heavy duty vehicle registrations in 2021 reached 14 200 units, China is leading, with about 13 000 new registrations, followed by EU with 410 registrations and US with 450 vehicles. The global stock reached 66 000 vehicles (0.1% share).

Total number of battery propelled (all types) ships in EU (in operation and ordered) as of 2022 reached 143, almost 25% of the world fleet counted to 578 vessels. The global leader is Norway with 251 vessels. Most often those are car/passenger ferries, offshore supply ships and other purpose ships.

Stationary applications

The stationary battery market of the EU27 more than doubled in 2021, with annual installations reaching 2.2 GW / 3.7 GWh. The cumulative installed capacity reached 4.6 GW / 7.7 GWh (mostly Li-ion batteries) and is forecasted to grow to 8 GW / 13.7 GWh by end-2022. EU share in the global installed capacity reached 14%. This relatively low share is explained with strong grid in EU and market-based approach for deployment of storage. Further acceleration is needed in line with the objectives of REPowerEU, notably to reduce dependence on gas peaking plants.

World-wide 10 GW / 22 GWh of battery storage was deployed in 2021. Global cumulative instalments reached 27 GW / 56 GWh in 2021.

Battery prices

In 2021, average global battery prices fell by 6% to around 116 EUR/kWh[1] (in EU market - around 150 EUR/kWh) continuing a long-term trend. However, now this is beginning to reverse with prices rising in 2022 due to supply-side shocks, (e.g. in Spring 2022 the price of lithium carbonate was up by 974% compared to 2021). Battery packs will be at least 15% more expensive in 2022 than in 2021. The system cost of grid scale Li-ion applications was around EUR 350/kWh in 2021 and, for home storage systems, roughly twice that.

Research and innovation:

Public R&I funding in the EU is rising considerably. Under the Horizon Europe programme, EUR 925 million have been earmarked for collaborative research on batteries for the period 2021-2027 (to be implemented through the Batteries Partnership), almost twice the funding under Horizon 2020. The batteries development is also supported by other initiatives like e.g. 2 Zero partnership, European Partnership for Zero Emission Waterborne Transport, Clean Sky partnership, etc.

A number of research and innovation needs are addressed by two Important Projects of Common European Interest. They involve companies and research organisations from 12 EU countries along the whole batteries value chain. IPCEIs involves both public and private funding: EUR 6.1 billion of public funding by participating Member States will unlock an additional EUR 14 billion funding from private sector.

The global trends in battery R&I show general shift to low cobalt chemistries (NMC811, 955, NCA, NMCA, and LNO) and cheap LFP. Also new chemistries, like solid state, LNP or iron trifluoride may play an important role in the future. The alternatives to Li-ion also are in the focus, with Na-ion being just commercialised from Chinese CATL with prospects in automotive sector and a lots of interest in flow batteries for stationary energy storage. On anode side most interest is given to include/increase content of silicon in active material or use of metal lithium anode.

In EU the most of R&I goes to high performance chemistries with prospects in automotive industry. Both, cathode and anode developments follow in this direction. Some interest is also given to the development of cheaper replacements of best performing chemistries that could be used in economic class vehicles.

There is a lag in publication of patenting data, but the global situation should largely still be the same. As of 2019, for at least 10 years in a row, a global leader in patenting the battery high value inventions was continuously Japan, followed by Korea. EU and China are close to each other, occupying third and fourth positions, US being fifth. However, the total number of inventions was highest in China, followed by Japan,

[1] BNEF, Battery Pack Prices Fall to an Average of $132/kWh, November 30, 2021. Conversion rate 30/11/2021: 0,8826 EUR/USD

Korea, EU and US. In global top 10 high-value inventions countries Germany was the 5th, France - 6th and Sweden 10th. In the rank of companies Bosch is listed on 5th place.

Looking at number of firms being innovators (2010-17 data), the global leaders of innovations in batteries are US, Japan, China, Germany and South Korea. Most (76%) of battery innovators identified globally are corporations, venture companies play more significant role only in US and to some extent in China. Automakers and battery manufacturers often invest in start-ups to get access to their technologies.

In 2021, global venture capital (VC) investments in battery developers reached all time-highs, amounting to € 10.6 billion, which is more than all investments realised since 2010. Both early stage and later stages investments were covered. Few large deals in battery manufacturers from Sweden (Northvolt, € 2.6 billion, later stage VC) and China (Svolt, € 2.6 billion, early stage VC and China Aviation Lithium Battery, € 1.5 billion, private equity growth) were executed in 2021.

Bibliometric trends for Li-ion batteries show increasing interest. The leading country is China, followed by RoW, EU and US. The growth rate for China and RoW is much faster than the one for EU and US.

The analysis of bibliometric trends for technologies and regions show that China is very interested in all solid state, sodium-ion and redox-flow batteries, by far leading in those chemistries. China is also leading the general Li-ion category, however other countries are not far behind. EU is rated high in general Li-ion category (3rd place), redox flow batteries (3rd place) and lead-acid batteries (also 3rd place). In those categories the number of publications is greater than half of those from the leader.

Value chain Analysis:

The EU industry has invested significantly in batteries value chain. In total, the European Battery Alliance has generated investments exceeding EUR 100 billion (mostly application segment and battery cell segment).

In 2021, all of EU mass-production of lithium-ion batteries still came from Asian manufacturers established in the EU, in Hungary and Poland (except of some niche markets). As new gigafactories are being built, Europe (especially Sweden and Germany) is set to gradually gain importance on the market. At the end of 2021 Swedish Northvolt produced its first battery cell made with 100% recycled nickel, manganese and cobalt and started commercial deliveries in 2022. They claim to have a highly efficient recycling process with recovery of up to 95% of the battery metals. Chinese CATL and American Tesla are about to start their production in Germany.

A number of EU headquartered companies are working on giga-factory projects, including ACC, VOLKSWAGEN, VERKOR, INOBAT, VARTA, FAAM/Lithops, Eneris/Leclanché and others.

The EU is expected to reach over 75 GWh installed cell production capacity by end-2022, compared to 44 GWh in mid-2021. EU production of Li-ion battery cells was estimated to reach about 16 GWh, which is still much lower than EU production of lead-acid batteries. Thanks to the projects underway, largely resulting from the initiatives of the European Battery Alliance, the EU is on track to meet 69% of Li-ion batteries demand by 2025, and 89% by 2030.

The upstream raw materials segment remains the least resilient of the battery value chain and spent batteries are still mostly sent to Asia for recycling. Despite several European initiatives the supply gap for battery raw materials increased in 2021. In particular graphite, cobalt and lithium are on the list of EU critical raw materials, but also nickel. In perspective of 2025 this will not change a lot, a projected domestic supply of raw materials will not exceed 15% of battery industry needs by 2025. By 2030 it might improve for manganese and lithium reaching 40% and 25% of EU battery industry needs respectively

Regarding active materials (cathode and anode) EU is weak in both, future domestic supply of cathodes may reach about 35% in 2025 and 45% in 2030. Domestic supply of anodes will remain below 10%.

In manufacturing of Li-ion cell production equipment, Asian companies are also leading and most of equipment is imported to EU from Asia. Manz is the only EU company playing an important role in this segment.

EU recycling capabilities will strengthen especially in 2030 perspective, reaching 40% of needs in 2025 and 70% in 2030. Last year brought slight increase of expectations for 2025 and significant increase for 2030.

The EU has its strongest role in final products. All EU automotive companies embraced the switch to e-mobility. In late 2020 leading EU truck producers – Daimler, Scania, Man, Volvo, Daf, Iveco, and Ford – signed a pledge to phase out traditional combustion engines by 2040.

EU trains producers Siemens and Alstom already hold the first contracts to supply battery driven trains (for non-electrified segments) starting from 2023. Swiss Stadler is also in the race.

Many electric ships are integrated at Damen shipyards (NL). Other EU shipyards are also involved, there seem to be no shipyards specifically specialised in electric ships. Leading EU companies for equipping ships with battery storage and electric propulsion are Echandia Marine and ABB (SE), Wärtsilä (FI), Danfoss (DK) and Siemens (DE).

Major companies in EU active in the stationary storage sector are Fluence, Sonnen, TOTAL/SAFT, Engie, ENEL X and ABB. There is also a number of small companies and start-ups developing their own systems.

While rapidly advancing on Li-ion battery value chain (notably cell production in the most performant NMC strand), the EU is progressing too slowly on stationary battery technologies based on abundant raw materials, e.g. flow batteries and sodium-ion batteries (the latter have also good EV potential *inter alia* based on developments in China). EU is also slower to embrace cheaper LFP type of li-ion technology increasingly used in Asia and less dependent on critical raw materials.

Over the last 10 years, only 7% of the world's flow battery projects were installed in Europe, with much more R&D and support taking place in North America and Asia. At the same time, Austrian CellCube belongs to global top-three RFB producers, together with Sumitomo Electric Industries Ltd. (JP) and UniEnergy Technologies (US). Recent establishment of Flow Batteries Europe can improve EU's competitiveness in this segment.

At the sodium-ion battery market there are 2 promising EU companies: Tiamat (FR) and Altris (SE), however for the time being the biggest players are Chinese CATL advancing with Na-ion cells intended for application in hybrid Li-ion/Na-ion EV battery packs and Indian Reliance Industries which recently acquired UK-based sodium-ion specialist Faradion.

Global market Analysis:

China controls 80% of the world's Li-ion battery raw material refining capacity, 77% of cell production capacity and 60% of battery component manufacturing capacity.

Global biggest suppliers of Li-ion batteries were: CATL, LG Energy Solution, BYD, Panasonic and SK Innovation (Q1 2022).

The EU trade deficit in Li-ion batteries continued to expand in 2021 and reached EUR 5.3 billion (+25% from 2020). Most of imports came from China, followed by South Korea and US. During 2019-21 period only two EU countries, Poland and Hungary have achieved positive trade balance. The largest EU exporter is Poland supplying mainly the internal EU market (88% of Polish export is EU internal). The biggest EU importer of batteries (also globally, before US) was Germany, satisfying its needs roughly in halves on internal EU and external markets.

While EU is responsible for roughly 19% of global EV production, it has very little of the upstream supply chain (except cobalt processing).

Electric bus production and deployment in the EU (7 356 e-buses in circulation at the end of 2021) is insignificant compared to China, that has over 90% of global stock of 670 000 e-buses.

In conclusion, the EU is strong in final products, especially EV production and deployment, except in the electric bus segment. It is also quickly catching up on cell manufacturing when it comes to Li-ion technology and it is on track to be close to self-sufficiency in battery production by 2030. Lack of domestic raw materials and advanced materials production is a persistent problem despite initiatives under way. Mining permitting is one of the issues to be addressed. The new proposal for a Battery Regulation will help Europe to become leader in the circular economy of batteries, starting from sustainable mining and ending with recycling. The EU should also step up technological capability in cheaper storage/longer-term storage (e.g. sodium-ion technology, flow batteries).

1 Introduction

According to the Green Deal and the REPowerEU plan[2] achieving the EU's climate and energy 2050 objectives will only be possible with significant technological advancement in technologies of critical importance. One of those critical technologies is battery electricity storage. Batteries are a key enabling technology for electrification of transport and wide adoption of intermittent renewable energy sources. Among large scale energy storage systems, batteries are one of the most energy efficient solutions achieving a round trip efficiency up to 95%.[3, 4] This allows to reach high overall energy efficiency of battery electric transport modes of up to 77%.[5]

Currently the transportation sector is the fastest growing market for batteries, thus this report is focusing on lithium-ion (Li-ion) batteries for electric vehicles (EV). However, other applications, such as stationary energy storage are of increasing importance. The battery technology develops towards improved Li-ion chemistry, but also towards alternative chemistries, looking for better performance, durability, safety, but also increasing sustainability and value chain security. Therefore, many indicators in this report will also assess other battery technologies and applications.

The methodology of the report is focused on the factual description of the actual state and referring to the previous period to highlight the changes. The Li-ion batteries are in the focus, however where possible information on the other chemistries is given.

In the application part, wherever "electrified vehicle" term is used it refers to full EVs (BEV) and plug-in hybrids (PHEV) together. Standard hybrid vehicles (HEV) are not considered in the report for their low battery capacities. Also use of batteries in fuel cell vehicles is not covered.

[2] COM(2022) 230 final *REPowerEU Plan*.

[3] US National Renewable Energy Laboratory, Energy Storage, Days of Service Sensitivity Analysis, 2019.

[4] https://batterytestcentre.com.au/project/lithium-ion/

[5] Transport & Environment, How to decarbonise European transport by 2050, 2018.

2 Technology State of the Art and Future Developments and Trends

The battery technologies develop fast, driven mainly by mobility sector. The R&I is focused on performance and durability improvements, safety and cost reduction. Those goals are realised by improvements of existing technologies, especially lithium-ion, but also mature lead-acid batteries that are being continuously modified and improved. In parallel new chemistries are being developed – like solid-state batteries or just commercialised sodium-ion technology. New types of cheaper and more sustainable flow batteries are being developed as demand for longer term storage is growing within energy system.

New technologies entering the markets are usually more expensive than the traditional ones, but are offering new or better functionalities, thus their commercialisation starts from high-end or niche markets. Only then, with increasing mass production and years of lessons learned more popular markets are taken and the technology can be widely adopted and often displace existing solutions. This exactly is happening to the batteries. Nickel-cadmium batteries are losing the market being replaced by newer solutions. Lead-acid batteries continue to benefit only from marginal increase in sales and can no longer keep market leader position. At the same time, popular lithium-ion technologies are gaining the mass market in mobility and stationary applications. Solid state batteries, too expensive for wide use in large systems, are gaining position on the niche market of earphones and small electronics. Finally hundreds of further chemistries are being developed and screened to find those few with potential of commercialisation and wide use.

The general trends in the R&D&I cover three areas: cost reduction, performance improvement and safety. Especially the safety aspects are important as significant safety issues can add difficulties to the development of all battery sector. Those R&D&I efforts include both, improvement of existing and new chemistries.

2.1 Technology readiness level (TRL)

Batteries are devices converting energy of chemical reactions directly into electrical energy. Depending on the design, batteries can be non-rechargeable (primary batteries, need to be disposed after emptying) or rechargeable (secondary batteries, can be charged by forcing the current backflow). Primary batteries are typically rather small devices, providing in a comfortable way small amounts of electrical energy to electrical appliances. In contrast, secondary batteries, in addition to powering our phones and laptops, became in recent years a very important element of modern economy, becoming a central point of electric mobility solutions, but also finding each year more prominent position in the landscape of stationary applications, including but not limited to frequency regulation on energy grids, integration of intermittent renewable energy sources, power management or back-up power. There are multiple battery chemistries and designs, differing (often significantly) with electric performance, durability, cost, range of operating temperatures, charge/discharge profile, safety features etc. For this reasons each application "prefers" some designs or chemistries, depending on actual application's characteristic conditions of use. This is valid for all applications, including mobility, stationary, portable or any other.

Mobility applications are currently the driver for battery technology development. Such batteries should provide enough energy (range) and power (acceleration) to meet user expectations, be small (to fit in the limited space in the vehicle), be light (heavy weight compromises range and acceleration characteristics of the vehicle), be sufficiently durable to cover the lifetime of the vehicle (e.g. for an EV equipped with a 100 kWh battery a typical range is about 500 km, 600 full charging cycles would suffice to drive this vehicle a distance of 300 000 km), and finally be safe in use. The energy density of battery packs ranges between 100-265 Wh/kg, or 250-670 Wh/L at pack level[6]. According to the BNEF 2021 EV outlook[7], average battery energy density of EVs is rising at 7% per year. In all mobility applications the R&D&I focusses on cost reduction, performance improvement, durability and safety.

- Battery electric vehicles (BEV): EV battery size is usually in the range between 30 kWh and 100 kWh with an average size of the battery pack in the EV sold in EU in 2021 of about 50 kWh, providing energy for propelling a vehicle. Those battery packs are most often designed using the cells available on the market, but some car manufacturers develop cells for a specific car. The EV segment is currently driving the innovation of Li-ion batteries. The battery management system (BMS) is complex, with thermal management allowing for both, cooling and heating. The technology is mature, at TRL 9, but innovation, performance improvement and substitution of critical raw materials continues. EVs are attracting more and more consumers, but the general switch from ICE to EV technology is still to come (EVs market share exceed this of ICE vehicles only on few national markets, e.g. in Norway). Those batteries are

[6] ReportLinker, Lithium-ion global market report 2021: COVID 19 impact and recovery to 2030, 2021.
[7] BloombergNEF, Electrical Vehicle Outlook 2021, 2021.

dominated by Li-ion family members, mainly employing NMC, NCA or LFP cathodes. A general trend is a move towards bigger cell formats, e.g. Tesla announced moving from 18650 cells to much bigger 4680 format.[8] In this way a ratio of passive to active cell materials is increased resulting in cost/kWh reduction, weight reduction, easier and cheaper installation in the car. From the batteries chemistry point of view, there is continuation of the trend to reduce the cobalt content in the batteries increasing the share of nickel (move towards NMC 811 and other Ni-reach cathodes). There is also an increased interest in LFP batteries for low-end EV segments. Anodes development is looking to increase Si content or to use metallic lithium. Development of post-Li technologies continue. At higher assembly level, the R&D seeks for cell-to-pack assembly technology (skipping the assembly level of modules) leading to easier, faster and cheaper system assembly and increased pack energy density. There's also another R&D trend, to combine the function of battery and structural components of the car. The technology leaders are bringing now this idea into mass production in first applications (Tesla Model Y). The EV producers are also tending to unify the battery components, including cells, packs, connections etc.

- Plug-in hybrid electric vehicles (PHEV): PHEV battery size is usually in the range between 5 kWh and 25 kWh with an average size of the battery pack in the PHEV sold in EU in 2021 of about 12 kWh providing energy for propelling a vehicle alone or cooperating with the downsized ICE motor.[9] In numbers, the share of PHEV vehicles is similar to that of EVs in EU in 2021. Also similar cells and chemistries are used. The technology is mature, at TRL 9.
- Hybrid electric vehicles (HEV): HEV battery size usually do not exceed 2 kWh and is providing energy for propelling a vehicle alone over a short distance or assisting the ICE motor (in contrast to micro or mild hybrids, which cannot be propelled from battery alone). The share of HEV vehicles in the total number of EU sold vehicles is greater than that of EVs or PHEVs, but due to much smaller battery size, the contribution of this segment to the global battery demand is less than 10% of the batteries demand from EVs. The applied cell design and chemistries are optimised for power, so the small battery can accept the energy of regenerative braking. In addition to Li-ion, also NiMH batteries are used in this segment. The technology is mature, at TRL 9.
- Mild- and micro-hybrid electric vehicles: deriving from HEVs a trend of "downsizing" the battery that is allowing to catch the most of the HEVs advantages at minimal cost. From HEVs it mainly differs by smaller battery capacity, battery voltage reduced to 48 V, simpler BMS and heat management systems. Also uses cells optimised for power. The technology is mature, at TRL 9, but rather young.
- E-buses: an e-bus battery system usually exceeds 100 kWh, and is usually bigger for far-distance vehicles than for city buses. Those batteries are usually optimised for energy for far-distance vehicles, and either for energy or power or a compromise of both for city buses. The latter depends on charging strategy: if the bus is charged during the stops in several points of its route or only at the end points or at the bus depot. The BMS is complex, with thermal management capabilities, especially in the systems recharged over short time with high power during the stops along the route. The technology is mature, at TRL 9. The share of e-buses in the EU fleet is still low, unlike in China. Those batteries are dominated by Li-ion family members, mainly NMC, NCA and LFP.
- SLI and EV's auxiliary power batteries: SLI stands for starter, light, ignition battery. It is a standard 12 V (24 V in trucks) battery in the car, present also in EVs and supplying power to on-board installations, but not for traction. In this application, the battery stays for most of the time fully charged, working in short pulses of high power to start an ICE engine and long periods of low power to provide energy to the on-board electronics when the car is parked. Thus the battery is exposed to a relatively high number (1 000 – 2 000) of rather shallow cycles and the number of deep discharges with depth of discharge (DoD) exceeding 50% is limited. It is a mature technology at TRL 9, while improvements still continue. It is dominated by lead-acid (Pb-A) chemistry, either in its classic version with liquid electrolyte, or in modernised version, based on gel electrolyte. The R&D&I except for cost, durability and safety focusses also on using secondary raw materials (recycled lead) and reduction of maintenance efforts in the battery use phase.
- Other (e.g. e-bikes, e-scooters): batteries for those applications are usually small (400 – 4 000 Wh) battery packs used for propelling or support propelling a light means of transport. Those batteries are designed using the cells available on the market, not developed for this specific application. Also the BMS is rather simple and no thermal management system is available. The quality of the applied batteries might be lower. Those batteries might be exposed to frequent deep DoD cycles. The technology is mature, at TRL 9. Those applications gain popularity in the recent years, and the market

[8] https://www.euronews.com/next/2022/01/25/panasonic-to-produce-new-longer-range-tesla-4680-ev-battery-at-600m-plant-in-2023-report

[9] http://autocaat.org/Technologies/Hybrid_and_Battery_Electric_Vehicles/HEV_Levels/

is expected to expand quickly. Those batteries are dominated by Li-ion family members, mainly LFP or in more demanding applications also NMC or NCA batteries.

Stationary application batteries is a more diverse family, with characteristics fine-tuned to each application. They compete with pumped hydro or compressed air energy storage technologies, which generally are more cost effective for long discharge and storage applications. Generally, these batteries are not exposed to vibrations and mechanical shocks and usually weight and volume are not critical issues. The key factors are durability (longer service/cycle life than in case of mobility batteries) and cost. However, as the battery production/design is driven by mobility applications, mainly EVs, the battery packs used in stationary applications are still often only slightly modified EV batteries built with battery cells designed for mobility applications. Also when the EV battery manufacturers advance to higher performance chemistries, the less performing technologies that become less popular for EVs can be deployed at a lower price for stationary storage. This is not optimal, as the technical requirements for the mobility and stationary batteries differ, but in this way the stationary applications use the design and production infrastructure dedicated to a much more developed mobility market profiting from gains through mass production. Anyways, the cost of 1 kWh of storage capacity in the stationary application is still significantly higher than 1 kWh of EV battery. It should be expected that with the growing stationary batteries market those technologies will separate and dedicated designs accounting for the specific needs of stationary storage will appear.

A chemistry dominating the stationary electric energy storage (EES) is Li-ion that reached a market share of 86%[10]. Li-ion batteries are most profitable in short-duration energy storage applications (e.g. hourly balancing, peak shaving and ancillary services) while above 4-6 h duration they are less cost effective. There are R&I projects targeting use of 2nd life EV batteries for stationary storage. Li-ion batteries compete on the market with well-established technologies like lead-acid (Pb-A), but also with new ones like redox flow batteries (RFBs). Flow batteries offer a unique advantage of decoupling the battery power (kW, depending on the stack size) from energy capacity (kWh, based on the volume of electrolyte tanks). This means that any combination of energy and power can be designed, including that suitable for seasonal energy storage.[11] The flow batteries also offer cycle life much longer than that of Li-ion or Pb-A batteries. RFBs are being developed applying a wide range of chemistries including those based on non-critical raw materials. Their TRLs vary between 4 and 9, depending on the chemistry. In 2021, sodium-ion (Na-ion) batteries were commercialized with intended use in EV batteries (2023 and later). It should be expected that these batteries enter also the stationary energy storage systems - ESS when the production is scaled up.

- Bulk energy storage and generation support: batteries optimised for energy, should allow for a high number of rather deep charge/discharge cycles, often working in daily cycles. Size of those systems may vary depending on the application, from few kWh in case of a household up to hundreds of MWh for grid utilities. The technology is mature, at TRL 9, while improvements continue, especially on cost reduction. Some battery-based solutions are available since decades, those are advanced lead-acid (Pb-A) based on gel electrolyte and high temperature sodium-sulfur and sodium-metal halide (ZEBRA) batteries. Alternatives to those battery systems became available only recently, adding more technological solutions to the market. They compete with other energy storage technologies, like pumped hydro or compressed air energy storage. Today, chemistries applied in new energy storage projects are mainly belonging to the Li-ion family, e.g. LFP, NMC, and NCA but recently also flow-batteries, sodium-ion (Na-ion) batteries or zinc based batteries became available. The R&D&I focusses on cost reduction, new system designs, scaling-up to the size of grid scale application, integration/connection to the grid, optimisation and digitalisation of battery operation, batteries durability.
- Frequency regulation on energy grids: batteries optimised for power, should allow for extremely high number of shallow charge/discharge cycles, working around 50% state of charge (SoC). The technology is mature, at TRL 9, including some battery based solutions, however the modern battery systems appeared on this field only recently, adding more technological solutions to the market. They compete with "traditional technologies", like generator inertia, additional generation, dedicated demand or other energy storage technologies (e.g. flywheels). Chemistries applied in grids frequency regulation are Li-ion family (LFP, NMC622), advanced Pb-A, high temperature sodium batteries and since recently also flow batteries.[12,13] Technically very well suited for this application is LTO variant of Li-ion chemistry, capable of performing 20 000 cycles or more, however this chemistry is investment intensive. Thus,

[10] RhoMotion Battery Energy Stationary Storage Outlook Q1 2022, 2022
[11] Daniele Gati, IDTechEx Overview of the Redox Flow Battery Market, 2021.
[12] https://invinity.com/first-flow-battery-qualifies-for-gb-frequency-response-market/
[13] https://invinity.com/flow-battery-response-time/

often less durable, but cheaper LFP is used. High temperature sodium-sulfur and sodium-metal halide (ZEBRA) batteries that operate at temperature around 300 °C, although old technologies, they proved their usefulness in the application. The R&D&I focusses on cost reduction, new battery system designs, integration/connection to the grid, optimisation and digitalisation of battery operation, batteries durability.

- Power management (peak shaving, shifting electricity consumption to lower price period, etc.): batteries with capacity power and cycle life optimised for given application, should allow for high number of rather deep charge/discharge cycles. The technology is mature, at TRL 9, however those applications are just gaining popularity in the recent years profiting from new battery chemistries availability, and still a market is expected to expand quickly. Those batteries are dominated by Li-ion family members, mainly LFP, NMC or NCA, however some older designs like sodium-sulfur and ZEBRA batteries (still being subject to further R&I) are also in use. The R&D&I focusses on cost reduction, new battery designs and batteries durability.
- Backup power: batteries optimised for long periods of stand-by at full charge, able to provide required power in short fraction of second, working basically at 100% SoC, with limited cycle life but long calendar lifetime. The number of deep discharges with DoD exceeding 50% is usually limited and depending on the application, but it might be that the battery is performing only deep discharge cycles, approaching its whole available capacity. It is a well mature technology at TRL 9. It is dominated by advanced Pb-A chemistry. The R&D&I focusses on cost reduction, using secondary raw materials (recycled lead), enhancement of durability and safety, screening potential alternative chemistries.

Portable application batteries (usually for small electronics) constitute a very broad and diversified family, composed of universal batteries of general use (AA, AAA, etc.) of both primary and secondary type; and specialised family members designed and fabricated for a particular model of electronic appliance.

- Primary batteries of general use, mostly in AA, AAA or other standard format, usually zinc-carbon or alkaline batteries, known also as 1.5 V battery. Other chemistries also possible for more specialized applications, e.g. primary lithium batteries (3 V). This technology is mature, TRL 9. The development is oriented on cost reduction.
- Button or coin cells of general use, usually standard alkaline, silver or zinc-air (Zn-air) batteries, also lithium primary or rechargeable Li-ion versions available. Mercury batteries – the chemistry popular for coin cells in the past, are not used anymore and are forbidden in the EU[14] for toxicity and environmental effects of mercury. This technology is mature, TRL 9. The development is oriented on cost reduction, in case of Zn-air batteries also increasing power and reducing drying out in periods when unused. The button cells format create a health issue for small children if swallowed, creating internal burns and/or releasing their content. There is a discussion on how to prevent this problem.
- Secondary (rechargeable) batteries of general use, mostly in AA, AAA or other standard format, usually Ni-MH chemistry with aqueous electrolyte, known also as 1.2 V rechargeable battery. This technology is mature, TRL 9. The development is oriented on cost reduction and increase of durability.
- Secondary (rechargeable) batteries for dedicated applications (cell-phone or laptop batteries, cord-less tools batteries and similar), single cell batteries for dedicated appliance or battery composed of few cells of standard format (e.g. 18650) connected together in a battery pack that is designed for dedicated appliance or a family of products.[15] Usually LCO, NMC, NCA or LFP chemistry. This technology is mature, TRL 9. There is still an intense R&D&I oriented on new products, increase of energy density, increase of fast charging capabilities, enhancement of cycle life, cost reduction, safety. New chemical formulations are also being developed.

[14] Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC

[15] https://www.powerforall-alliance.com/en/

TRL levels for selected battery technologies

Table 1. TRL levels for Li-ion chemistries, including some non-Li-ion – 2021. For details see Annex I.

Chemistry				
Cathode	Anode	Electrolyte	Generation[16]	TRL
Li-ion				
LFP	C	Organic liquid	1	9
NCA	C	Organic liquid	1	9
NMC111	C	Organic liquid	2a	9
NMC532	C	Organic liquid	2b	9
NMC622	C	Organic liquid	2b	9
NMC622	C/Si (5-10% Si)	Organic liquid	3a	9
NMC811	C/Si (5-10% Si)	Organic liquid	3a	9
HE-NMC	Si/C (>10% Si)	Organic liquid	3b	9 in 2025
HVS (LNMO)	Si/C (>10% Si)	Organic liquid	3b	9 in 2025
LCO	C	Organic liquid	-	9
LMO	C	Organic liquid	-	9
	LTO	Organic liquid	-	9
BMLMP	NA	NA	-	6
ASSB Li-ion				
LCO, NMC, LMO, NCA	Si/C (>10%)	Solid state	4a	5-6, 9*
LCO, NMC, LMO, NCA	Li metal	Solid state	4b	5-6
ASSB Li-S				
Li_2S	Li metal	Solid state	4	4, 9**
Li-air				
O_2	Li metal	Different considered	5	4
Na-ion				
PBA	HC	Organic liquid	-	9***
Redox-Flow (RFB)				
Vanadium RFB (VRFB)			-	9
Iron RFB			-	9
Zinc-bromine RFB (ZBRFB)			-	9
Zinc-bromine non-RFB			-	9
Organic RFB			-	4-5
molten salt batteries				
sodium-sulfur battery			-	9
sodium–nickel–chloride battery / sodium–metal–halide / ZEBRA battery			-	9

[16] Nationale Plattform Elektromobilität: Roadmap integrierte Zell-und Batterieproduktion Deutschland, Jan. 2016

Liquid metal / liquid calcium (Ambri) battery	-	6-7

TRL 9* - the TRL 9 is achieved for some market segments (e.g. earbud, wearables) or special operation conditions (e.g. BlueSolution by Bolloré)
TRL 9** - the TRL 9 is achieved for some niche applications (e.g. space, military)
TRL 9*** - the TRL 9 is achieved only in 2021 and still at initial sage of wider technology deployment.

Source: JRC analysis.

2.2 Installed energy Capacity, Generation/Production

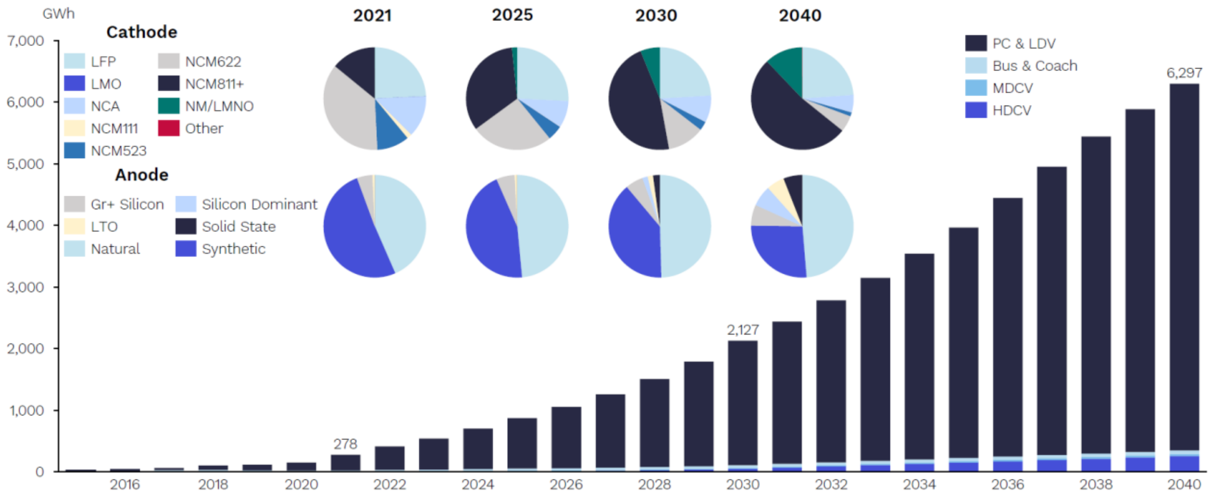
Over 90% of clean energy transition-related additions to battery capacity in EU were related to e-mobility in 2021[17]. The typical use pattern of stationary batteries is different from that of batteries in mobility application. The stationary systems are used for longer time, doing more charge/discharge cycles in their life thereby accounting for more energy throughput per installed capacity. They are also in more regular use, performing the charge/discharge cycles at (usually) daily basis and are (dis)charged at lower and more stable C-rates. Also the typical depth of discharge may differ. Stationary batteries will play an important role in supporting fast-charging of EVs.

Mobility application batteries in contrary are designed for shorter lives (less cycles and shorter calendar life) but more irregular uses, including often days without service, fast charging events, variable discharge rates to follow the traffic requirements, variable weather conditions, vibrations etc.

Capacity installed: batteries for mobility applications

The capacity of all batteries installed worldwide in vehicles in 2021 was 278 GWh. It is expected that annual installations will exceed 2 100 GWh by 2030, and more 6 300 GWh by 2040. Most of this increase will be due to increase of the market of personal and LDVs. The chemistry evolution analysis suggest that currently dominating NMC622 will decrease, replaced by NMC811+ (NMC811+ is the name grouping high nickel chemistries, NMC811, NMC955, NMCA) that is already appearing on the market and growing. LFP – the second most popular cathode chemistry will keep its market share. NCA and NMC532 formulations will be slowly pushed out of the market. From 2025 new NMC-related formulations and LMNO are expected to become available, and slowly will catch their market. On the anode side, the synthetic graphite will lose market share, while the natural one will keep stable. Graphite+Si blends will slowly gain market. From 2030, it is expected that silicon dominant blend with graphite and LTO will start to gain market share.

Figure 1. EV battery demand outlook in division per vehicle class and chemistry



Source: RhoMotion, EV & Battery Quarterly Outlook Q4 2021, 2021

[17] Derived from ACEA data on EV sales and EMMES data on stationary storage deployments (excluding pumped hydro)

Car sales

During 2021 China has accelerated sales of electrified vehicles reaching 3.3 million units and outperforming EU with 2.3 million and US at 0.63 million. The EU share of electrified vehicles in the market was 18% and still remains higher than in China (16%), however the distance has significantly shortened.[18] The US market share of electrified vehicles more than doubled in 2021 reaching almost 4.3%, still however remaining one fourth of the EU share.[19] 2022 forecasts give 9 million units for worldwide market with >50% belonging to China. This indicates a faster growth of the Chinese market than estimated earlier, and faster than in the EU.

The EU registration data of new vehicles indicate that the fast increasing trend of electrified vehicles registrations that started in begin 2020 is continued, exceeding 400 000 vehicles in Q1 2022, about 20% increase comparing to Q1 2021. The EU new registration leader (in terms on absolute numbers) is DE, followed by FR, SE and IT, while in market share terms the leader is SE, followed by DK, Fi and NL. The share of BEVs and PHEVs is almost half-by-halve with slightly more BEVs and faster growth comparing to PHEVs. The similar proportion is observed in all EU MS, with only few exceptions (BE, ES, SE, DK, FI) where the number of PHEVs exceed that for BEVs; opposite situation is observed in NL and AT. The data for the first quarter of 2022 indicate a potential for new records in 2022. The Q1 2022 EVs market share was 10.0% followed by 8.9% share for PHEV, both reaching historic heights.

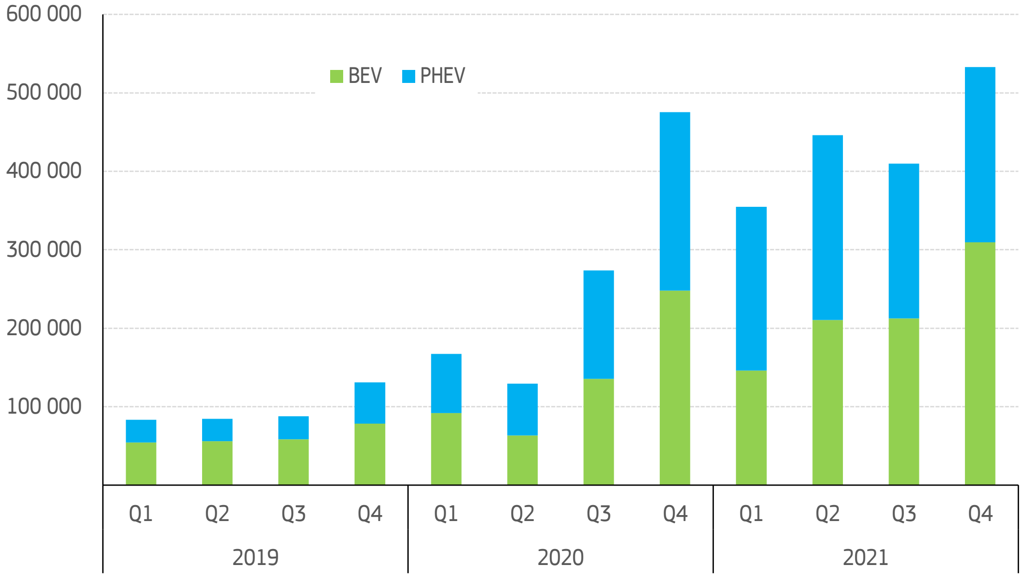
More than 50 million (with at least 1.5 TWh of batteries summary capacity)[20] EVs are expected on EU roads by 2030.[21] The EU Council has recently agreed an EU-wide ban on sale of conventional, ICE cars from 2035.

European Alternative fuels Observatory EAFO (2021 M1+N1 data) reports 270 million of passenger cars, in this 2.18 million of EVs and 1.85 million of PHEVs (0.81% and 0.68% respectively).[22]

During 2021 the number of electrified vehicles on the EU roads almost doubled reaching four millions, an equivalent of almost 150 GWh storage capacity given an average battery capacity of 55 kilowatt-hours (kWh) for BEVs and 14 kWh for PHEVs.[19]

The further growth of PC + LDV EV sales in EU is expected to reach 3.5 million vehicles in 2025 (31% of all vehicles in this class sold in 2025), 7 million in 2030 (55%) and about 11 million in 2040 (87%).[31]

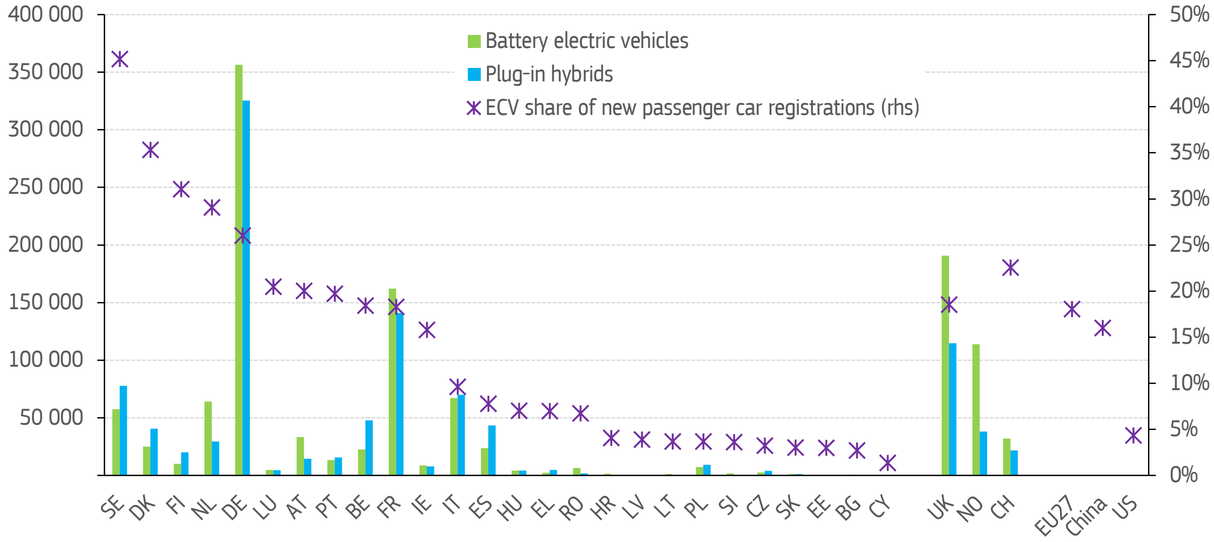
Figure 2. EU quarterly sales of electrified vehicles.



Source: EU based on ACEA data.

[18] ACEA, 2022.
[19] IEA Global EV outlook 2022, 2022
[20] Policy scenarios for delivering the European Green Deal, Fit for 55 package, European Commission, 2021
[21] central MIX scenario of the Fit for 55 proposals
[22] https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27

Figure 3. Electrified vehicles sales in EU member states and selected world markets.



Source: EU based on ACEA data.

Capacity installed: e-buses and heavy-duty vehicles

Global e-bus registrations increased by 40% in 2021 and reached 92 000 vehicles. The market is dominated by China with 93% share (86 000 vehicles, 26% of China bus market), followed by Europe – 3.6% (3 100 vehicles, 10% of Europe bus market) and US – 1.5% (1 300 vehicles, about 1% of US bus market). India is finalising a tender for 5 500 e-buses, which will place it high in the rank. The global stock of e-buses reached 670 000, 4% share of all buses world-wide.

The world e-bus market is expected to reach 300 000 in 2025 and 390 000 in 2030. The e-bus stock will reach 1.7 million in 2025 and 3 million in 2030.[19]

In EU in 2021 France was the leading market for electric buses with 622 units sold (+247%), followed by Germany (613 units; +58%) and Denmark (224 units; +3 633%). The Netherlands lost its first position from 2020 after its sales fell by 58% in 2021. The EU stock of e-buses reached 6 150 units, 0.9% of the whole bus fleet.

Global electric heavy duty (N2+N3) vehicle registrations doubled in 2021, reaching 14 200 units (0.3% share in new registrations) and global stock reached 66 000 vehicles (0.1% share). China continues to lead, with about 13 000 new registrations in 2021, a 150% increase year to year. Electric heavy duty vehicle registrations in Europe reached 650 vehicles and in the United States increased to about 450 vehicles. The electric trucks are still below 1% of sales in both. The EU stock of heavy duty vehicles is 6.2 million units, 0.24% of which are electrified. The projections expect faster development of the EV HDCV market about 2027.

The EU's leading truck manufacturers and climate researchers agreed in December 2020 that by 2040 all new trucks sold must be fossil free[23].

Capacity installed: maritime applications

Total number of battery propelled (pure electric, plug-in and hybrid) ships in EU (in operation and ordered as of 2022) reached 143, almost 25% of the world fleet counted to 578 vessels. The global leader is Norway with 251 vessels. Most often those are car/passenger ferries (257 worldwide), offshore supply ships (73 worldwide) and other purpose ships (152).[24]

[23] ACEA, All new trucks sold must be fossil free by 2040, 15 December 2020

[24] https://alternative-fuels-observatory.ec.europa.eu/transport-mode/maritime-sea/vessels

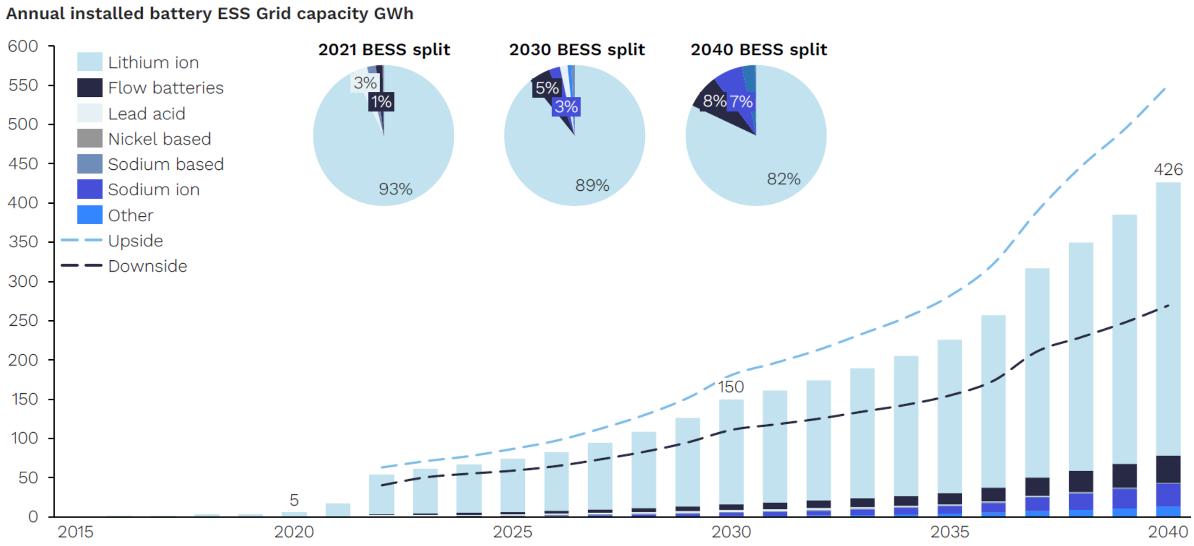
Capacity installed: stationary batteries for clean energy transition

Global situation

World-wide 10 GW / 22 GWh of battery storage was deployed in 2021. Global cumulative instalments reached 27 GW / 56 GWh[25] in 2021.

In 2021, 93% of the BESS installed at grid scale were based on Li-ion technology. 3% were still Pb-A and 1% were RFBs based. All remaining technologies accounted for 3%. The role of RFBs, Na-ion and other Na-based chemistries (Na-S, ZEBRA) will increase in the future, pushing Pb-A technology out of the market and reducing the domination of Li-ion, e.g. in begin 2022 the Japanese grid operator approved Na-S based system (from NGK) to provide balancing services including frequency response.[26]

Figure 4. Grid scale BESS global outlook by chemistry type.



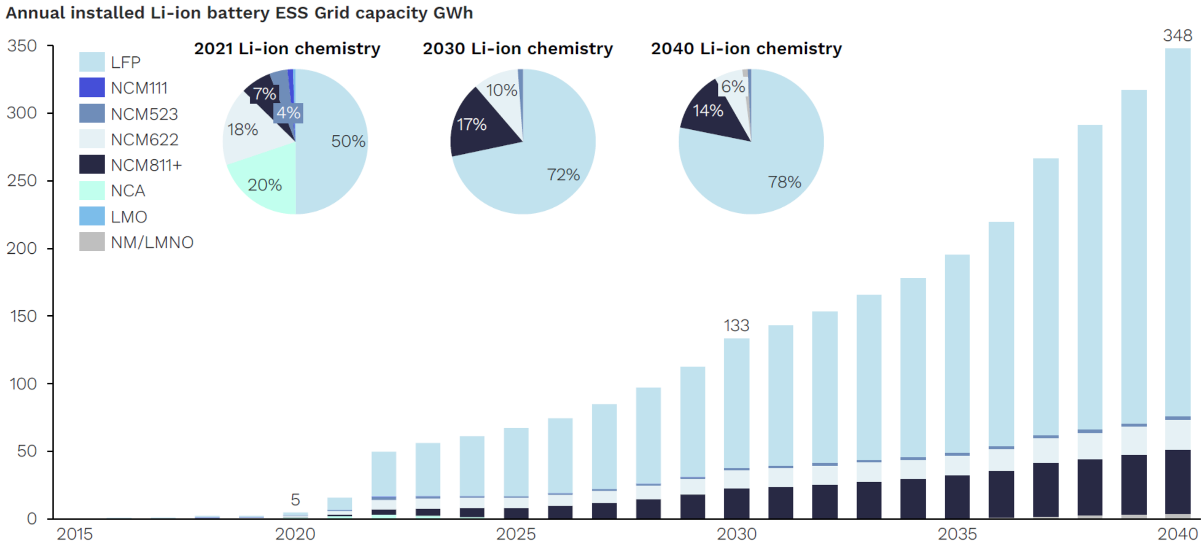
Source: RhoMotion, Battery Energy Stationary Storage Outlook Q1 2022, 2022.

Looking more in detail into the Li-ion technology, it should be noted that in 2021 the dominating (50%) chemistry was LFP, followed by NCA (20%), NMC622 (18%) and NMC811+ (7%). In future, the role of LFP will increase, NMC811+ will be peaking around 2030 and later decrease, due to the high cost of Ni and Co. NMC622 will start to decrease before NMC811+.

[25] Energy storage news based on BNEF, April 2022

[26] https://www.energy-storage.news/vehicle-to-grid-and-sodium-sulfur-batteries-win-right-to-provide-grid-balancing-in-japan/

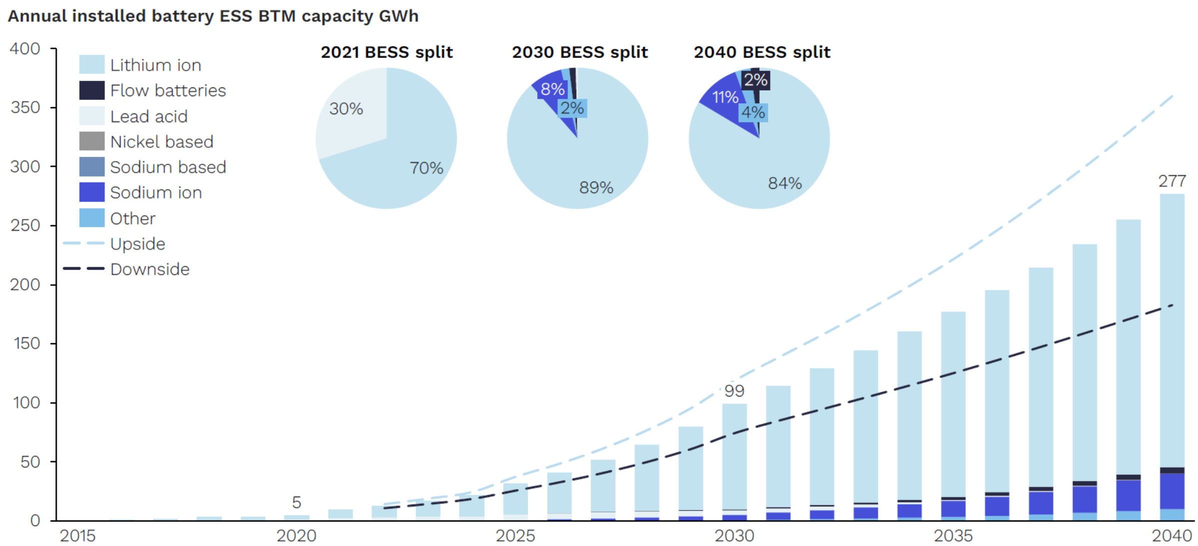
Figure 5. Global grid scale Li-ion BESS outlook by chemistry.



Source: RhoMotion, Battery Energy Stationary Storage Outlook Q1 2022, 2022.

For behind the meter storage, the 2021 market split was 70% for Li-ion and 30% for Pb-A, however it is expected that Pb-A will lose market share. Most of this space will be taken over by Li-ion, which will reach 85-90%, Na-ion will reach 8% and remaining few per cent will go to RFBs and "other" category.

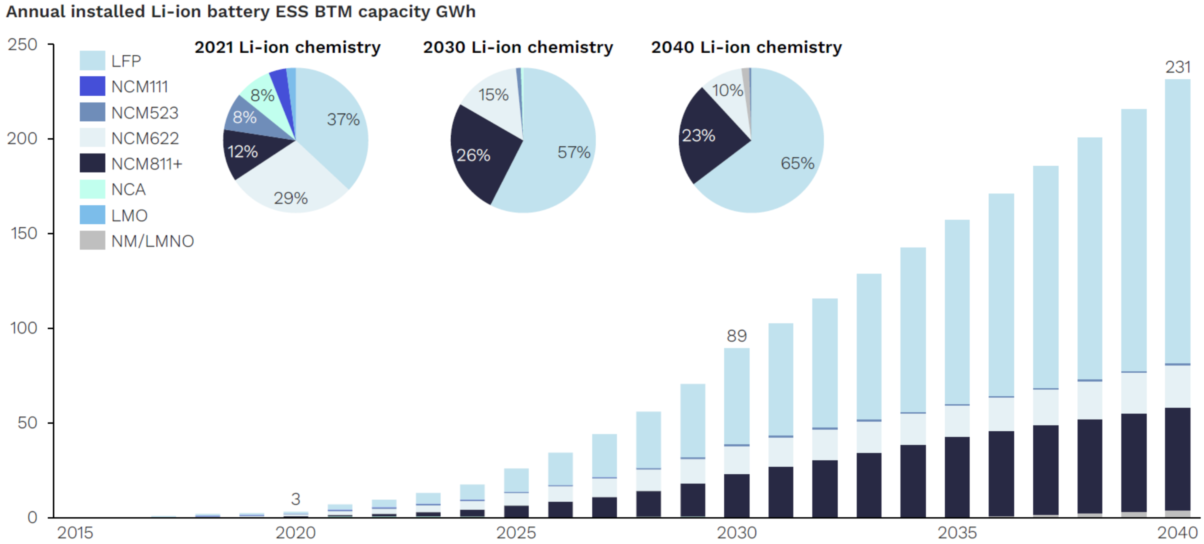
Figure 6. Behind-the-meter BESS outlook by technology type.



Source: RhoMotion, Battery Energy Stationary Storage Outlook Q1 2022, 2022.

Dividing the Li-ion technology into smaller chemistry groups, it can be noticed that currently the market is divided between several chemistries: LFP is leading (37%), followed by NMC622 (29%), NMC811+ (12%), NMC532 and NCA (8% for each) and a little of NMC111 and LMO. In the future, this variety will be reduced and the market will concentrate on three chemistries: LFP (about 60%), NMC811+ (25%) and ca. 10-15% of NMC622.

Figure 7. BTM Li-ion BESS outlook by chemistry.



Source: RhoMotion, Battery Energy Stationary Storage Outlook Q1 2022, 2022.

Europa and MS

In Europe the total annual energy storage market reached 2.2 GW / 3.7 GWh in 2021,[27] more than doubling the annual storage deployments seen in 2020. The global storage market reached 26 GWh at the same time. In the short term (2022), the EU BESS deployment will be about 6.0 GWh, which will be far behind US (23 GWh) and China (30 GWh) and less than 9% of global deployment (66 GWh). In the long term, the EU is expected to reach 160 GWh / 80 GW of stationary batteries by 2030[20] and a market share in global BESS deployment might slightly increase and reach about 15% of in 2040. The global market of battery energy storage systems (BESS) is anticipated to double every 3 years in the period from 2020 to 2040.

Table 2. EU new and cumulative installations.

power [MW] / energy capacity [MWh]		
	annual	cumulative
2020	907 / 1 606	2 408 / 3 951
2021	2 182 / 3 738	4 590 / 7 688
2022	3 393 / 6 044	7 983 / 13 733

Source: EASE/EMMES 6.0.

While Europe outpaces both China and the US for renewable energy capacity growth, it is not the case for stationary battery deployment. The EU has a much more robust and dense electricity grid, limiting dependence on storage. With required fundamental rebuilding of the EU energy systems aiming at mitigation climate change and limiting dependence on external energy carriers, the situation may significantly change. For the moment, however, the trends of the markets growth do not indicate that EU may outpace or even approach other regions, particularly US and China. In EU the BESS deployments are dominated by front of the meter systems. The grid level installations are also dominating the US and Canada markets while in China and RoW the grid scale installations and BTM systems are adding similar storage capacities.

In EU, Germany stands out with the largest number of *home battery systems* installed every year, with cumulative capacity reaching about 3.4 GWh across more than 400 000 households by the end of 2021.[10] In Germany, battery storage systems are installed in over 70% of today's residential solar installations. Most German federal states support storage through direct upfront subsidies, typically with energy content-based incentives ranging between EUR 200–300 per kWh. More importantly, and as opposed to some Member States,

[27] EASE/EMMES 6.0

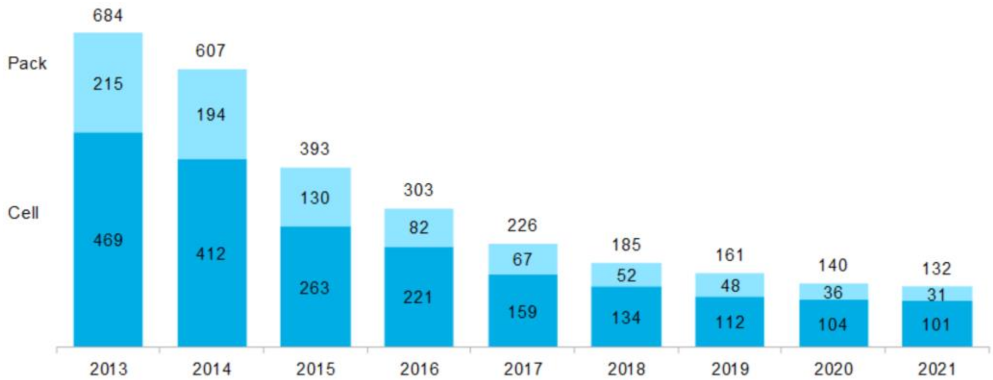
Germany does not employ full net metering support schemes for residential PV installations[28] which dis-incentivise self-consumption and the installation of battery energy storage systems. Promoting self-consumption has gained Germany two-thirds of the EU residential battery storage market.[29] The home storage systems market recently has speed up also in Italy.

2.3 Technology Cost – Present and Potential Future Trends

A growing demand for Li-ion batteries from the automotive sector, and on the supply side growing production capability, including effect of scale, development of supply chains, competition etc. are the main drivers shaping prices of Li-ion batteries, which are decreasing over the last years. According to the BloombergNEF's annual battery price survey, battery prices fell from above USD 1 200/kWh in 2010 by 89% in real terms to USD 132/kWh in 2021, including an annual drop of 6% from USD 140/kWh in 2020.[30] These prices represent an average across all applications, including different types of EVs, buses and stationary storage. For BEV packs, the 2021 price was $118/kWh on a volume-weighted average basis. At the cell level, average BEV price was $97/kWh. BloombergNEF also report the regional price differences: battery packs were cheapest in China, at $111/kWh while in the U.S. and Europe the cost was respectively 40% and 60% higher (implying the cost of up to EUR 150 per KWh in the EU) . This difference reflects the relative immaturity of US and EU markets and differences in shares of end-uses.

Price reduction in 2021 reflects also the wider use of low-cost LFP cells instead of more expensive NMC. On average, LFP cells were almost 30% cheaper per kWh than NMC cells in 2021. The Li-ion batteries price decrease trend has been disturbed at the end of 2021 due to supply-side shocks (e.g. lithium carbonate prices rose almost 10-fold in spring 2022 y/y). This effect is expected to increase the price of batteries by 15% in 2022.[19] This increase is however expected to be a short term, and the prices should continue the decreasing trend after about 2 years, at least in real prices.

Figure 8. Volume weighted average pack and cell price split (real 2021 USD/kWh).



Source: BloombergNEF, Nov 2021

Battery cost – mobility applications – road transport

BNEF predicts that by 2024, average EV pack prices should fall below $100/kWh. This should allow automakers to produce and sell mass-market EVs at the same price as comparable ICE vehicles in some markets (assuming no subsidies, but actual pricing will vary by automaker and geography).

In short term, however, high raw material prices can cause average pack prices rise to $135/kWh in 2022 in nominal terms, what could delay the point at which prices fall below $100/kWh by about two years (with general prices increase, this should be seen in fixed prices' terms only). RhoMotion provide data consistent with BNEF and predict that the EV battery system cost in EU for LFP chemistry will fall to 100 USD/kWh in 2030.

[28] With the retail electricity rate for households being about 0.30 EUR/kWh for many years now, and the feed-in tariff offered by the EEG continuing to go down steadily on a monthly basis, the value for increasing self-consumption is high. Furthermore, PV systems may export only up to 60% of their electricity production on the EEG feed-in tariff, incentivising homeowners willing to install higher capacity PV systems to invest in a coupled BESS.

[29] Solar Power Europe, European market outlook for residential battery storage 2020-2024, 2020

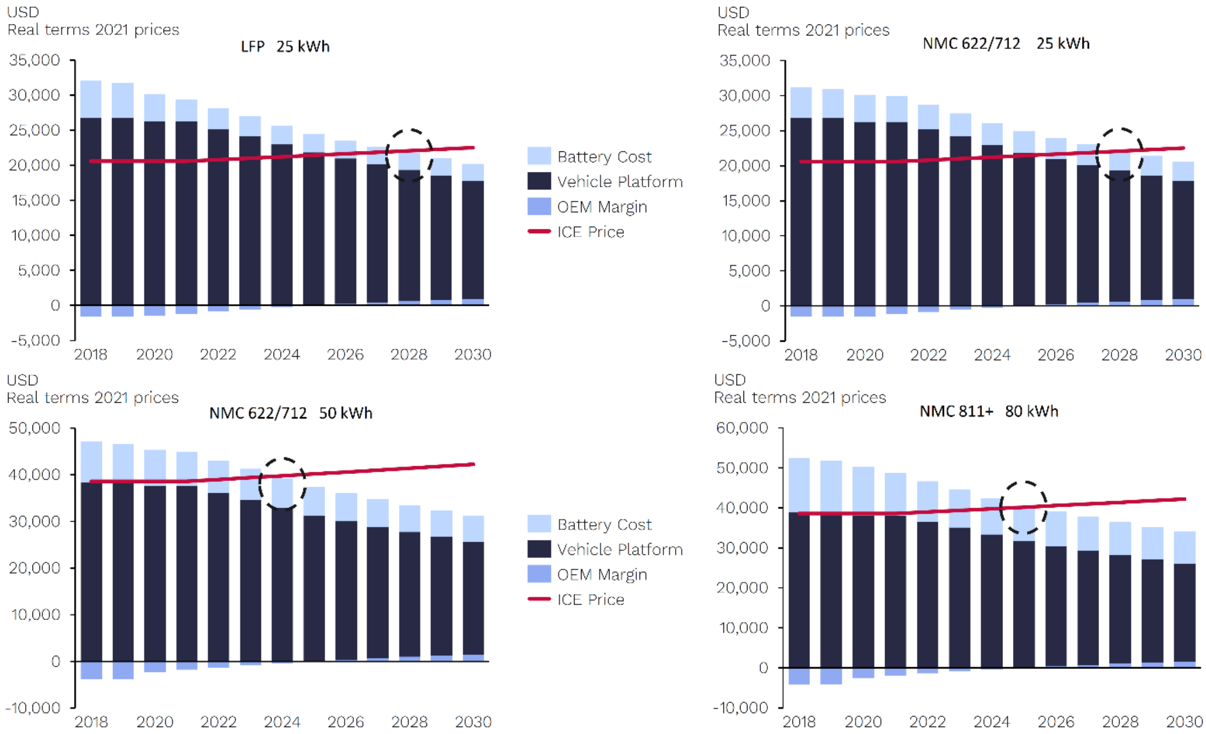
[30] https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/

In EU currently the price for EV batteries at system level vary between 125 EUR/KWh for LFP batteries up to 150 EUR/KWh for NMC622 or NMC712. Till 2030 those prices are expected to decrease to 95 to 110 EUR/KWh respectively.

RhoMotion provided also an outlook of the EV price evolution till 2030 with division between personal EV segments (small/medium/large) and also for battery cost and vehicle platform price for most relevant chemistries and presented those against ICE price outlook. The analysis shows that purchase price parity for EV/ICE vehicles is expected in 2024-2028 for different car segments, with the shortest time for middle size vehicles. Taking into account the total costs of ownership the parity of EV with ICE vehicles has already been reached in more than 60% of the MS national markets in the EU.[63] Therefore the share of government incentives in the total world-wide spending on electric cars has decreased over the last five years from over 20% in 2017 and 16% in 2018 down to 12% in 2019, below 11% in 2020 and 10% in 2021.[31]

An interesting observation is that the future price reduction of EVs is depending mostly on the cost reduction of an EV platform, with only low contribution from the battery itself. This indicates that the EVs are not really technically mature products, and there are still significant possibilities for improvements, despite being in serial production since more than 20 years.

Figure 9. Prediction of price evolution in EU of different segment EV, price parity with an equivalent IEC car indicated.



Source: RhoMotion, EV & Battery Quarterly Outlook Q4 2021, 2021.

Cost of stationary Li-ion systems

Worldwide Li-ion batteries make up about 90% of stationary battery storage market. The prices for stationary Li-ion systems are dropping, but the cost reduction has been slower than in road transport sector. There are a number of additional cost components (e.g. inverters, balance of system hardware, soft costs such as engineering, procurement and construction) that come into play, and there are many use cases with different requirements. Today, the whole system costs between 300 and 400 €/kWh (for grid-scale applications),[32] depending on configuration of the storage system out of which the cost of Li-ion battery system is between 100 and 140 €/kWh depending on the chemistry. The cost of other types of battery storage systems varies from 150 to 400 USD/kWh, depending on technology for Pb-A and Zn-Br RFBs respectively.[10]

[31] *RhoMotion, EV & Battery Quarterly Outlook Q4 2021, 2021*

[32] Aurora Energy Research, How high can battery cost get?, 2022

Reducing BESS cost is key for mass deployment throughout Europe, even if current energy crisis contributes to competitiveness of BESS solutions. There are environmental, economic and political driving forces to substitute large conventional thermal power plants by a combination of renewables electricity generation and batteries.

BESS market solutions are less developed than EVs and thus, it may be expected that the potential for cost reduction is relatively higher than in mobility applications. Increasing market maturity will reduce cost. As battery cells are more mature than BESS solutions, costs reductions are expected to focus on integration, balance of system and auxiliaries. Despite expected reductions of BESS prices in longer term, in 2022 an increase is projected due to strong increase of raw materials prices and general increased inflation. In longer term the prices are expected to come back to the decreasing trend (in fixed prices).[32]

Home batteries with a storage capacity of ~10 kWh cost 600 – 2 000 USD/kWh, i.e. twice or even more expensive than grid scale installations.[10] Nevertheless, they often already pay off, especially in the southern EU regions. With sufficiently high irradiation factors and difference in electricity price and feed-in tariff of ~EUR 0.15 per kWh or more, the pay-back time of home batteries is less than 10 years. An even higher difference between electricity and feed-in prices in Germany, coupled with public support for deployment of storage, make Germany the largest European market for home batteries.

2.4 Public R&I funding

The data on public support of battery R&I is not readily available for most countries, especially in Asia. Thus, an assessment of the relative EU position in this respect is not possible.

The analysis for the EU is performed on the basis of JRC TIMS (CORDIS database) data from H2020 projects and available data from HEU. This also mean that some data from 2021 are not available, if the grant agreement signature is still ongoing.

Public R&I funding in EU is rising considerably. Under the Horizon Europe programme, EUR 925 million have been earmarked for collaborative research on batteries for the period 2021-2027 - to be implemented through the Batteries Partnership.[33] This is almost twice the funding under Horizon 2020. A continuation of the Battery 2030+ initiative, focused on ICT based research, is now funded under the Batteries Partnership within Horizon Europe. In addition, the battery integration is funded under the 2 Zero partnership - a partnership to achieve carbon-neutrality in road transport, European Partnership for Zero Emission Waterborne Transport, Clean Sky partnership and other headings of Climate, energy and mobility work programme of Horizon Europe (e.g. many calls related to renewable energy and smart energy systems will support innovative deployments of stationary batteries and EV integration aspects not covered by specific partnerships). Horizon Europe funding will also allow to step up support to the European Technology and Innovation Platform Batteries Europe to foster a common R&I agenda throughout EU and facilitate its implementation in a coordinated way. Batteries Europe platform has become R&I coordination strand of the European Battery Alliance. The Community Research and Development Information Service (CORDIS[34]) data analysis covering years 2014-2021 show that the public support from EU to the projects developing different battery technologies was more than 405 million EUR, and the number of supported projects reached 167. The table below show the distribution of those funds between different battery technologies and end-use applications.

Table 3. EU public funding of battery R&I in years 2014-2021.

technology or application	technology or application support* [million EUR]	technology or application support* [% of total]	number of projects*
Li-ion	295.2	72.8	114
Li-ion with metallic Li anode	64.3	15.9	15
Li-ion with Si rich anode	65.1	16.1	16
solid state battery (SSB or ASSB)	47.6	11.7	19
lithium-sulfur (Li-S)	33.3	8.2	8

[33] https://bepassociation.eu/about/batt4eu-partnership/
[34] https://cordis.europa.eu/about

sodium-ion (Na-ion)	10.2	2.5	11
redox-flow (RFB)	51.4	12.7	23
lead-acid (Pb-A)	15.2	3.7	12
mobility applications	294.9	72.7	90
stationary applications	214.4	52.9	80
total battery support	405	100	167

* Usually projects focus on more than one chemistry/application, so they do not sum to 100% / total funding

Source: JRC analysis based on CORDIS data.

The main field of interest is in Li-ion batteries, so in the improvements of technology already existing on the market. Technologies being the more advanced versions of the existing technologies, like Li-ion with metallic lithium or Si-dominated anodes and solid state batteries attract similar attention, and about 10-15% of financial support. Similar attention is given to the development of redox-flow batteries. A future technology, lithium-sulfur attracted proportionally smaller attention, about 8% of financial support. Development of Na-ion batteries has not been a priority of the EU. Only 2.5% of the funds were directed to support this technology, despite the fact that it is neither relying on critical nor on expensive materials. The support to the development of lead-acid (this money however do not come from the batteries' dedicated part of the budget, but from some side streams of H2020) batteries was greater than that given to the Na-ion technology, despite the fact that use of lead in the SLI accumulators - main use of Pb-A technology is generally not allowed, but exempted until better replacement batteries are developed, see the vehicles EoL directive, 2000/53/WE. Application of batteries in mobility areas is more supported than in the stationary.

Under the H2020 Future and Emerging Technologies the initiative on Future Battery Technologies[35] was launched which resulted with e.g. 2030+ project[36] that support projects implementing the battery 2030+ roadmap.[37] It aims in accelerating the development of technologies and building a European battery cell manufacturing industry based on clean energy and circular economy. To reach this it base on EU strengths and in coordinated and collaborative environment it brings together the most important stakeholders in the industry, research, policymaking and public.

The SET Plan Action on batteries is implemented by Batteries Europe,[38] the technology platform of the European Battery Alliance which is supported by the EC since 2019.[39] Batteries Europe targets R&I activities contained in the Strategic Research Agenda (SRA) for batteries[40] and roadmaps for various segments of the value chain. The updated SRA should be seen as the new batteries implementation plan and identify gaps in funding and neglected topics which could lead to weaknesses in the value chain. A batteries were recognised as a Strategic Value Chain.[41] Batteries Europe is committed to continuously update the SRA on the basis of technological developments in the field of batteries. Batteries Europe activity lead to establishing two large Important Projects of Common European Interest (IPCEIs) on batteries. IPCEIs are not focused on R&I *per se*, but rather on raising production capabilities, however only projects fulfilling condition of minimum required innovativeness were supported, and under the IPCEIs a number of research and innovation needs were addressed. The first coordinated by France started in 2020, and the second by Germany was implemented in 2021. They involve 12 EU countries and tens of companies and research organisations across the EU, along the whole batteries value chain. IPCEIs involves both public and private funding: EUR 6.1 billion of public funding by participating member states will unlock an additional EUR 14 billion funding from private sector.

Circularity aspects, including batteries reuse and recycling are addressed under Circular Economy Action Plan[42] of the European Green Deal. This however is not the only supporting scheme, as the projects tackling the recycling aspects are also financed from all other streams of battery technologies support.

[35] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-fet_en.pdf
[36] https://battery2030.eu/
[37] https://battery2030.eu/wp-content/uploads/2021/08/c_860904-l_1-k_roadmap-27-march.pdf
[38] https://energy.ec.europa.eu/topics/research-and-technology/batteries-europe_en
[39] https://setis.ec.europa.eu/implementing-actions/batteries_en
[40] https://ec.europa.eu/energy/sites/ener/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf
[41] https://ec.europa.eu/docsroom/documents/37824/attachments/2/translations/en/renditions/pdf
[42] https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

At national level, a number of Member States are strengthening their R&I capacity. One prominent example is the Fraunhofer Gesellschaft (Germany) with its own "battery alliance", consisting of a number of institutes.[43] Other important R&I players include CEA (France), ENEA (Italy), CIC energiGUNE (Spain) and many others.

2.5 Private R&D funding

Private Equity refers to capital investments made into companies that are not publicly traded. Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. More details on the methodology in the footnote.[44]

In 2010-17 period a 76% of battery innovators identified globally were corporations. Among the top five countries that host 74% of identified innovators, this is the case for Japan (2nd), Germany (4th) and South Korea (5th). Only the US (1st) and to some extent China (3rd) report a significant base of venture capital companies. In the EU, which accounts for 22% of the identified innovators, most is hosted by Germany, France and the Netherlands. Automakers and battery manufacturers often invest in start-ups to get access to their technologies.

In 2021, global VC investments in battery developers reached all time-highs, amounting to € 10.6 billion which is more than all investments realised since 2010. Both early stage and later stages investments were covered. Few large deals in battery manufacturers from Sweden (Northvolt, € 2.6 billion, later stage VC) and China (Svolt, € 2.6 billion, early stage VC and China Aviation Lithium Battery, € 1.5 billion, PE growth) were executed in 2021. As of Apr 2022 the total market capitalisation of five biggest start-ups analysed by BNEF (QuantumScape, Enovix, Li-Cycle, Solid Power and SES) reached 12.3 billion USD.[45]

The start-up companies are active on all fields of batteries R&I, from evolutionary improvements of existing technologies to break-through chemistries, called as post Li-ion.

Mostly funded by industry, innovation also continues on established battery technologies, such as lead-acid and nickel technologies[46].

The two IPCEIs on batteries R&I (including first industrial deployment) started in 2020 and 2021 will bring EUR 14 billion of private investment into batteries value chain development in EU (next to the public money).

Beyond R&I funding, the EU industry has invested significantly in batteries and end use integration. In total, the European Battery Alliance has generated investments of EUR 127 billion.

2.6 Patenting trends

Data analysis: JRC based on data from the European Patent Office (EPO), patent data based on PATSTAT database 2021 autumn version (JRC update: February 2021). CPC codes: Y02E 60/10, Y02T 10/70, Y02W 30/84, Y04S 10/14. The analysis considers only patent applicants. A patent family was used as a proxy of invention.

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[43] https://www.batterien.fraunhofer.de/en.html

[44] The early and later stages indicators aggregate different types of equity investments in a selection of companies and along the different stages of their growth. The companies are selected based on their activity description (keyword selection, expert review). Only pre-venture (that received Angel or Seed funding, or are <2 years old and not received funding) and venture capital companies (companies that at some point, have been part of the portfolio of a venture capital investment firm) are included.
The early stages indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed and Early stage VC1 investments; it also include public grants. At the time they raise such investments, usually they are start-ups. Those companies often rely on innovative solutions and business models, and investments aim at financing the companies' operational expenditures and investment needs until they can scale their revenues.
The later stages indicator reflect growth investments for the scale-up of start-ups or larger SMEs. It include Late Stage VC2, Small M&A3 and Private Equity Growth/Expansion.
The lists of companies include two distinct populations: VC and corporate companies. Corporate companies are companies with a patenting activity among the subsidiaries of top R&D investors from the EU Industrial R&D investment Scoreboard. VC companies are selected based on investments.
All identified companies are included irrespectively of their current operational status, investments or patenting activities, e.g. VC companies may currently be, or have been start-ups, larger SMEs that grew into larger companies, went public or were acquired by larger ones. They may also currently be out of business.
The lists represent two subsets of all market players only, the aim is however to show the dynamics of emerging innovators with growth potential and large corporates responsible for most of private R&I.
The count of companies corresponds to the number of companies active in the current period. Active corporate companies have High Value Patents over the current period. Active VC companies have either been founded (irrespectively of received investments) or have received investments (irrespectively of their founding year) over the current period.

[45] Battery Startups 2022: Key Trends, BNEF, 2022

[46] EUROBAT, Battery Innovation Roadmap 2030, 2020.

- Patent families (or inventions) measure the inventive activity. Patent families include all documents relevant to a distinct invention (e.g. applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology.

- High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.

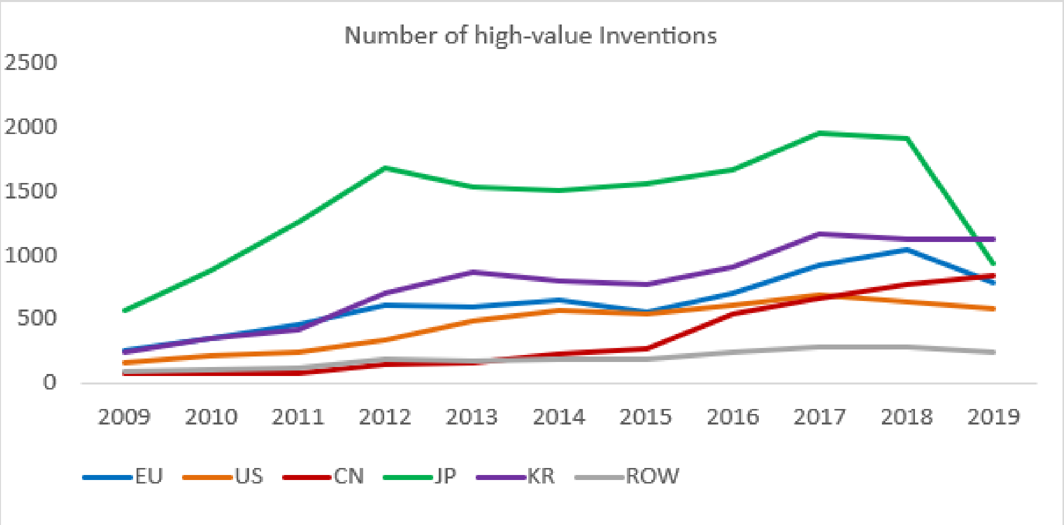
The battery specialisation index (SI) represents patenting intensity in a battery technology for a given country (region) relative to geographical area taken as reference. According to the definition, if the battery specialisation index is = 0, the intensity is equal to the world average; if it is < 0 than intensity lower than the world average; if the battery specialisation index is > 0 than the country patenting effort is higher than the world average.[47] More details on the methodology behind the indicators is available in the literature.[48,49,50,51,52]

Li-ion batteries has been developed in Japan. This is why most patent applications have been filed outside the EU, mainly in the East Asia. Japan takes the first place in the high-value inventions in perspective of the last 10 years. The second is Korea, EU is on the third place.

The significant drop of Japan (also EU) in 2019 is most probably the effect of Cov-19. The lockdown increased time of applications processing, thus 2019 applications are probably not processed/reported yet.

In 2017-2019 period the total number of inventions was highest for China (35 500, 51% share), followed by Japan (13 900, 20%) and Korea (9 100, 13%). EU (5 400, 8%) is ranked fourth, before US (3 700, 5%). The share of international and high-value inventions from China is lowest reported (2% and 6% respectively), so China is mostly protecting its own market. The international protection of Chinese inventions goes mostly to US and EU. Japan (the most internationally active country) divides its interest proportionally in equal parts to all markets. Korea focusses on US, EU and to a bit less extent on China. US also focusses on EU and slightly less on China, and RoW.

Figure 10. Number of high-value inventions by region.



Source: JRC based on EPO Patstat.

[47] A. Fiorini, A. Georgakaki, J. Jimenez Navarro, A. Marmier, F. Pasimeni, E. Tzimas (2017) Energy R&I financing and patenting trends in the EU: Country dashboards 2017 edition EUR 29003 EN, Publications Office of the European Union, Luxembourg DOI: 10.2760/605647

[48] F. Pasimeni, A. Fiorini, A. Georgakaki (2021) International landscape of the inventive activity on climate change mitigation technologies. A patent analysis. Energy Strategy Reviews, DOI: 10.1016/j.esr.2021.100677

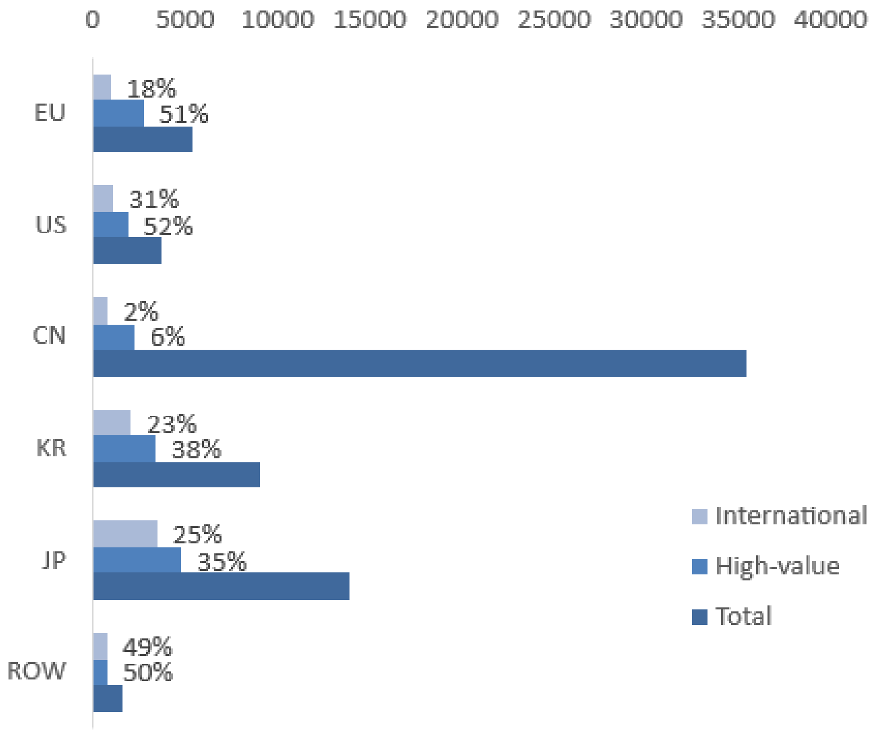
[49] F. Pasimeni, A. Georgakaki (2020) Patent-Based Indicators: Main Concepts and Data Availability. JRC121685, https://setis.ec.europa.eu/patent-based-indicators-main-concepts-and-data-availability_en

[50] F. Pasimeni, A. Fiorini, A. Georgakaki (2019) Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. World Patent Information, 59, 101927 DOI: 10.1016/j.wpi.2019.101927

[51] F. Pasimeni (2019) SQL query to increase data accuracy and completeness in PATSTAT. World Patent Information, 57, 1-7. DOI: 10.1016/j.wpi.2019.02.001

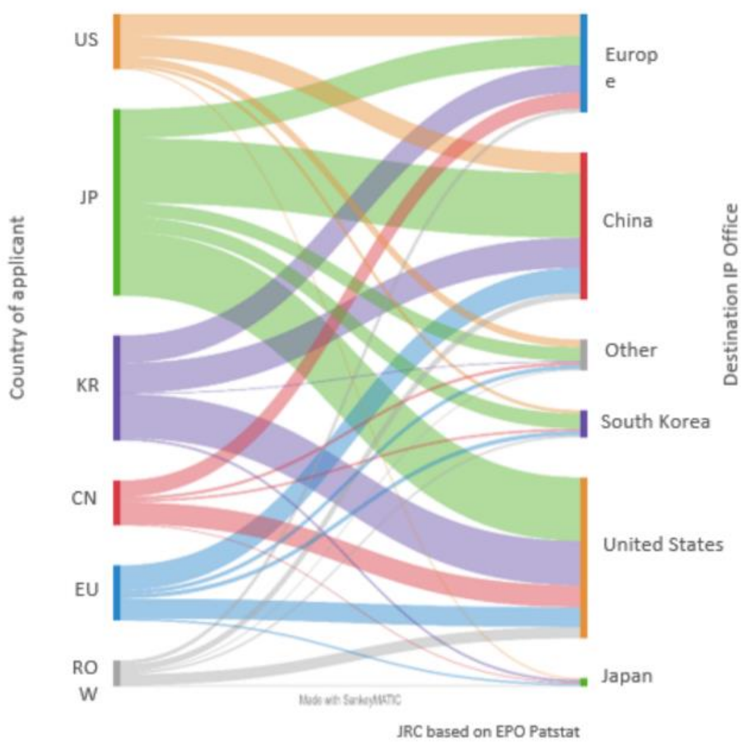
[52] A. Fiorini, A. Georgakaki, F. Pasimeni, E. Tzimas (2017) Monitoring R&I in Low-Carbon Energy Technologies. EUR 28446 EN, Publications Office of the European Union, Luxembourg, DOI: 10.2760/434051

Figure 11. Number and type of inventions by region in 2017-19 period.



Source: JRC based on EPO Patstat.

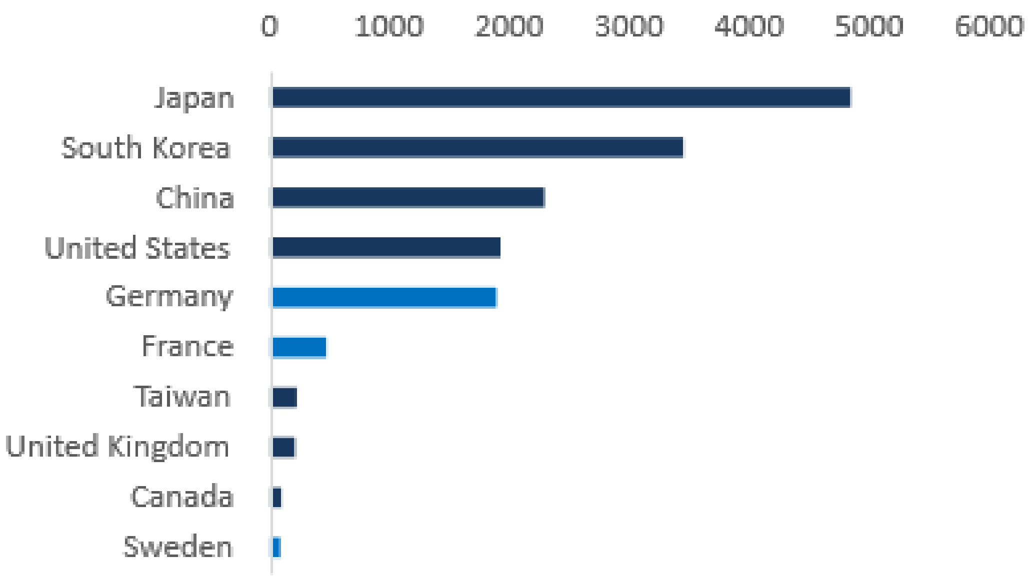
Figure 12. International protection of high-value inventions.



Source: JRC based on EPO Patstat.

Among Top 10 countries in 2017-2019 in high-value inventions three EU counties were ranked, Germany (5th place), France (6th) and Sweden (10th).

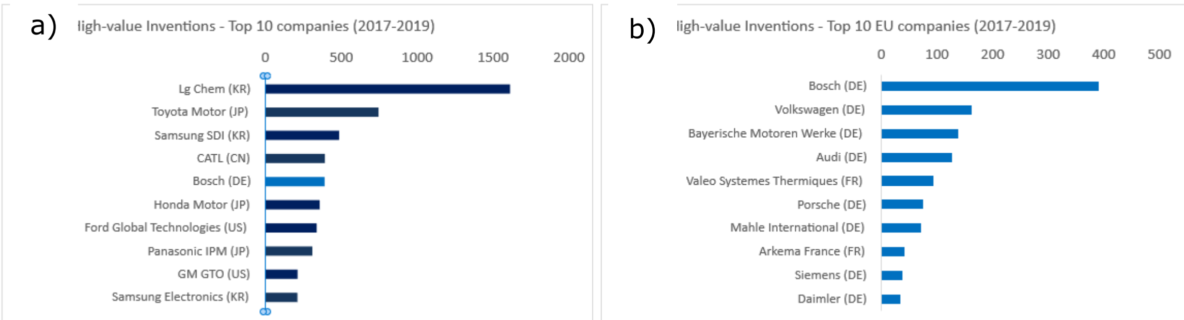
Figure 13. High-value inventions 2017-2019 - top 10 countries.



Source: JRC based on EPO Patstat

Among Top 10 companies in 2017-2019 in high-value inventions only one EU company is listed, Bosch (DE, 5th place).

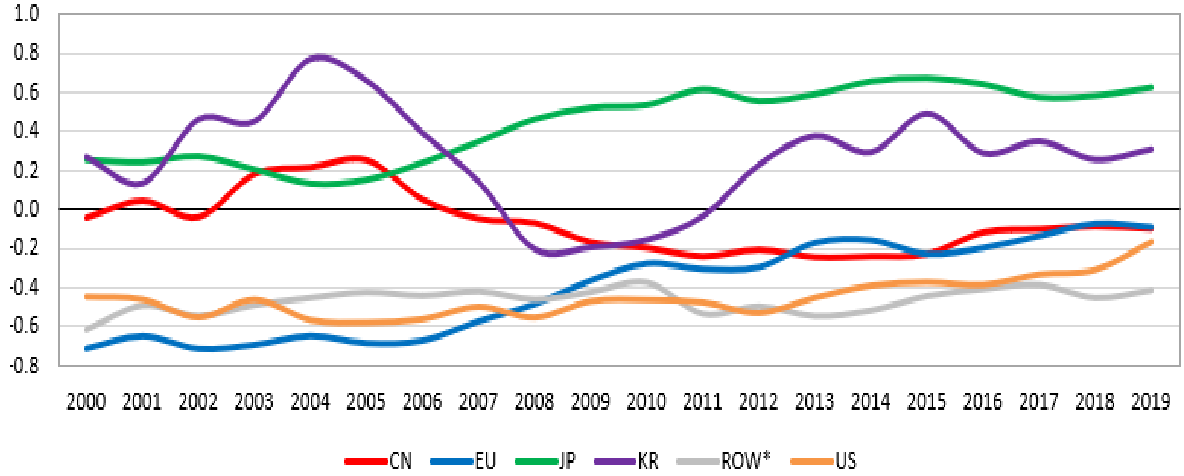
Figure 14. High-value inventions - top 10 companies, a) global, b) in EU.



Source: JRC based on EPO Patstat.

A battery specialisation index shows that Japan is leading in battery technology development continuously since 2007. Korea (leader before 2007) is on strong second position. EU is competing for the third position with China. US shows fast improvement on its 5th position.

Figure 15. Battery specialisation index.



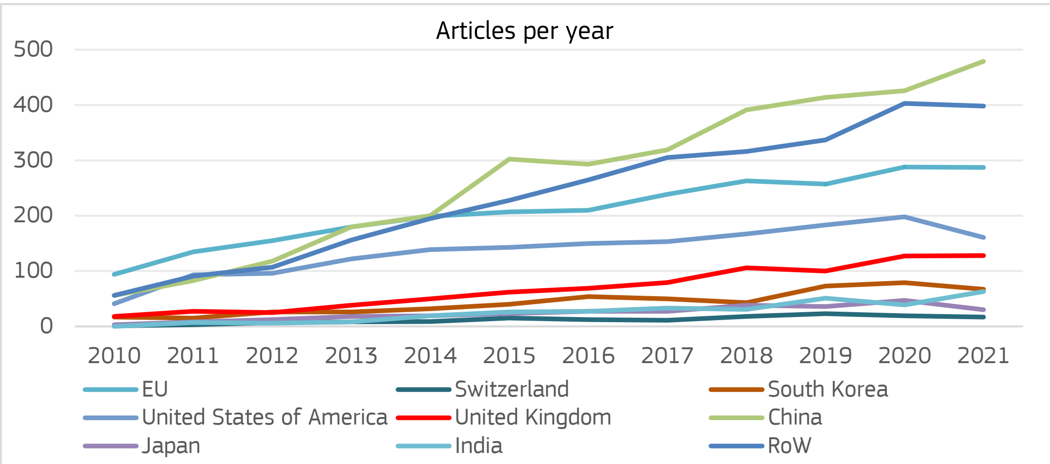
Source: JRC based on EPO Patstat.

2.7 Bibliometric trends/Level of scientific publications

The analysis is based on JRC TIM (Scopus database).[53]

Bibliometric trends for Li-ion batteries show increasing interest with this general chemistry. The leading country is China, followed by RoW, EU and US. The growth rate for China and RoW is much faster than the one for EU and US.

Figure 16. Bibliometric trends for Li-ion batteries.



Source: JRC based on TIM data.

Between the EU countries the lead holds Spain followed by Italy and Germany.

Bibliometric trends for all solid-state batteries: the trends show very fast-growing interest, especially after 2015. The leading country is China, followed by US, EU and RoW. The growth rate for China is much faster

[53] The following search queries were used:

Li-ion - topic:("lithium ion battery"~2 OR "li ion battery"~2) AND class:article;

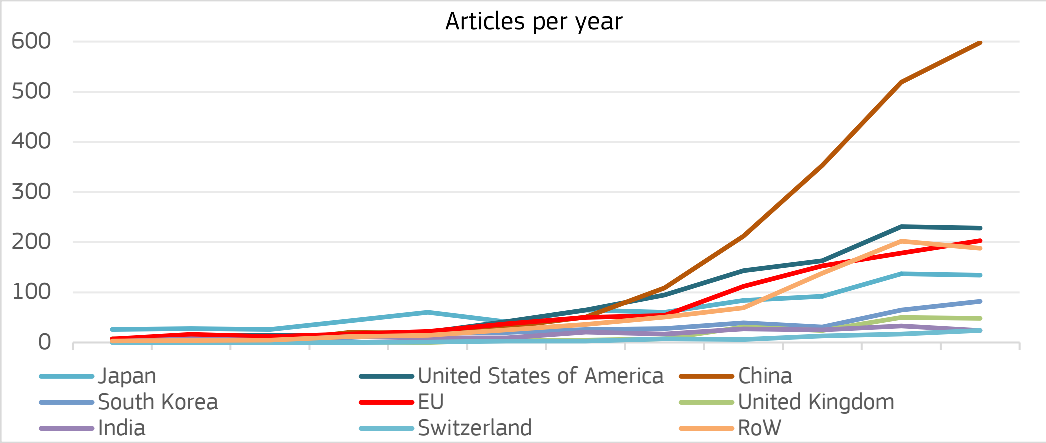
All solid state - topic:("solid state battery"~2 OR "SSB battery"~2 OR "all solid state battery"~2 OR "ASSB battery"~2) AND class:article;

Pb-A - topic:("lead acid battery"~2 OR "Pb acid battery"~2 OR "Pb A battery"~2) AND class:article;

Na-ion - topic:("Sodium-ion battery"~2 OR "Na ion battery"~3 OR "NIB battery" OR "SIB battery") AND class:article;

RFBs - topic:("flow battery" OR (("redox flow" OR VRFB) AND battery)) AND class:article than for all other countries. Between the EU countries the leader is clearly Germany followed by France and Spain.

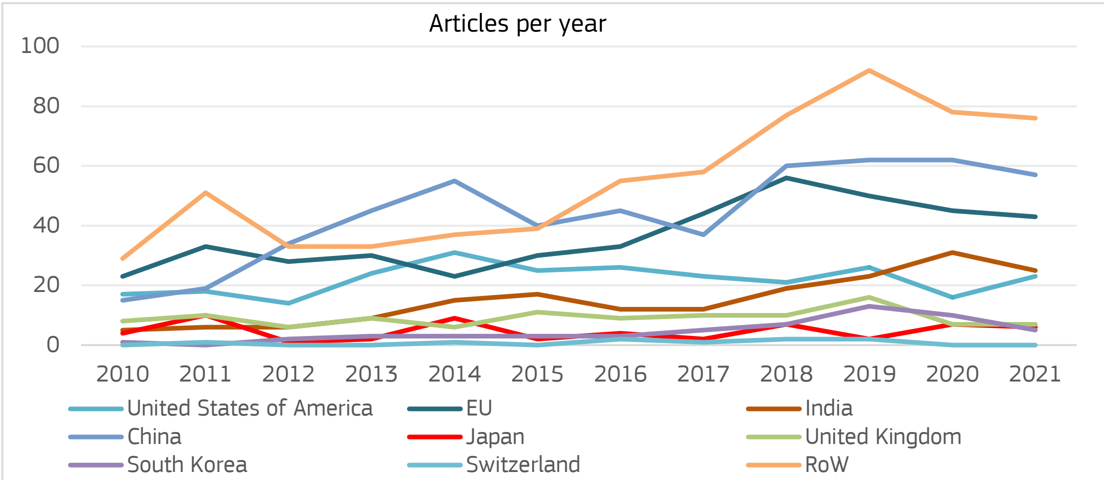
Figure 17. Bibliometric trends for all solid state batteries.



Source: JRC based on TIM data.

Bibliometric trends for Pb-A batteries the trends show limited growth or stagnation. The leader is RoW, followed by China and EU, all experiencing slow increase. US, being at similar level to India is experiencing stagnation, but in contrast India is presenting growth. Between the EU countries there's no clear leader. Spain and Germany are changing on the lead, Italy, Poland and France also keep relatively high, and several other countries are following.

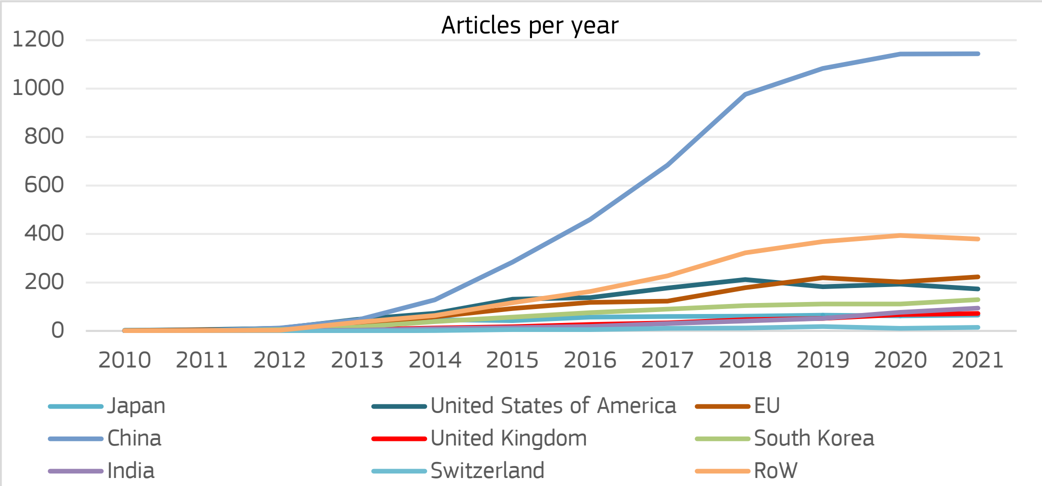
Figure 18. Bibliometric trends for Pb-A batteries.



Source: JRC based on TIM data.

Bibliometric trends for Na-ion batteries the trends show booming interest of leading China in period 2013-18, with similar trend (but at lower level of interest) appearing for RoW being on the second place, and limited growth for the third EU and fourth US. The interest in UK and India do not show slowdown in last four years as for leading China and RoW.

Figure 19. Bibliometric trends for Na-ion batteries.

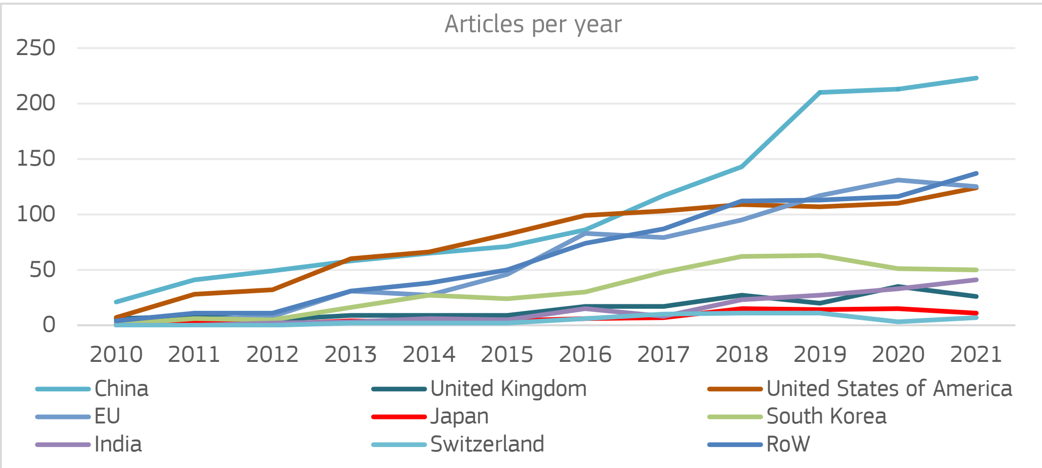


Source: JRC based on TIM data.

In the EU a clear leader is Germany that published twice as many as the second France which was just a bit better than Spain. Fastest growing country is Italy, that almost equalled with Spain. Also Sweden and Poland show some activity.

Bibliometric trends for RFBs the trends show growing interest of China – current leader, well overpassing RoW, EU and US, being at almost the same level. Fifth South Korea is just in front of India, which since 2017 present clearly growing interest.

Figure 20. Bibliometric trends for redox-flow batteries.



Source: JRC based on TIM data.

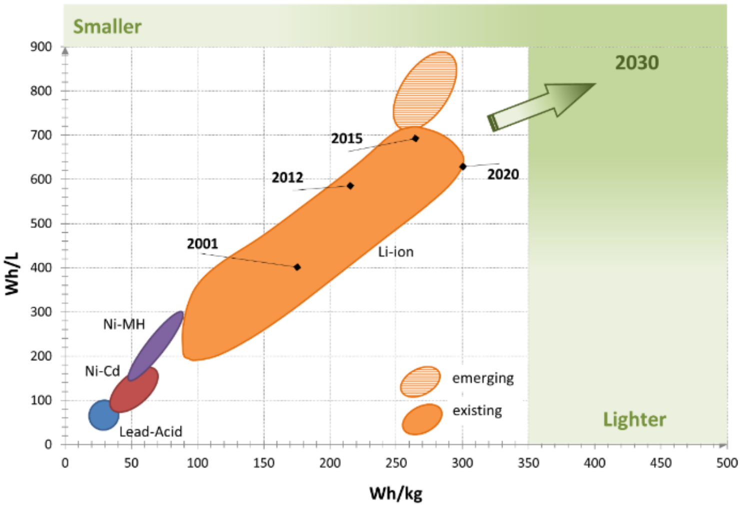
In the EU a clear leader is Germany that published more than twice as many articles as the jumping to the second place France followed by Spain and Italy that were for many years changing on the second position.

2.8 Impact and Trends of EU-supported Research and Innovation

International context

Various battery chemistries exist today and are being further developed. These battery chemistries may differ depending on whether the application focus is mobility or stationary usage. In 2020, Batteries Europe technology platform published a strategic research agenda for the entire batteries value chain. In 2021, it was detailed in technology road-maps for all segments of the value chain as well as guidance on cross-cutting issues such as safety, sustainability, digitalisation, and skills.

Figure 21. Energy density of Li-ion batteries at cell level over recent years.



Source: JRC, 2020[54]

Li-ion batteries were developed for portable electronics, they are leading in EVs and are fast growing in stationary applications replacing there in some uses Pb-A and Ni-MH technologies. "Li-ion" refer to a number of technologies which use an electrolyte composed of a lithium salt dissolved in an organic solvent. A carbon (graphite) anode is typically used, though alternative active materials are investigated. The name of the sub-technology generally refer to the cathode formulation (LTO being an exemption), e.g. an LCO battery uses a carbon (graphite) anode and a lithium cobalt oxide ($LiCoO_2$) cathode.

Cathode active materials R&I trends

As presented during the Advanced Automotive Battery Conference, AABC in December 2021, 2020 data on world cathode materials production show: 46% NMC, 19% LCO, 18% LFP, 16% NCA, and 1% LMO.

In the base projection for 2030 (and continuing in direction of 2040) BloombergNEF expect a dominant role for nickel-rich cathodes such as NMC, NCA, and similar NMCA and LNO. The contribution of LFP will remain relatively stable at about 20%, while the LCO (mostly used in portable electronics) share will diminish to close to zero because of high cost of cobalt and concerns around safety. Some new chemistries will appear reaching substantial market penetration, such as high-voltage LNMO and lithium-rich NMC. In an alternative scenario, BloombergNEF see the potential for a deeper changes, in which market would be dominated by roughly equal proportions of lithium nickel phosphate (LNP, $LiNiPO_4$), iron trifluoride (FeF_3), and LFP in the next 20 to 30 years. In both scenarios cobalt is projected to be replaced by cheaper and easier available metals such as nickel and, ideally, iron and manganese.[55]

Below some most recent examples of cathode active materials developments, showing the directions of R&I.

Umicore, a big cathode material supplier headquartered in Belgium, presented their cathode roadmap showing that materials with more than 80% nickel are already in the qualification and industrialization stage. On the horizon are manganese-rich electrodes with nearly zero cobalt, high-voltage spinels, and nickel- and cobalt-free cathodes. Both single-crystals and polycrystalline particles and their combinations are explored. Also materials for solid-state batteries are investigated, specifically tailored for the solid-solid cathode-electrolyte interfaces, including size and shape control and a homogeneous, conformal coating. In 2021, Umicore opened their first cathode active material plant outside Asia, a carbon-neutral facility located in Nysa, Poland.[55]

American CAMX is developing low-cobalt and high-nickel cathode materials. They focused on grain boundary engineering in polycrystalline high nickel cathode materials such as NCA, NMC, and LNO. The company strategy is not to completely eliminate cobalt, but rather to utilize advantages already available at low cobalt content of 3% - 5%. Their cathode material features various classes of high nickel materials with cobalt-enriched grain boundaries and different stabilizing elements such as magnesium, aluminium or manganese. Reported advantages for those materials manufacturing include low residual lithium, elimination of the need for water

[54] Updated from Strategic Energy Technology (SET) Plan: At the heart of Energy Research and Innovation in Europe. SET PLAN 10th anniversary 2007-2017; doi:10.2777/476339 (2017)
[55] https://www.batterypoweronline.com/news/new-directions-in-lithium-ion-battery-cathodes-from-aabc-2021/

washing, and the possibility to use lower grade lithium hydroxide precursors. At the battery level, CAMX sees improvements in rate capability, accessible states-of-charge, cycle life, and low-temperature performance.[55]

Massachusetts Institute of Technology presented new electrolytes that exhibit higher stability and can work with energy-dense lithium metal anodes paired with NMC and LMO or high-voltage LCO cathodes. This is in contrary to the traditional electrolyte formulation (lithium hexafluorophosphate, $LiPF_6$ and a mixture of alkyl carbonates) which suffer from breakdown due to reactivity between carbonate liquids and state-of-the-art cathode materials such as NMC811.[55]

French CEA-LITEN is working on lithium- and manganese-rich post-NMC materials with low cobalt, high-voltage spinel LNMO and disordered rocksalt phases that are seen as a next-generation candidate with higher energy density compared with existing materials. Disordered rocksalt cathode materials face challenges with rate capability, stability, and cyclability, and CEA-LITEN is working to overcome these issues by incorporating fluorine as a dopant via ball milling, developing coatings, and exploring new lithium-rich compounds like mixed sulfide-selenides ($Li_2TiS_xSe_{3-x}$).[55]

The Oak Ridge National Laboratory, USA is developing a new class of nickel-rich layered cathodes for batteries. This material is composed of lithium, nickel, iron, aluminium, and oxygen with the general formula $LiNi_xFe_yAl_zO_2$ ($x+y+z=1$; $0.9 \geq x \geq 0.8$) abbreviated as NFA. Introduced aluminium and iron improves structural stability and safety of the material. NFA has a layered structure with the same space group as NCA. Specific capacities about 200 mAh/g and operating voltage window are similar to those of NCA and NMC811.[56]

Anode active materials R&I trends

On the anode side, the current Li-ion batteries utilize carbon active material which is natural or artificial graphite, petroleum coke, carbon fibre, pyrolysis resin carbon, blend of those carbonaceous materials or blend of carbons with small amount of Si (usually <10 $_{wt.}$%). The development trend is to the replace the mentioned currently dominating substances with a material in which Si is dominating (carbonaceous materials being the rest) or with lithium metal. This change would lead to significant increase of the battery capacity, however both routes leads to the significant challenges: Si is expanding and contracting by a factor more than 3 upon battery charging and discharging causing mechanical stress to the battery components that leads to its fast degradation; metallic lithium in contrary is costly and difficult to process as lithium is a very soft metal, and requires protective inert atmosphere during production and handling.

In March 2022, NEO Battery Materials (CAN) informed about advancing its silicon anode production technology in a proprietary, single-step process, utilizing cheap pure metallurgical-grade silicon particles. This materials provide an initial specific energy of about 2 500 mAh/g, a 40-70% higher compared to SiO_x, SiC, or other composite silicon materials. Initial coulombic efficiencies (ICE) for this material anode have exceeded 86% and it showed a "good capacity retention" after 300 charge/discharge cycles. The company is in the final stage of setting up the R&D Scale-Up Centre in South Korea. Operation of the facility will enhance the production of the silicon anode materials. The company will perform additional R&D with graphite anode active materials to manufacture silicon-graphite composite anodes. The first refined sample of NBMSiDE has been provided to a Europe-based battery materials company, and a second delivery is planned in April. NEO is also conducting sample tests with several Asia-based and European battery manufacturers.[57]

There are no commercial products utilizing tin based anode materials, including oxides, nitrides, and alloys, other metal alloys (silicon, germanium, aluminium, antimony, magnesium and others).[58]

Electrolyte materials and other R&I trends

Electrolytes R&D focusses on development of additives aiming to improve durability, performance and safety of batteries, formulations compatible with high voltage (>4.25 V), cell design, increased silicon content or metallic lithium anodes, in longer perspective development of solid state electrolytes especially room-temperature polymer electrolytes for solid state batteries. As a temporary solution it is also observed adding some small amounts of liquid electrolyte to solid state batteries to increase contact of the active materials with solid electrolyte.

The general trend in batteries R&D is digitalisation and automation of batteries production (digital twins of production facilities) or big-data-driven components recycling or repurposing. Also the need for batteries

[56] https://nickelinstitute.org/en/about-nickel-and-its-applications/nickel-in-batteries/high-nickel-cathodes-an-overview/

[57] https://www.globenewswire.com/news-release/2022/03/31/2414050/0/en/NEO-Battery-Materials-Provides-Corporate-Update-on-InterBattery-2022-Full-Cell-Testing-with-High-Energy-Capacity-Si-Anodes-and-R-D-Scale-Up-Centre-Operations.html

[58] https://www.mis-asia.com/News/Global-lithium-batteries-market-trend-2022-2026-What-are-the-main-materials-of-lithium-batteries-by-Newsmis-asia.html

recycling becomes more and more accepted and put into practice as a source of secondary raw materials, but also as a proper treatment of the EoL batteries.

The most recent status of development of each Li-ion chemistry, including some non-Li-ion chemistries is available in the Annex I.

EU R&I support to selected chemistries and applications

This analysis is performed on the basis of JRC TIMS (CORDIS database) data from H2020 projects and available data from HEU. This also mean that some data from 2021 are not available, if the grant agreement signature is still ongoing. If the project develop more than one chemistry or application, the support is counted for all mentioned chemistries or applications. For the search criteria used per each category please look to the footnote.[59] The projects count for the years in which are started (signing the grant agreement).

During years 2014-2021 the public support of EU to the projects developing different battery technologies was ~405 million EUR. This translates into an annual contribution of 0.11 EUR per citizen to support development of the technology that is of key importance for mitigation of climate change.

There is a clear unbalance in distribution of the EU support between before-2004 and post-2004 EU member states. The "newcomers" receive about 3% of the EU support, while 97% are received by the "old" EU member states.

Below the analysis of the EU R&I support attributed to each technology, chemistry or application. The detailed money distribution per country is presented in Annex II.

Li-ion, general

The most supported was the general Li-ion technology. The support was given to 114 projects involving entities from 30 countries, 24 belonging to the EU. The total support was 295.3 million EUR, which was about 72.8% of total support to battery technologies.

Li-ion with metallic Li anode

The Li-ion technology with metallic lithium anode was the most supported Li-ion sub-technology. The support was given to 15 projects grouping entities from 21 countries, 15 of them belonging to the EU. The total support was 64.3 million EUR (15.9% of total support to battery technologies)

Li-ion with Si dominant anode

The Li-ion technology with Si dominant anode was supported at the level similar to that of Li-ion with Li metallic anodes. The support was given to 16 projects involving entities from 16 countries, 12 of them belonging to the EU. The total support was 65.1 million EUR (16.1% of total support to battery technologies)

All solid state batteries

The battery technology with solid state electrolyte (mostly Li-ion, but not limited to it) was supported at the level slightly lower than two previously described Li-ion sub-technologies. The support was given to 19 projects gathering entities from 21 countries, 13 of them belonging to the EU. The total support was 47.6 million EUR (11.7% of total support to battery technologies).

Li-S batteries

The battery technology still waiting for wider commercialisation which is prospective from EU point of view is lithium-sulfur. It was supported at the level slightly lower than solid state batteries, reflecting its expected later

[59] Batteries, all solid state - topic:("solid state battery"~2 OR "SSB battery"~2 OR "all solid state battery"~2 OR "ASSB battery"~2) AND emm_programme:h2020;

Batteries, Lead Acid - topic:("lead acid battery"~2 OR "Pb acid battery"~2 OR "Pb A battery"~2) AND emm_programme:h2020;

Batteries, Li ion (general) - topic:("lithium ion battery"~2 OR "li ion battery"~2) AND emm_programme:h2020;

Batteries, Lithium metal - topic:(("Li metal" OR "lithium metal")AND (battery OR anode)) AND emm_programme:h2020;

Batteries, Lithium Sulfur - topic:(("Lithium sulfur" OR "lithium sulphur" OR "Li S")AND (battery OR cathode)) AND emm_programme:h2020;

Batteries, redox flow - topic:("flow battery" OR (("redox flow" OR VRFB) AND battery)) AND emm_programme:h2020;

Batteries, Silicon anodes - topic:(("Si anode"~2 OR "silicon anode"~2) AND battery) AND emm_programme:h2020;

Batteries, Sodium ion - topic:("Sodium-ion battery"~2 OR "Na ion battery"~3 OR "NIB battery" OR "SIB battery") AND emm_programme:h2020;

Battery applications, mobility - ti:battery AND topic:(mobility OR mobile OR vehicle OR transport) AND emm_programme:h2020;

Batteries app, stationary - ti:battery AND topic:(stationary OR static OR "stand by" OR "energy storage") AND emm_programme:h2020 commercialisation. The support was given to 8 projects, and entities from 14 countries, 11 of them belonging to the EU. The total support was 33.3 million EUR (8.2% of total support to the battery technologies)

Redox-flow batteries

The redox-flow technology represent a whole bunch of battery chemistries, some already commercialised while others just being developed. EU support to this technology was similar to the support level of solid state batteries. The number of projects in analysed period was 23. The support was given to entities from 24 countries, 18 of them belonging to the EU. The total support was 51.4 million EUR (12.7% of total support to the battery technologies).

Na-ion batteries

A Na-ion battery technology is developed by very few players in EU. It was however already commercialised by Chinese CATL in 2021. EU support to this technology was very limited. The number of projects in analysed period was limited to 11. The support was given to entities from 7 countries, 6 of them belonging to the EU. The total support was 10.2 million EUR (2.5% of total support to the battery technologies).

Pb-A batteries

The lead-acid batteries is an old, well commercialized technology, in which EU is strong, but based on lead, which is widely known to be an toxic metal. EU support to this technology was limited and not belonging to the "mainstream" battery research heading, where the Pb-A batteries were excluded for a few years already and a number of projects in analysed period limited to 11. The support was given to entities from 10 countries, 8 of them belonging to the EU. The total support was 15.2 million EUR (3.7% of total support to the battery technologies).

Mobility applications

The mobility application of batteries was the main use-case area supported by EU. The EU has strong automotive industry that stands in front of mobility electrification challenge. EU support to development of technologies that can help in this respect is a strategic need. The trend in the support level is clearly increasing, with 90 projects supported in the analysed period. The support was given to entities from 43 countries, 26 of them belonging to the EU. The total support was 294.9 million EUR (72.8% of total support to the battery technologies).

Stationary applications

The stationary energy storage application of batteries was the second main use-case area supported by EU. The EU stands in front of a challenge to increase the renewables share in the energy mix, and the BESS can play important role in balancing those intermittent sources. EU support to development of stationary BESS technologies is a practical need. The trend in the support level is clearly increasing, with 80 projects supported in the analysed period. The support was given to entities from 42 countries, 26 of them belonging to the EU. The total support was 214.4 million EUR (52.9% of total support to the battery technologies)

The above analysis leads to the immediate conclusions:

1. The level of support to the battery technologies from EU research budget, is about 11 eurocent per habitant per year.

2. There is a clear unbalance in distribution of the EU support between before-2004 and post-2004 EU member states. The "newcomers" receive about 3% of the EU support, while 97% targets the "old" EU member states.

3. EU support to development of Na-ion technology, which is not depending on any critical raw material is very limited.

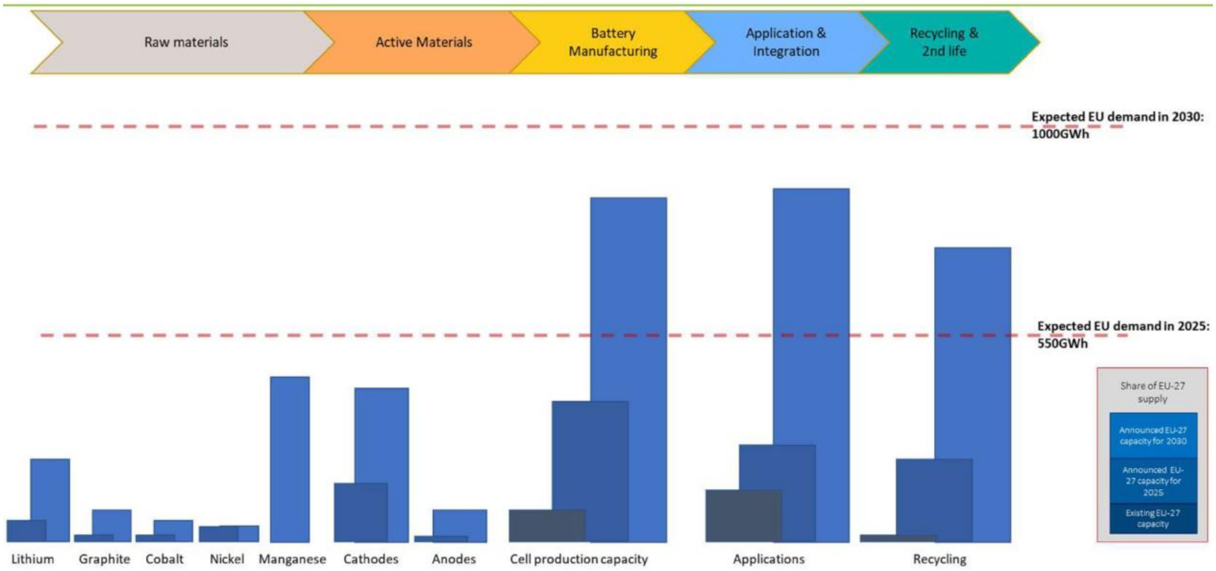
3 Value Chain Analysis

As recently as in 2016[60], the EU was severely lagging in key segments of the Li-ion battery value chain. It was largely absent in key raw materials markets (lithium, cobalt, graphite) and the Li-ion cells market. Particularly in processed materials, the EU activity in cathode and electrolyte markets was limited, and EU was absent from anode market.

2017 marked the start of EU's industrial policy on batteries when the Commission outlined the concept of the European Battery Alliance with EU countries and industrial actors. A strategic action plan for batteries, covering the whole process from producer to end-user, was adopted in May 2018[61]. Since autumn 2019, the Business Investment Platform of the European Battery Alliance gathers stakeholders along the entire battery value chain to accelerate transactions between investee and investor[62].

Thanks to investments of mainly Asian companies in EU based subsidiaries and actions of the European Battery Alliance that was launched in 2017, EU is turning into a region with well-developed battery eco-system across the entire value chain. Major EU initiatives are being implemented by the EU based on the Action Plan on Batteries. They are complemented by a buoyant industry network facilitated by EIT Innoenergy – EBA250.[63,64]

Figure 22. Expected supply and demand balance in Europe from present day to 2030 for the batteries value chain.



Source: EBA250, 2021.

The upstream raw materials segment remains the least resilient of the battery value chain and spent batteries are still mostly sent to Asia for recycling. Despite several European initiatives the supply gap for battery raw materials increased in 2021[65]. In particular graphite cobalt and lithium that are on the list of EU critical raw materials, but also nickel. Anode production is also a weak point, but recently there have been some positive developments, mostly in Finland and Sweden[66]. Within last year the following changes could be observed:

expected EU demand in 2025 increased from 400 GWh to 550 GWh and in 2030 from 900 GWh to 1 000 GWh,

expected lithium supply significantly dropped in both time perspectives,

expected manganese supply slightly increased in 2030 perspective,

expected cathode materials supply slightly decreased in both time perspectives,

expected anode materials supply slightly increased in 2030 perspective,

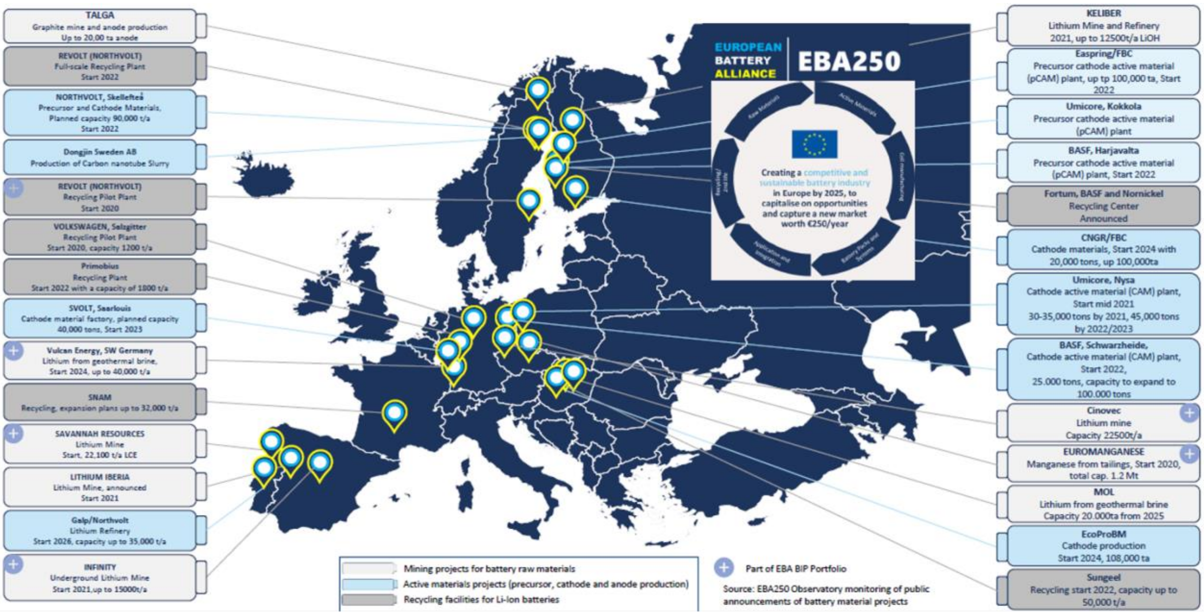
expected cell production not increased or increased slower than expected demand in both time perspectives,

[60] JRC Lithium ion battery value chain and related opportunities for Europe, 2016.
[61] https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en
[62] https://eit.europa.eu/news-events/news/european-battery-alliance-eit-innoenergy-launch-business-investment-platform
[63] https://www.eba250.com/
[64] Avicene Energy, The rechargeable battery market 2020, 2020
[65] EIT Innoenergy, Contribution for High-Level ministerial meeting on batteries, February 2022.
[66] https://www.eba250.com/supply-of-graphite-from-europe/

expected applications significantly reduced for current situation (probably data update) and for 2025, for 2030 remain stable,

expected recycling slightly increased for 2025 and significantly increased for 2030.

Figure 23. Existing and announced battery raw material projects in Europe.



Source: EBA250, 2021.

Australia and Canada are the two countries with the greatest potential to provide additional and low-risk supply to the EU for almost all battery raw materials. Enhancing recycling has potential to decrease EU's supply dependency. It is estimated that by 2040 recycling could contribute to up to 51% and 42% of Cobalt and Nickel EU demand, respectively.[67]

3.1 Turnover

There is no sufficient data to perform the analysis.

3.2 Gross value added

Similarly to turnover, statistical data for gross value added is also not available.

3.3 Environmental and Socio-economic Sustainability

The production and the adoption of more sustainable batteries in the EU is a key aspects for the EU Green Deal goals, and they will promote a more sustainable and competitive battery industry across Europe and globally[68]. The Battery Regulation proposal (COM(2020) 798/3 final) will support the reduction of both environmental and social impacts along the whole value-chain of batteries, promoting the adoption of more sustainable and circular batteries in various applications. Thanks to this initiative the EU is a frontrunner on environmental and socio-economic sustainability of batteries.

3.4 Role of EU Companies

Currently the leading cell producers in EU are mostly the local subsidiaries of Far East or US companies (given actual production capacity[69] and in brackets planned total production capacity – not to be confused with actual production). Those are, e.g.:

[67] https://rmis.jrc.ec.europa.eu/?page=analysis-of-supply-chain-challenges-49b749

[68] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2312

[69] https://www.greencarcongress.com/2022/03/20220312-benchmark.html

- LG Energy Solutions – 32 (65) GWh (PL)
- Samsung – 20 (50) GWh (HU)
- SK Innovation – 7.5 (17) GWh (HU)
- Tesla – (120) GWh (DE, about to start production)
- CATL – (24) GWh (DE)

EU owned companies are also active and are preparing a number of battery cell production facilities:

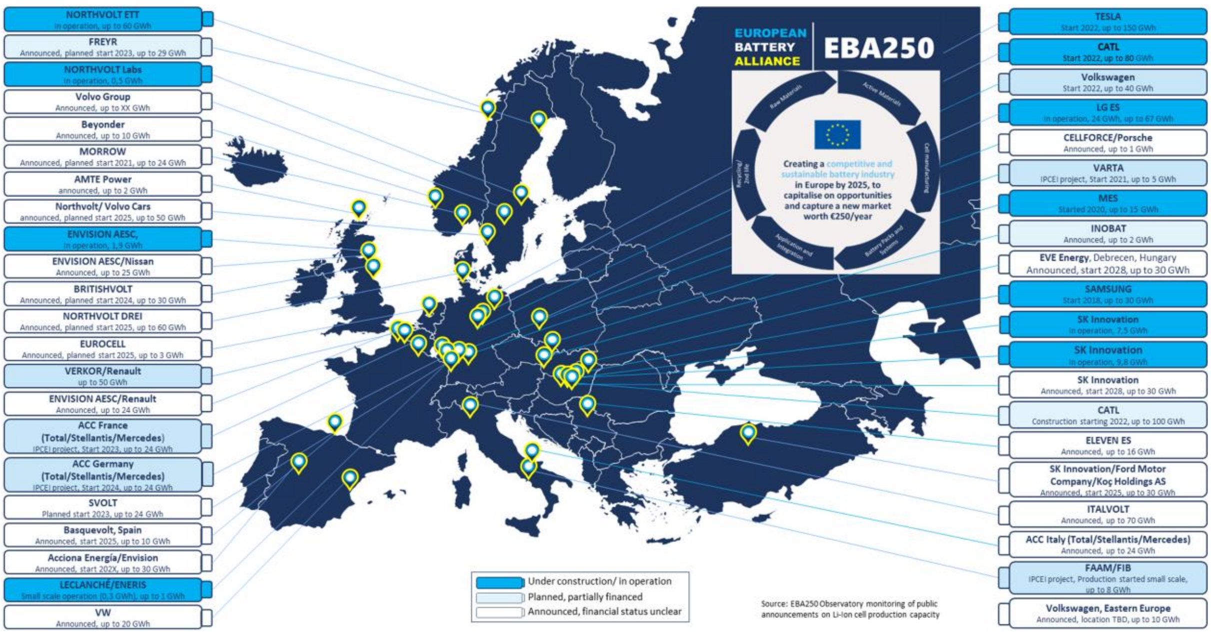
- NORTHVOLT – 16 (60) GWh (S)
- MES – 0.2 GWh (CZ)
- CELLFORCE – 0.1 GWh (DE – JV of Porsche/Fraunhofer)
- ACC (2x32) GWh (F and DE – JV of TOTAL/Stellantis)
- VOLKSWAGEN – (24) GWh (DE)
- VERKOR – (16) GWh (F)
- INOBAT – (10) GWh (SK)
- VARTA – (10) GWh (DE)
- FAAM/LITHOPS – (8) GWh (I)
- Eneris/Leclanché – (2.5) GWh (DE)

VOLKSWAGEN and Northvolt produced first battery in Dec 2021 and MES HE3DA (CZ) factory is operational since Sep 2020.

The field is very dynamic, the actual production capacity of existing projects is being updated with sites development, the final planned production capacity even more often and the new projects are being announced both, from EU and Asian companies, e.g. Amte power, Basquevolt, Beyonder, BMZ, Eurocell, Eleven ES, EVE energy.

Battery production facilities are also set in Norway and UK (planned 85 GWh and 70 GWh respectively).

Figure 24. Existing and announced battery cell production plants in Europe.



Source: EBA250, 2021.

Those battery cells producers are attracting also their partners and cooperates, extending the battery value chain in EU. Those are companies either up in the value chain, like Umicore – plant of cathode active materials in Nysa (PL), SK IE Technology world largest plant of Li-ion battery separators in Silesia Region (PL), Enchem electrolyte plant in Komarom (HU); or dawn in the value chain – like Mercedes plant of EV battery packs in Jawor (PL). All those companies build their supply chains, also locally.

The 2021 installed production capacity in EU summed to 71 GWh and is projected to reach at least 75 GWh in end 2022.

Over the last 10 years, only 7% of the world's flow battery projects were installed in Europe, with much more R&D and support taking place in North America and Asia. At the same time, Austrian CellCube belongs to global top-three RFB producers, together with Sumitomo Electric Industries Ltd. (JP) and UniEnergy Technologies (US). In Apr 2021, 16 European flow battery stakeholders came together to form Flow Batteries Europe (FBE). Currently, FBE has four larger industry members (CellCube, Largo Clean Energy, Voith, and W.L. Gore & Associates), and four start-ups (Bryte Batteries, Pinflow Energy Storage, Vanevo and Volterion), which are working on vanadium chemistries. Some of these members are also considering opening up to other chemistries in the future. FBE also has two members – JenaBatteries and KEMIWATT – which are working on organic chemistries.[70]

Major EU companies in EV production area, source: RhoMotion:[31]

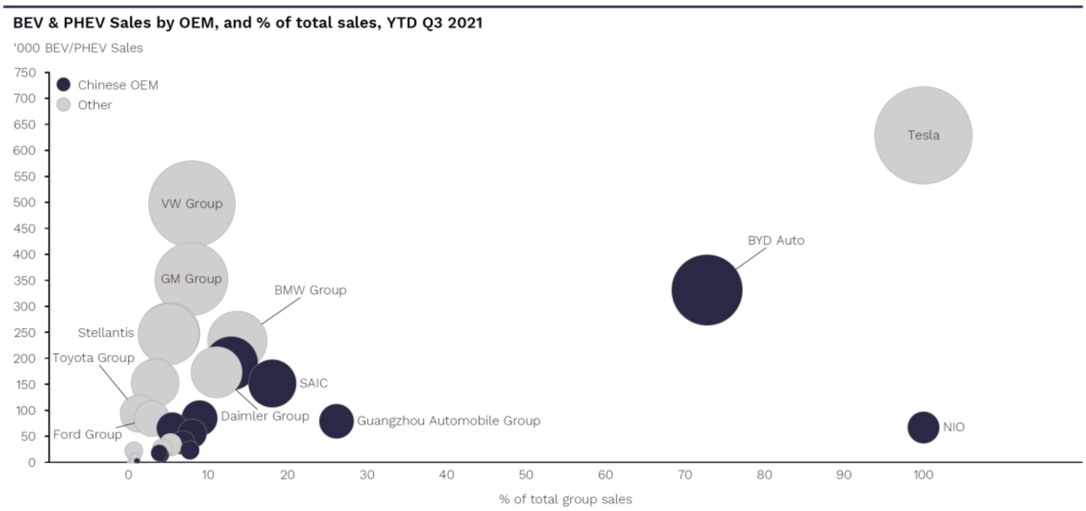
- Volkswagen group - by 2030 70% of its vehicles sold in Europe (50% in US and 50% in China) will be fully electric which represents 5 million cars, it will invest $19 billion in electrification and digitalisation by 2025, significant investment expected in unified prismatic-type battery cell production in Europe. Six EV battery cell gigafactories planned to come online by 2030, the first two in Sweden (2023) and Germany (2024) respectively through a joint venture with Northvolt (S) and a partnership with Gotion (China). The newest (Jul 2022, during oral presentation on a conference) information however is that Volkswagen is going to stop the business with Northvolt.
- Daimler – by 2025 50% of sales to be electrified, majority of these to be BEVs, all models will be offered in electrified version (either BEV or PHEV). By 2030 it plans to be fully-electric. Currently the EQS utilises NCM811 with more high nickel chemistries being developed. To reduce costs, a high manganese NMC and LFP (referred to as LFP 2.0) will be used. The company will need 200 GWh/y of battery capacity by 2030. Production of batteries will take place in eight new gigafactories. Daimler is partnering with Farasis and CATL to set production in Europe. It also holds a 1/3 stake in ACC with Stellantis and TotalEnergies.
- BMW – aim to have 25 new electrified models (>50% BEV) available by 2023 – two years ahead of its original plan. BMW set a European target that 33% of its vehicles sold should have an electric drive trains by 2025 and 50% by 2030 (the latter is also a global target). BMW will produce high-voltage batteries and battery components at three locations in Germany. In 2021, Leipzig and Regensburg plants launched series production of components for high voltage batteries. BMW Group, together with Ford Motor and Volta Energy Technologies, has invested $130 million in the US-based solid-state battery start-up, Solid Power.
- Stellantis group - aiming for 70% electrified cars sales in Europe (40% in US and 100% in China) by 2030 (Peugeot will offer an electrified version of each model by 2023), will invest $35 billion in electrification and software by 2025. It plans to produce in-house 260 GWh/y of batteries in five facilities in Europe and North America through JVs and partnerships with ACC, CATL, BYD, Svolt, Samsung SDI, and LG Energy solutions. Stellantis will use battery packs ranging from 32 kWh to 200 kWh, and two dedicated battery chemistries, LMFP for low-cost vehicles and NMx for performance vehicles. Stellantis will build one gigafactory with LG ES (40 GWh/y), another with Samsung SDI (23 - 40 GWh/y) and will convert a plant in Douvrin as part of 1/3:1/3:1/3 JV with Daimler and TotalEnergies;
- Renault group - increasing EV sales share to 65% by 2025 and 90% by 2030. It plans to launch 10 new BEVs by 2025. Current EV battery is NMC chemistry, partnering with Envision and Verkor: Envision plans to develop a gigafactory in Dubai with a capacity of 9 GWh/y in 2024 and 24 GWh/y by 2030. Verkor plans to build its first gigafactory in France in 2026 with an initial capacity of 10 GWh/y and will increase this to 20 GWh by 2030. Nissan and Envision will jointly build a 6 GWh/y battery plant in Tokyo by 2023 which will grow to 18 GWh/y in five years. Nissan and Envision also plan a UK gigafactory in Sunderland – initially 11 GWh/y, with a 38 GWh/y potential.
- Tesla, 100% electric already now, with its Gigafactory 4 near Berlin, (500 000 EV/y capacity) became an EU producer, however the most important markets for Tesla remain US and China. The commercial operation of Gigafactory 4 started in 2022. In 2021, Tesla is going to start 4680 battery cells production in its plant in Grünheide (DE) in 2022. In 2021, the Chinese government granted approval

[70] https://www.flowbatterieseurope.eu/

for Tesla to produce and sell Model Y Standard Range that is equipped with LFP batteries produced in Shanghai plant. The Model Y Long Range is currently imported to Europe from China, based on NMC811 cells from CATL.

- Geely, an owner of Volvo Car Group announced that Volvo will reach 50% of BEV in global sells by 2025 and 100% by 2030. Volvo via a 50:50 JV with Northvolt will produce in Gothenburg EV batteries for Volvo's and Polestar's next-generation BEVs. Construction of the plant will start in 2023 and production will begin in 2025. The plant will have a cell production capacity of up to 50 GWh, enough for half a million cars per year. Its R&D centre located in Gothenburg will go online in 2022. Volvo considers sourcing 15 GWh of battery cells annually from Northvolt Ett's plant in Skellefteå, Sweden, from 2024.
- Tata, an owner of Jaguar Land Rover plan for its Jaguar brand to be entirely electric by 2025, and to launch e-models of its entire vehicle line up by 2030. The Land Rover brand will launch six BEVs over the next five years, with the first coming in 2024. 60% of Land Rovers will be zero emission by 2030. Its new EVs will be mainly produced in its Solihull plant in the UK.
- Toyota began production of hybrid electric transmissions for powertrains at its Walbrzych plant in Poland. The Toyota Europe's strategy targets an annual sales of 1.5 million vehicles by 2025, 90% of which will have electrified powertrains.

Figure 25. Current position of the leading car producers on the global market.



Source: RhoMotion, EV & Battery Quarterly Outlook Q4 2021, 2021.

There are numerous EU players entering the electric bus market: Solaris (PL), Volvo, Daimler, VDL, Ebusco (NL), Bluebus - Bolloré, Alstom, Iveco Heulliez (FR), Irizar (ES) Linkker, Sileo (DE), Caetano (PT), etc.

At the end of 2020 leading EU truck producers: Daimler, Scania, Man, Volvo, Daf, Iveco, and Ford – have signed a pledge to phase out traditional combustion engines by 2040[71].

Nikola Motors and IVECO has inaugurated the Nikola Tre production facility at the IVECO manufacturing facility in Ulm (DE), serial production of the 720 kWh battery electric vehicle is expected for end 2022, prototypes underwent customer testing in 2021.

Siemens[72] and Alstom[73] hold the first contracts in the field of battery driven trains - Alstom will deliver 11 Coradia Continental BEMU trains starting from 2023 to Germany for the Leipzig-Chemnitz route, which requires the train to cover 80 km of non-electrified track. Swiss train manufacturer Stadler will supply more than 160 trains and locomotives in Europe and North America, ABB will provide battery and traction systems to Stadler.

Many electric ships are integrated at Damen shipyards (NL)[74] even if storage solutions are provided by other companies. Other EU shipyards are also involved as there seem to be no shipyards specifically specialised in

[71] ACEA, All new trucks sold must be fossil free by 2040, 15 December 2020 Joshua Hill, Europe's biggest truck-makers agree to 2040 diesel phase out, plan $A160bn spend, The Driven, 17 December 2020.
[72] Green Car Reports (Bengt Halvorson), Battery-powered electric trains will soon bring cleaner air- especially in Europe, 29 March 2020.
[73] https://alternative-fuels-observatory.ec.europa.eu/transport-mode/rail.
[74] https://www.damen.com/en/innovation/electrification

electric ships. Leading companies in the EU for equipping ships with battery storage and electric propulsion include: Echandia Marine and ABB in Sweden, Wärtsilä in Finland, Danfoss in Denmark and Siemens in Germany

Major EU companies are active in the stationary storage sector including Fluence (world second place after Tesla and before BYD, co-owned by Siemens and American AES), Sonnen (owned by SHELL), TOTAL/SAFT, Engie, ENEL X and ABB. There is also a number of small companies and start-ups developing their own systems usually suitable for home storage/small business applications and based on battery cells acquired from other producers.

In 2021 Fluence announced it will jointly develop grid-scale battery storage technology with Northvolt.

3.5 Employment in value chain incl. R&I employment

There is no data available, Eurostat do not publish the data with required granularity and the EurObserv'ER do not publish data on batteries.

Development of battery value chain in EU could create more than one million of new jobs. This employment increase will happen despite development of machine learning algorithms and digitalisation and automation of production processes.[75]

EBA250 Academy was established in 2021 that in partnership with local training professionals will build a pan-European education ecosystem, develop and share curricula and training content based on the battery industry's skills needs. That will reduce the cost to up- and reskill workers and increase the efficiency and quality of training for 160 000 workers that will be trained every year.

The analysis of the current and future employment and skills needs is the goal of the Alliance for Batteries Technology, Training and Skills (ALBATTS), a European funded project designing a blueprint for competences and training schemes of the future, in the battery and electromobility sector.[76]

3.6 Energy intensity/labour productivity

There is no data available regarding the energy intensity and labour productivity disaggregated to the technology level, thus the analysis is based on general figures.

Energy intensity

All factories in the pipe-line will be new and energy efficient. Also, there is a general trend of increasing use of renewable energy in batteries production, often based on direct PPAs with the renewable energy producers.

A trend towards ever bigger EVs (SUV market is quickest growing EV market)[19] implies high energy consumption at production and utilisation stages and risks increasing dependence on critical raw materials. According to IEA, currently sport utility vehicle (SUV) models account for half of the available electric car models in all markets around the world. In Europe, the share of electric SUV models is even higher than for the overall market. This may be a temporary trend related to the wealthier part of population opting quicker for e-mobility, leading to most polluting cars being replaced first.

In this respect, China, unlike EU, has an official policy of reducing average power consumption of new pure electric passenger cars to 12.0 kWh/100 km by 2025.[77] Today, the best sold model on Chinese market, a small EV, consumes 8.1 kWh per 100 km.

Labour productivity

Labour cost account for a relatively small share of the overall battery production cost. The battery production is a sector applying high automation levels. The EU factories are/will be new and highly automated.

3.7 EU production Data (Annual production values)

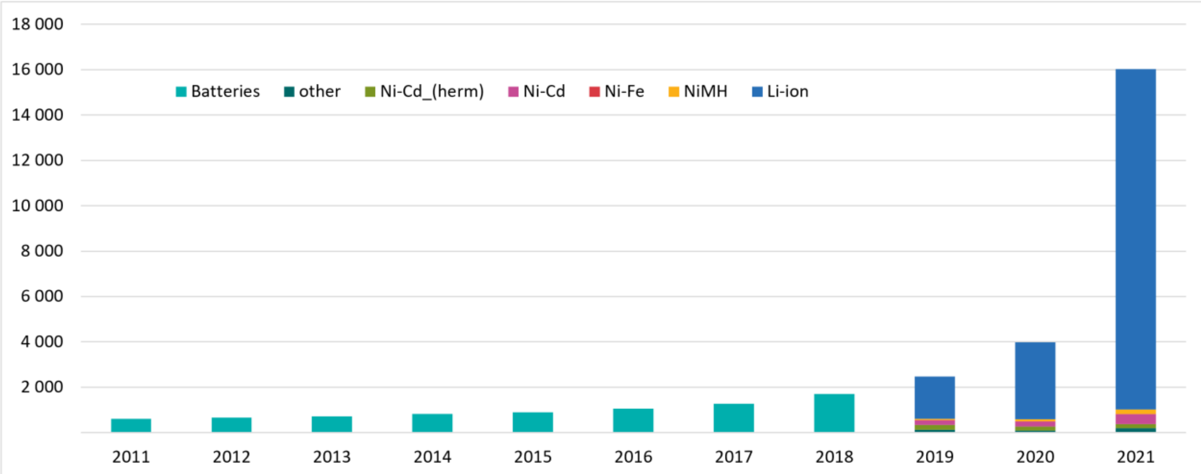
JRC analysis based on PRODCOM data. Codes: 27202300 (discontinued in 2019); as of 2019 split into: 27202310, 27202320, 27202330, 27202340, 27202350, and 27202395. Some countries keep their production data confidential. This production however is included in the "EU total" numbers. That's why the sum of countries production is lower than EU total. It should be also pointed that the PRODCOM codes do not distinguish between battery cell, module or system (e.g. EV battery) incorporating cells, thus a double counting may occur.

In 2021, most batteries produced in the EU (in terms of storage capacity) were still lead-acid batteries and their production continues to benefit from moderate growth of around 3% per year. EU production of Li-ion batteries

[75] Batteries Europe General Assembly 21/06/2022
[76] https://www.project-albatts.eu/en/home
[77] State Council Information Office of the People's Republic of China, New energy vehicle industrial development plan (2021-2035), 2020.

is still behind that of the lead-acid batteries, however a dynamics of the sector and the e-mobility boom is now moving Li-ion batteries to the forefront thanks to their superior energy density.

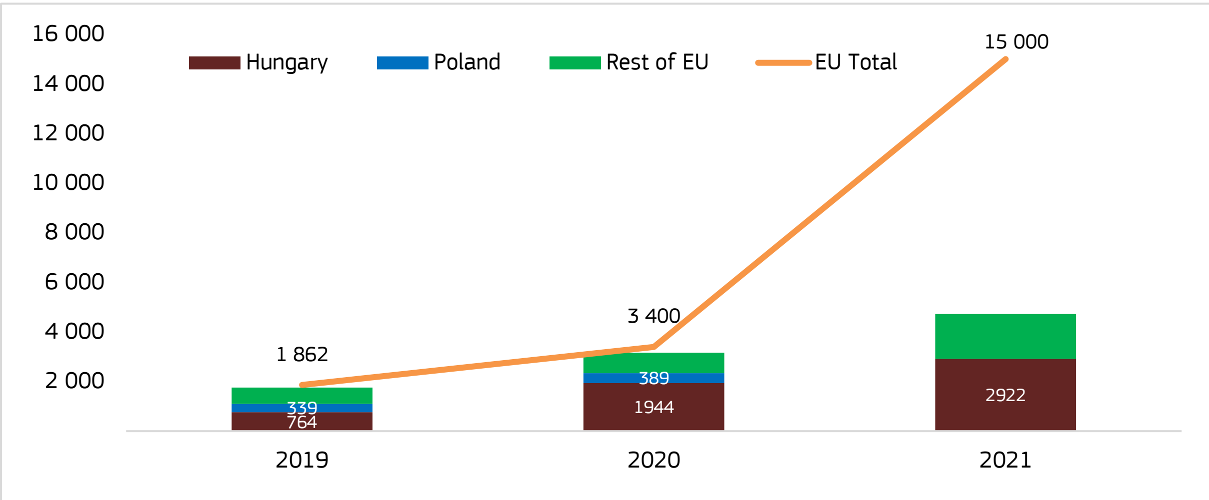
Figure 26. Total value of non-Pb-A batteries production in the EU per chemistry (PRODCOM code) [EUR Million].



Source: JRC based on PRODCOM data.

Mostly subsidiaries of Korean companies make up the community production of Li-ion battery cells in the EU. In 2021 the estimated actual EU production was about 16 GWh.

Figure 27. Total value of Li-ion batteries* production in the EU and Top Producer Countries [EUR Million].



* Li-ion batteries is a wide category, starting with Li-ion battery cell and ending with EV Li-ion battery pack or an BESS system.

Source: JRC based on PRODCOM data.

EU is expected to reach 75 GWh of installed production capacity by end of 2022, compared to 44 GWh in mid-2021.[78] Annual production volumes are increasing, however the time is needed until the production can reach the level of installed capacity (e.g. for the first Tesla giga-factory it took 5 years).

[78] https://www.greencarcongress.com/2022/03/20220312-benchmark.html

It is also projected that EU will have a manufacturing capacity of some 379 GWh by 2025 and some 886 GWh by 2030. If all 42 announced projects are delivered on time, they would be sufficient to meet 69% and 89% of the increasing demand for batteries by 2025 and 2030, respectively.[79,63]

EU head-quartered companies (such as Northvolt, Saft and Varta), currently occupying high-end Li-ion niche applications, are preparing for mass production for e-mobility and energy storage.

VW will go for a new business model for the production of batteries for electric vehicles based on a single, massive-scale “unified cell” platform. The unified cell is expected to enter production in 2023 in cooperation with NorthVolt (the latest news is that this cooperation will be stopped). In total, *Volkswagen* plans to bring *240 GWh* of battery production capacity to Europe by 2030 (and a third of it by 2025). This would be enough battery-making capability to supply 4 to 4.5 million EVs per year[80].

[79] EIT Innoenergy, Contribution for High-Level ministerial meeting on batteries, February 2022
[80] https://www.sae.org/news/2021/03/volkswagen-unified-cell-battery

4 EU position and Global competitiveness

4.1 Global & EU market leaders

In 2020 global market of Li-ion batteries exceeded that for lead-acid batteries in value $47 billion vs $37.5 billion. In terms of storage capacity, Pb-A batteries sales were still ahead in 2021 with 410 GWh vs 305 GWh for Li-ion respectively, however if the trends continue, in 2022 the Li-ion should outpace Pb-A batteries reaching about 490 GWh. The production of Pb-A batteries still benefit from moderate growth of 1-3% per year, depending on the market segment.

The EU has a strong position on Pb-A battery market, with a turnover of over EUR 7 billion, and a net-export. Europe accounts for ~20% of global supply, which is about 75 GWh/year.[81,82,83]

In the cathode materials sector, EU has two strong players Umicore and BASF, however is still importing most of these materials from Asia[84]. Other companies are also investing in EU, e.g. Korea's EcoPro BM will build first overseas plant in Hungary (108 000 tons a year, with the goal to increase to 480 000 tons by 2026), Johnson Matthey is setting up a new factory in Konin to supply eLNO Ni-rich cathode materials for automotive applications (sold in 2022 to Australian EV Metals Group). World leaders are Fujitsu, Hitachi Chemical, LG Chem, Mitsubishi Chemical, NICHIA, and Sumitomo Chemicals[85]. Chinese GEM is an important player in Li-ion cathode precursors[86] and collaborates with Korean EcoPro.

In other advanced materials for batteries, except polymers for Li-ion batteries (Solvay), EU is rather weak. However SK IE Technology is setting the world largest plant of Li-ion battery separators in Silesia Region (PL), Enchem operates already an electrolyte plant in Poland and decided to set another one in Komarom (HU). The last one will also be equipped with an NMP refinery. In 2022, another Korean company, Dongwha Electrolyte, completed construction of an electrolyte production plant in Soskut (HU). Foosung will set in Kędzierzyn-Koźle (PL) by 2024 a plant for Li-ion electrolyte additives.

In the battery cells sector, all leading manufacturers are Asian (Q1 2022 data):

1. CATL: 33.3 GWh (35 %)
2. LG Energy Solution: 15.1 GWh (15.9 %)
3. BYD: 10.5 GWh (11.9 %)
4. Panasonic: 9.4 GWh (9.9 %)
5. SK On: 6.3 GWh (6.6 %)
6. CALB: 4.2 GWh (4.4 %)
7. Samsung SDI: 3.8 %
8. Gotion High-Tech: 2.7 %
9. Svolt Energy: 1.3 %
10. Eve Energy: 1.2 %
11. Others: 8.2 %

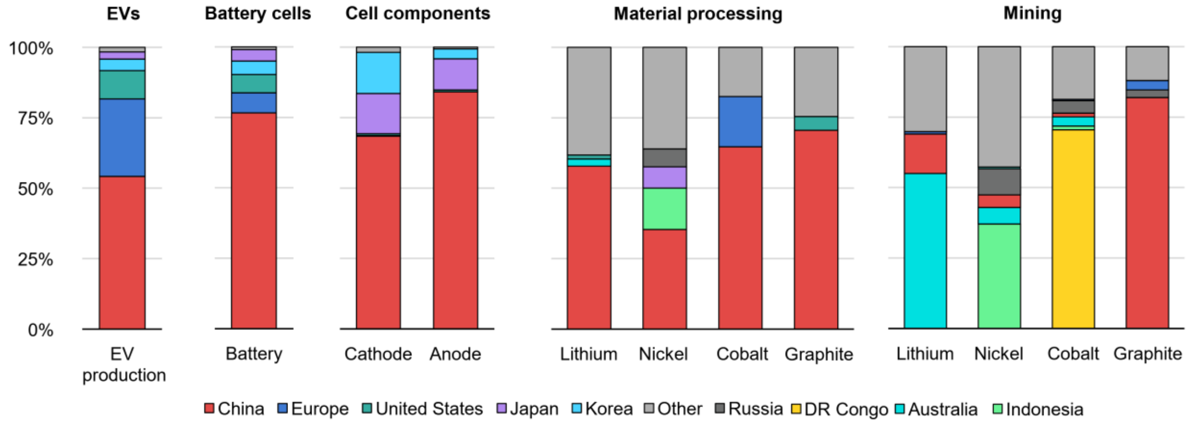
Korean and Chinese companies already have, or are setting up now a production facilities in the EU. Today, they are responsible for most of EU production, e.g. Poland is the world's second exporter of Li-ion batteries due to LG Chem production. According to BNEF, 77% of cell production capacity is controlled by China. This should change with a number of EU head-quartered companies setting up Li-ion battery cell production facilities. With EU's Green Deal agenda, demand and production capacities for Li-ion batteries are growing faster in Europe than in any other region of the world. According to Fraunhofer, the EU's share in this global battery manufacturing capacity will increase from around 7-8% in April 2021 up to 24% in 2025 and 29% in 2030.[87] A significant part of this growth, however, should be attributed to growth of local subsidiaries of Asian and US companies.

Notwithstanding the general dominance of Asian manufacturers, European SAFT and VARTA play an important role in high-end niche applications for Li-ion cells. Leclanché is a main European producer of Li-ion battery energy storage systems for waterborne applications.[88]

[81] Avicenne energy, EU battery demand and supply (2019-2030) in a global context, 2021: https://www.eurobat.org/images/Avicenne_EU_Market_-_summary_110321.pdf
[82] Statista, 2021
[83] Markets and Markets, Battery energy storage system market, 2020.
[84] Green Car Congress, 2021: https://www.greencarcongress.com/2021/01/20210108-roskill.html
[85] Polaris Market Research, Lithium-ion battery cathode market size global industry report, 2020.
[86] Roskill (Ying Liu), Nickel sulphate: GEM and ECOPRO to build high-nickel Li-ion precursor capacity in Fujian, 17 Apr 2020.
[87] Fraunhofer ISI, April 2021
[88] https://www.leclanche.com/solutions/e-transport-solutions/e-marine/

Although Asia is currently the global hub of EV battery making, European manufacturers should be able to compete on price, because the biggest costs in battery making are (raw) materials, the capital-intensive manufacturing process and the cost of energy. In these three areas, there is hardly any competitive disadvantage compared to Asian manufacturers. The share of labour in the overall cost of a battery is limited, and the difference between the labour cost in Europe and Asia is offset by the cost of shipping batteries to Europe[89].

Figure 28. Geographical distribution of production/capacity by element of the supply chain in 2021.



Source: IEA Global Electric Vehicle Outlook 2022.

In manufacturing of Li-ion cell production equipment, Asian companies are leading and most of equipment is being imported from Asia. Manz is the only EU company playing an important role in this segment.[90,91]

Over the last 10 years, only 7% of the world's flow battery projects were installed in Europe, with much more R&D and commercial support taking place in North America and Asia[92]. At the same time, Austrian CellCube belongs to top-three RFB producers in the world, together with Sumitomo Electric Industries Ltd. (JP) and UniEnergy Technologies (US).[93] Recent establishment of Flow Batteries Europe association can help to improve EU's competitiveness in this segment.[94]

According to "Sodium Ion Battery Market - Growth, Trends, and Forecasts (2020 - 2025)" two promising EU companies, Tiamat (FR) and Altris (SE) are developing Na-Ion chemistry[95]. Europe has a possibility to become technology leader in this market. In 2021, however, CATL (CN) released its Na-ion cells with application in hybrid Li-ion/Na-ion EV battery packs. In 2022, CATL and Reliance Industries (IN) acquired UK-based sodium-ion specialist Faradion. Comparing the potential of CATL / Reliance and that of Tiamat or Altris, it is not very likely that EU will play a significant role in this chemistry in the foreseeable future.

EU plays very strong role when it comes to battery systems and final products, especially electric vehicles. EU is a net exporter of vehicles. It also is a net exporter of electrified vehicles in terms of value, however is still a net importer in terms of number of vehicles. The general tendency is that final products are manufactured in the end-use jurisdictions – China, EU, US (i.e. not much inter-continental trade is expected). Main EU manufacturers have production facilities in major global markets, China and US, as do key US producers. Chinese automotive companies are just entering the EU market for electric cars[96] and stationary storage. US based Tesla remains leading EV manufacturer.[97]

All EU car manufacturers embraced electrification race and compete on the global market. In March 2022 American Tesla became also an EU car manufacturer after opening its factory in Grünheide (DE). Chinese BYD, SAIC, NIO, Xpeng are joining the world leaders in EV manufacturing profiting from huge size and regulations of

[89] SAFT, ACC's European EV battery venture on track for production, 2020:
[90] Decisive Market Insights, Lithium battery manufacturing equipment market report, 2021.
[91] Manz AG: Https://www.manz.com/en/industries/battery-production/
[92] Robin Whitlock, Flow Batteries Europe (FBE) established to represent flow battery stakeholders, Renewable Energy Magazine 03 May 2021.
[93] JRC Batteries - Technology Development Report 2020
[94] https://flowbatterieseurope.eu/
[95] Mordor Intelligence LLP, Sodium Ion Battery Market - Growth, Trends, and Forecasts (2020 - 2025), 2020.
[96] https://www.autoexpress.co.uk/nio/354921/chinese-ev-brand-nio-enters-european-market
[97] Statista, 2021. Data retrieved: https://www.statista.com/statistics/977407/global-sales-of-plugin-electric-vehicles-by-brand

Chinese market._VW and other EU based manufacturers are also profiting from Chinese market and already set up production facilities in China.

Currently EU is responsible for roughly 19% of global production of electrified vehicles (1.3 out of 6.6 million)[98], and in an optimistic scenario, EU may achieve an annual production of 6 million by 2025[99]. The global data firm, LMC Automotive, estimates China will produce over eight million electric cars a year by 2028, compared with 2.9 million in 2021[100]. US also set a clear course towards electrification under the Biden administration [101].

According to EBA250, in 2020 a parity of the total cost of ownership (TCO) of EVs with ICE vehicles was achieved in EU. This is important for EVs' competitiveness since about 60% of the automotive market consists of leasing cars that is focusing on monthly costs, not on the cost for purchasing the vehicle. A general trend of falling costs of EVs are of course adding to this picture, also increasing attractiveness of EV's. The high price of conventional fuels compensate for increase of battery prices in 2022. With a maximum charging speed exceeding 10 km driving range per charging minute (and still rising) for most models, and an average range above 350 km, also range anxiety becomes less of an obstacle.

China is the world's largest producing region of electric buses (86 000 in 2020). This has been initially facilitated by considerable support to acquisitions of electric buses, while from 2021 strict public procurement rules regarding "new energy vehicles" play an important role. According to these rules, BEVs, plug-ins and FCEVs should account for not less than 80% of the vehicles newly added (or replacing old ones) to public transport areas of key regions to prevent atmospheric pollution. Largest producers are: Yutong, BYD, CRRC, Zhongtong and Suzhou King Long. In comparison, the EU market for electric buses accounted for 2 300 units in 2021. The majority of the EU market appears to be held by EU companies, primarily Solaris (now under Spanish CAF), Mercedes-Benz, Iveco Bus – Heuliez, Volvo, VDL and others[102,103], however Chinese Yutong and BYD are also very strong on the EU market as China was much quicker to embrace electrification of bus transport. The global stock of electric buses reached 670 000 units.[19]

The battery powered heavy duty vehicles market is nascent, with China by far leading the sales.[31] All EU truck manufacturers are committed to sell only zero-emission trucks by 2040. A significant effort will be needed to reach this point. American Tesla and Nikola are already present on the market and Chinese BYD and Japanese Toyota have already been making profit[104]. Volvo Trucks was the market leader for heavy all-electric trucks in Europe in 2021 with a market share of 42%. The company took orders, including letters of intent to buy, for more than 1 100 electric trucks worldwide.

The Nordic EU countries and Norway are world leaders in electrification of short sea shipping and provision of onshore power supply and related R&I[105]. For example, Siemens in collaboration with Echandia won the contract to equip the largest electric-ferry fleet in India (78 ferries)[106]. Danfoss Editron is part of the team delivering Thailand's first fleet of fully-electric passenger ferries[107]. In 2021, ABB won a major deal for equipping 10 all-electric ferries in Lisbon[108]. Echandia, ABB, Siemens, Wärtsilä, Danfoss are among leading EU companies equipping electric/hybrid ships.

Alstom[109] and Siemens are key players in Europe and respectively world 2nd and 3rd largest producers of railway equipment, Chinese CRRC being a leader.

In the upcoming market of urban air taxi's there are many opportunities for EU companies including CityAirbus and other EU start-ups[110]. At the same time there is already considerable competition, e.g. American Airlines, Virgin Atlantic and aircraft leasing group Avolon have made preliminary commitments to buy up to 1 000 electric air taxis from a British start-up "Vertical Aerospace".[111]

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[98] Based on Prodcom 2021 production data for EU and IEA data on 2021 global sales of EVs
[99] https://ec.europa.eu/commission/presscorner/detail/en/speech_20_2378
[100] https://www.statista.com/statistics/425481/china-annual-new-energy-vehicle-production-by-type/
[101] Time (Joey Lautrup), The Biden administration is trying to kickstart the great American electric vehicle race, 19 April 2021.
[102] Sustainable Bus, The pandemic doesn't stop the European e-bus market: +22% in 2020, 19 February 2021.
[103] https://www.sustainable-bus.com/news/eu-electric-bus-market-2021/
[104] https://www.electrive.com/2020/12/15/major-truck-makers-pledge-to-go-zero-emission-by-2040/
[105] Nordic Council of Ministers, Beatriz Martinez Romera, Tristan Smith, Ben Milligan, Karin Andersson and Maria Grahn, Workshop Report: Nordic Action for a Transformation to Low-carbon Shipping, 2017.
[106] Echandia, 2020: https://echandia.se/echandia-marine-division-wins-battery-contract-for-the-worlds-largest-fleet-of-electric-passenger-ferries/
[107] Danfoss, Thailand's first fleet of fully-electric passenger ferries to hit the water in 2020, 01 October 2020.
[108] ShipInsight, ABB wins major deal for 10 all-electric ferries in Lisbon, 13 April 2021.
[109] Now including also rail division of Canadian Bombardier
[110] https://siliconcanals.com/news/future-of-urban-air-mobility-in-europe/
[111] Financial Times, UK air taxi start-up finds early buyers for 1 000 vehicles, https://www.ft.com/content/072a7577-ed23-4cb4-9bc0-2395e892d0ad

While an EU stationary storage market is only gradually developing, the EU already have a strong player, Fluence (co-owned by German Siemens and American AEG) remaining the top utility-scale energy storage system integrator in the world.[112]

Sonnen (now owned by SHELL) is the leading EU company in home storage, with main competitors being US Tesla and Korean LG Chem[113,114]. Sonnen has put Germany's and the EU's largest virtual battery into operation.

Tesla remains world leader with 4 GWh (+32% y/y) stationary batteries deployment in 2021 worldwide. In 2022, the BESS branch of Tesla is expected to outpace its automotive section.[10] In September 2021 Tesla announced new Megapack factory with 40 GWh/y capacity. The demand by far exceeds Tesla's production, the bottleneck remain supply chain.

BYD is a leading Chinese automobile OEM with in-house battery production capacity. BYD entered the BESS market in 2008 and has delivered over 1.7 GWh storage products to nearly 300 cities worldwide.

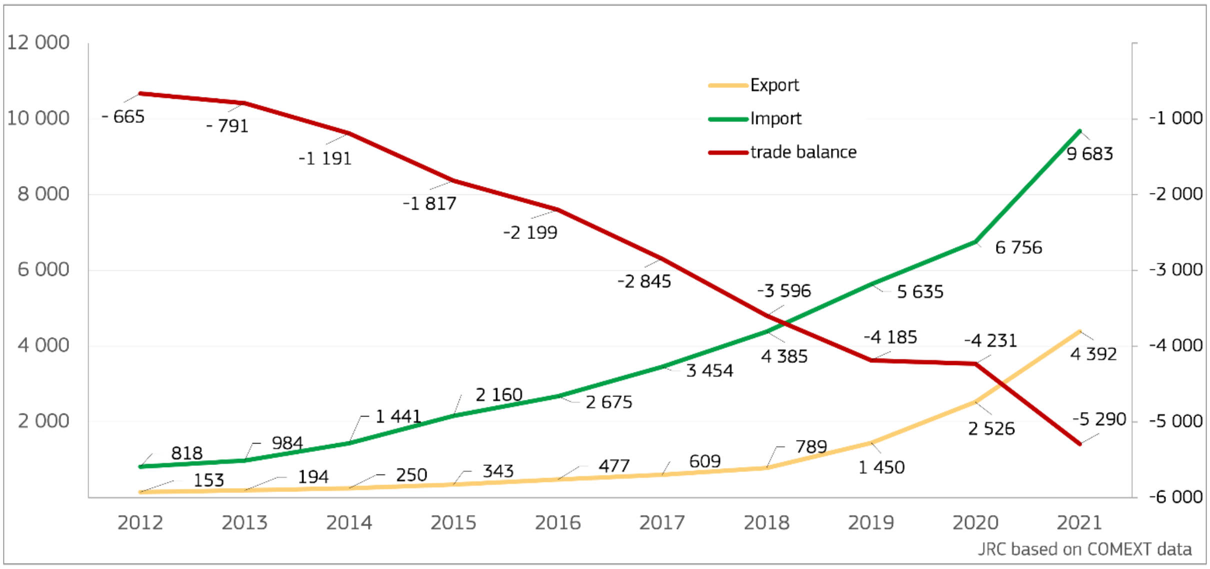
4.2 Trade (Import/export) and trade balance

JRC analysis based on COMEXT and COMTRADE data. COMEXT code: 850760, COMTRADE code: 850760. Trade data on export include also re-export.

EU imports almost all raw materials and components needed for battery production. However the existing cell production facilities attract raw material suppliers and a development of local supply chains around those production centres can already be observed. EU is a nett batteries importer, however it imports mostly battery cells and modules (at low assembly level) while export battery packs and systems (higher value added products). EU also imports most of cell manufacturing equipment.

In 2021, the EU import of batteries increased by 43% and the export raised by 74%. Despite this, the EU remained a net importer of batteries and its negative trade balance reached the record -5 290 EUR Million, 25% more than in 2020.

Figure 29. Trends in EU external export and import of batteries and in a battery trade balance (million EUR).



Source: JRC based on COMEXT data.

The biggest EU importer of batteries (also biggest in the world scale, before US) was Germany, satisfying its needs (17 600 EUR Million) more or less in halves on internal EU and external markets. Germany is also the second largest exporter of batteries (9 700 EUR Million) in similar proportion of EU to non-EU exports. The largest EU exporter (12 600 EUR Million), is Poland, supplying mainly the internal EU market (88% of polish export is EU internal). Poland is also the second in the world scale battery exporter, after China (12 600 vs 25 600 EUR Million respectively). Hungary is the third EU exporter of batteries (7 000 EUR Million), also supplying

[112] Energy Storage News (Andy Colthorpe), Guidehouse: Fluence ahead of Tesla in global utility-scale energy storage leaderboard, 29 January 2021.

[113] Reuters (Vera Eckert), Christoph Steitz, Shell-owned German solar battery firm sonnen sets sights on growth, 15 January 2021.

[114] YSG Solar, Top 50 Energy Storage Companies in 2021, 12 January 2021: https://www.ysgsolar.com/blog/top-50-energy-storage-companies-2021-ysg-solar

mainly the internal EU market. This is as both countries host battery cell production facilities of Korean companies. The most of EU produced batteries exported outside EU reached US (2 400 EUR Million), followed by Mexico, China and UK. The biggest supplier of batteries to the EU was China (12 800 EUR Million), followed by South Korea and US.

In the EU in period 2019-2021 only two countries, Poland and Hungary has achieved positive trade balance.

The fast development of the positive trade balance in Poland and Hungary is the result of investments of Korean subsidiaries, LG Chem in Poland and SK Innovation and Samsung SDI in Hungary that started production in 2017-2019 and still scaling up. The other projects are on different stages of development and are expected to enter the market in next few years.

The demand side of the market is slowly increasing activity since approx. 2012, and since 2019 significantly increasing, following the trends in automotive industry driven by markets and policy developments. While being net exporter of cars, EU was importing slightly more BEV and PHEV than exporting in 2020 (in pieces), however the value of exported BEVs and PHEVs was already greater than those imported.[115,116] Also, the exports of EVs is growing faster than imports. It has to be noted that cars are mostly produced in the region of consumers. E.g. EU automotive companies are scaling up their subsidiaries in China, rather than exporting cars. US car manufacturers do the same. EU companies have subsidiaries also in other regions, notably US. Also EU itself hosts a number of subsidiaries of foreign automotive companies.

4.3 Resources efficiency and dependence in relation to EU competitiveness

Most of raw and refined materials are imported. China holds 80% of the world's battery raw material refining capacity.[117]

In 2020 the Commission added lithium to Critical Raw Materials list[118]. It is clear that EU cannot allow to replace current reliance on fossil fuels with dependency on critical raw materials. Supply of the raw materials is of biggest concern.

According to EBA250, Europe should be able to cover up to 20% of the battery ecosystem's needs for lithium by 2025 thanks to projects under way. An encouraging development is the trend to investigate also larger occurrences of geothermal brines as possible lithium resources, such as the Rheingraben on both sides of the German-French border where Vulcan Energy Resources just has completed a very positive pre-feasibility study. Other areas of great geological potential for extraction of lithium from brines are found in the Pannonian Basin, Hungary. So far, no lithium refining projects are under way in Europe.

The cobalt and nickel mining projects under way may roughly satisfy up to 4% and 2% of the European demand, respectively[119]. The Democratic Republic of Congo alone produces 64% of the world's cobalt supply[120]. This being said, Europe, is a relatively important producer of refined cobalt with Finland (10%) and Belgium (5%) having the largest share of the world's production after China.[121,122] The cobalt refinery in Kokkola, Finland, (now owned by Umicore) is the largest cobalt refinery outside of China. This supply however will not be able to satisfy growing demand from EU battery producers.

European supply of graphite for 2030 is likely to remain well below 5% of the European demand.

EU subsidiaries of Asian companies might face fewer raw materials bottlenecks as many raw materials are mined in Asia and most are processed in Asia. At the same time they are exposed to the geopolitical risks, and the central management of the company might decide if they want to produce more in the EU located subsidiary or in the mother company in Asia. EU headquartered battery companies should unlock the potential of local raw material deposits.

EU is in possession of the batteries that at the end of life might be a source of secondary raw materials. Currently most of the batteries at the end of life are sent to Asia. The recycling industry is concentrated in China and South Korea, where the vast majority of the batteries are also made, but there are several dozen recycling start-ups in North America and Europe. Chinese GEM and Brunp (CATL subsidiary) and a number of other Chinese

[115] Eurostat, 2021. Data retrieved: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210524-1

[116] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_hybrid_and_electric_cars#Overall.2C_the_EU_exports_more_hybrid_and_electric_cars_than_it_imports

[117] Marian Willuhn, National lithium-ion battery supply chains ranked, PV Magazine, 16 September 2020.

[118] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1542 .

[119] EBA250

[120] European Commission, Report on Raw Materials for Battery Applications, 22 November 2018, SWD(2018) 245/2 final

[121] British Geological Survey, World Mineral Production 2015-2019, 2021.

[122] Statista, 2021. Data retrieved: https://www.statista.com/statistics/339798/annual-cobalt-refinery-capacity-by-country/

and Korean companies account for up to 88% of the market[123]. Competition is so intense in China that recyclers are willing to pay for used batteries, which is not yet the case in EU. For the time being, Umicore, with its world-wide capacities, is the only company headquartered outside Asia belonging to leading global recyclers[124]. For the EU it is a lost chance to satisfy at least a part of its demand with local supply of the raw materials and lost chance to reduce dependence on supply from third countries. Development of recycling technologies should be strongly supported.

Overall, recycling capacities in the EU are still low. Umicore's existing facility in Belgium has an installed capacity of 7 000 tons per year and Northvolt's recycling plant will have the capability to recycle approximately 25 000 tons of battery cells per year from 2022. Limited recycling capacity will be added in 2021 through VW pilot recycling plant in Salzgitter (1 200 t/year) and Fortum's plant in Ikaalinen (3 000 t/year). There is also a Nickelhütte Aue (3 000 t/year), Accurec, Redux (2 000 t/year) in Germany, smaller recyclers (<1 000 t/year), SNAM, EDI, TES-AMM (former Recupyl) in France, AkkuSer in Finland or Duesenfeld, Promesa in Germany. In May 2022 Hydrovolt, a battery recycling joint venture between Northvolt and Hydro, has started commercial recycling operations at its plant in Fredrikstad, Norway, with capacity to process 12 000 tonnes of battery packs a year.

Other projects have been announced and are under development which will enable Europe to recover important raw materials, such as lithium, cobalt and nickel. Yet, capacities will need to ramp up much more quickly to meet the increasing amount of batteries that reach their end-of-life in some years from now.

At the end of 2021 Swedish Northvolt produced its first battery cell made with 100% recycled nickel, manganese and cobalt and started commercial deliveries in 2022. They claim to have a highly efficient recycling process with recovery of up to 95% of the battery metals.[125]

In addition, the batteries value chain will benefit from the European Raw Materials Alliance (ERMA)[126] launched in September 2020, as part of an Action Plan on Critical Raw Materials[127].

[123] Greentechmedia, How China Is Cornering the Lithium-Ion Cell Recycling Market, 11 September 2019.

[124] In4Research, Lithium ion Battery Recycling Market - Strategic recommendations, Trends, Segmentation, Use case Analysis, Competitive Intelligence, Global and Regional Forecast (to 2026), 2020.

[125] NorthVolt, November 12, 2021 "Northvolt produces first fully recycled battery cell"

[126] https://erma.eu/

[127] COM (2020) 474

5 Conclusions

5.1 Overall Conclusions

EU is strong in the segment of integration/final products (EVs and stationary storage).

It is rather weak when it comes to raw materials, advanced materials (cathode materials, electrolyte, separator are improving) and equipment for manufacturing of Li-ion cells. Recycling capacities currently insufficient are expected to improve after 2025. This leads to imports from third countries and in case of recycling – export of EoL batteries to third countries.

In the central part of the value chain – Li-ion cell manufacturing, EU is gradually increasing its weight, for the moment mostly due to the daughter companies of Korean producers. EU capital owned battery cell production also develops fast, but still is at early stage. It will still take a number of years before EU can become largely self-sufficient in Li-ion cell production.

Battery R&D is mostly coming from mobility applications EV sector.

In long term price of batteries decrease, however this trend was broken in the second half of 2021 and prices are expected to continue rising throughout 2022; in longer perspective, the price should continue decreasing, possibly as of 2023 at least in fixed prices.

Stationary system prices are much higher for kWh of stored energy than EV batteries, due to additional system elements costs.

EU focuses on high-end battery cells for mobility and transport, not investing much in development and production of lower performing, cheaper batteries e.g. LFP, Na-ion, non-vanadium RFB that could well serve a stationary applications. Those technologies are also less dependent (LFP) or independent (Na-ion, non-vanadium RFB) of critical raw materials. This way of reduction of dependency on critical raw materials is not sufficiently exploited.

Na-ion batteries get commercialised by CATL (China) and the Europe is weakening its position in this technology (e.g. UK Faradion, developer and producer of Na-ion batteries was bought by India's Reliance Industries).

Batteries are enablers for wider deployment of intermittent RES, also in context of increasing energy independency from Russia.

In case China ally with Russia and restrictions on China are forced, there is serious risk for battery materials supply chains, as most of materials refining is done in China.

Development of recycling technologies should be strongly supported to reduce EU dependence on external supply of raw materials.

5.2 SWOT Analysis

STRENGTHS	WEAKNESS
• Large ecosystem around batteries in a growing economic sector. EBA250 Business investment platform facilitating match making between investees and investors • All key world producers of batteries are establishing their subsidiaries in EU or have plans to do so. Annual total production capacities of batteries in the EU are steadily growing. Dependence on imported battery cells is set to decrease. • EU has decades long expertise in high-end Li-ion battery cells (Saft, Varta, Leclanché) • At least 10 EU headquartered companies are advancing with giga-factory plans for Li-ion cells. • Very strong companies in end-products sector (EVs and storage systems); their active involvement in Li-ion battery cells giga-factory projects • EU has strategic research agenda for the entire batteries value chain (Batteries Europe, 2020) • Europe is increasing R&I spending, notably through multi-billion Member States-led IPCEIs and increased EU funding. • EU has specialists highly educated in electrochemistry. • EU has safety experts, regulations and general awareness.	• Battery industry is highly dependent on third countries for sourcing of raw materials. • EU has no lithium refining capacity • Battery cell production equipment is largely imported from Asia. • EU head-quartered companies don't yet have large experience in mass production of Li-ion batteries. For the time being, EU needs are mostly satisfied by subsidiaries of South Korean companies in Poland and Hungary. • EoL Batteries are largely exported to Asia for recycling, even EU headquartered Umicore has most of recycling capabilities in Asia. • The deficit in batteries trade of EU keep growing, however this trend is likely to change soon. • Asian firms clearly lead in the global race for battery technology, American being also an important players. It is to observe how the situation develop with recent initiatives to support R&I and production. • In some MS support to residential PV (feed-in conditions) is organised in a way that there are no incentives for self-consumption and storage. • Lack of skilled workers at technical level across most of the value chain (facilitating measures are in preparation). • EU is rather weak in the development and production of Na-ion batteries, technology that do not rely on any critical raw material.
OPPORTUNITIES	**THREATS**
• Increased attention to the issue of raw materials through creation of the European Raw Materials Alliance. Possibility to attract investments in mining in the EU. • Coordination of different battery R&I activities can be strengthened using Batteries Europe technology platform • Expand EU strength in battery manufacturing systems engineering based on EU players such as Manz • Expand EU competence in active materials beyond cathode materials • Building strong Li-ion battery recycling industry based on strength of companies such as Umicore, this would also allow to better utilize raw materials already in	• Europe is increasingly dependent for both, raw materials and also some active materials, on third countries. EU headquartered battery cell producers may even be more concerned than EU subsidiaries of Asian companies. • Current trend towards ever bigger EVs may compromise energy efficiency and exacerbate the issue of raw materials, unless it is a temporary trend and contributes to most polluting cars being replaced first. Consumer awareness is necessary. • EU head-quartered companies face a big challenge of being able to mass-produce battery cells at competitive prices. • Charging infrastructure deployment may not be advancing at a needed pace (albeit number of

possession and reduce dependence on third countries. • Build on the strength of Nordic countries in electrification of short-sea shipping and provision of shore side electricity • MS using possibilities under regional aid, environmental and R&I aid rules to intervene in cases of market failure. More active use of national allocations of EU funds for the benefit of weaker segments of the value chain. • Future EU Regulation on Batteries and Waste batteries can help Europe becoming a world leader in sustainable batteries and limit market access of batteries with large CO_2 footprint. • EBA250 Academy provides good opportunities to close skills gap, but the effort from each MS is needed to deploy the new training platform across EU. • Increasing demand for batteries might support development of EU production, boost the EU innovativeness and economy. Strengthening of demand relates to: - an EU level ban for ICE cars and vans from 2035 - strengthened EU CO_2 norms for transport for 2030 - RED III directive - cities moving towards zero emission zones - other similar activities • Strengthened battery production, especially of "cheap" batteries will allow increased supply from renewable energy sources, unlocking the emissions reduction targets and helping to mitigate climate change. • Growing batteries production would create environment for cooperating entities to develop, build value chains, use effects of scale and lessons learned to further decrease costs, all this with benefits to the EU economies. • Investing in zero-CRM technologies would allow to develop battery solutions not exposed to risk of high prices and reduce dependence from third countries. It would also reduce a price pressure on materials that are needed in high-end solutions by reducing demand form other applications.	measures to address the issue are in the pipeline) • Development of grid infrastructure may hinder deployment of charging infrastructure or direct heavy road transport (if this electrification path is adopted) • EU focuses on high-end battery cells for mobility transport, not investing much in development and production of lower performing, cheaper batteries that are also less exposed to prices volatility and less depending on supply of critical raw materials, e.g. LFP, Na-ion, non-vanadium RFB, or in longer perspective Li-S • Increasing demand for batteries in situation of negative trade balance might be not only an opportunity, but also a risk to worsen the trade balance and strengthen the dependence on third countries

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List of abbreviations and definitions

18650 one of standard formats of cylindrical batteries; 18 mm diameter, 65 mm length

4680 one of standard formats of cylindrical batteries; 46 mm diameter, 80 mm length

AA one of standard formats of cylindrical batteries; 14 mm diameter, 50 mm length

AABC Advanced Automotive Battery Conference

AAA one of standard formats of cylindrical batteries; 10.5 mm diameter, 44.5 mm length

ACEA European Automobile Manufacturers' Association

ASSB all solid-state battery

BEV battery electric vehicles

BESS battery energy storage system

BMLMP bio-mineralized lithium metal phosphate

BNEF Bloomberg New Energy Finance

CAPEX capital expenditures, funds used by a company to acquire or maintain physical assets

CATL Contemporary Amperex Technology Co., Limited

CEA French Alternative Energies and Atomic Energy Commission

CEE central and east Europe

CETO Clear Energy Technologies Observatory

CINDECS European Climate Neutral industry Competitiveness Scoreboard

CORDIS Community Research and Development Information Service, European Commission's database of information about projects funded by the EU's framework programmes for research and innovation (FP1 to Horizon 2020)

CRM critical raw material

DoD depth of discharge

DG Directorate General

EAFO European Alternative Fuels Observatory

ECV electrified vehicle, either EV or PHEV

EES electric energy storage

EFTA European Free Trade Association

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

EoL end of life

EROEI energy return on energy invested, the energy produced over the lifetime of an energy production system divided by the energy necessary to build, maintain, dismantle and recycle the system

ESS energy storage systems

EU European Union

EV electric vehicle

GDP gross domestic product

GHG greenhouse gasses

HC hard carbon

HDCV heavy duty commercial vehicle

HE Horizon Europe

HE-NMC high energy NMC; cathode material chemistry, known also as layered- or asymmetric-NMC

HEV hybrid electric vehicles

HVS high voltage spinel; cathode material chemistry, known also as LNMO

ICE internal combustion engine

ICE initial coulombic efficiency

IEA International Energy Agency

IPCEI Important Projects of Common European Interest

IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LCA	lifecycle analysis
LCC	Life-cycle costing
LCO	lithium cobalt oxide; battery chemistry
LCoE	levelized cost of energy
LDV	light duty vehicle
LFP	lithium iron phosphate; battery chemistry
Li-ion	lithium-ion, family of battery chemistries
LiSER	Lithium Slim Energy Reserve, C4V's patented technology
LMO	lithium manganese oxide; battery chemistry
LNMO	$LiMn_{1.5}Ni_{0.5}O_4$ spinel; cathode material chemistry, known also as high voltage spinel, HVS
LNO	lithium nickel oxide; battery chemistry
LNP	lithium nickel phosphate; battery chemistry
LTO	lithium titanium oxide; battery chemistry
MDCV	medium duty commercial vehicle
MS	member state
Na-ion	sodium-ion; battery chemistry
NCA	lithium nickel cobalt aluminium oxide; battery chemistry
NFA	lithium nickel iron aluminium oxide; battery chemistry
NGV	natural gas (powered) vehicle
Ni-MH	nickel-metal hydride; battery chemistry
NMC	lithium nickel manganese cobalt oxide; battery chemistry
NMCA	lithium nickel manganese cobalt aluminium oxide; battery chemistry
NMP	N-methylpyrrolidone, a solvent used during Li-ion battery electrode manufacturing
MDCV	medium duty commercial vehicle
OPEX	operating expenditure, an ongoing cost for running a product, business, or system
Pb-A	lead-acid, family of battery chemistries
PBA	prussian blue analogues
PC	personal car
PEFCR	product environmental footprint category rules
PFSA	perfluorinated sulfonic acid
PHEV	plug-in hybrid electric vehicle
PPA	power purchase agreement
PTFE	polytetrafluoroethylene, teflon
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RES	renewable energy sources
RFB	redox-flow batteries
rhs	right hand scale
R&I	research and innovation
RoW	rest of world
S-LCA	Social Life Cycle Assessment
SLI	starter, light, ignition battery
SoC	State of charge
SSB	solid state battery, synonym to ASSB
TCO	total costs of ownership
TRL	technology readiness level

TWh	terawatt hour, unit of energy equal to 10^{12} Wh
UCV	upper cut-off voltage
UK	United Kingdom
US	United States
VC	venture capital
VRFB	vanadium redox-flow battery
XFC	extreme fast charging
ZBRFB	zinc–bromine redox flow battery
ZEBRA	ZEolite Battery Research Africa or sodium-metal halide; battery chemistry
Zn-air	zinc-air; battery chemistry

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Annex I Status of development of selected battery chemistries

Table 4. Status of development of Li-ion chemistries and some non-Li-ion – 2021.

<table>
<tr><td colspan="5">Chemistry</td></tr>
<tr><td>cathode</td><td>anode</td><td>Electrolyte</td><td>generation</td><td>TRL</td></tr>
<tr><td colspan="5">R&D&I status / latest news</td></tr>
<tr><td colspan="5">Li-ion</td></tr>
<tr><td>LFP</td><td>C</td><td>Organic liquid</td><td>1</td><td>9</td></tr>
<tr><td colspan="5">LFP chemistry is of high thermal stability, long life, and uses a cheap cathode materials. Energy density lower comparing to NMC cells. It is the first choice chemistry for stationary storage applications. For the long time it was seen as unsuitable for EV's, but now it is entering the budget segment of EVs. This trend seems will be continued. Observed increase of manufacturing capabilities.

Tesla announced moving from NCA to LFP battery chemistry for all its standard-range EVs worldwide, before LFP battery cars were sold only in China; Ford Motor and Volkswagen expressed interest in LFP battery chemistry for lower-priced models, particularly for commercial vehicles like delivery vans that don't need multi-hundred mile range.[128]

As of 1 Jul 2021 CATL announced the Jinjiang 100 MWh Energy Storage Power Station has been operated safely for 535 days, with a total energy discharge of 68.52 GWh. It was successfully connected to the grid on 15 Jan 2020, with 30 MW/108 MWh based on 12 000-cycle ultra-long-life energy storage batteries that were used for the first time. Relying on life compensation technology, the long-life batteries are the first LFP batteries with a life of over 12 000 cycles in the industry, far exceeding the average of 3 000 - 6 000 cycles of other products on the market. The service life is expected to exceed 20 years with charging and discharging 1.5 - 2.0 times a day. Following this development Energy Storage Development Co., Ltd. (SG-CATL) and China Huadian Corporation Ltd. (CHD) also kicked off a 300 MW / 600 MWh energy storage project. At the same time, this technology has been adapted for use in the vehicle batteries, resulting with a 16 years of service life and a total range of over 2 million kilometres EV batteries. This ultra-long life could make possible practical implementation of V2X.[129]

Chinese Gotion High-Tech has already industrialized its 210 Wh/kg LFP battery and plan to start the mass production of the 230 Wh/g LFP batteries by the end of 2022.[130]

In Jan 2022 SVOLT presented it's new "short-blade battery" series of cells intended for EVs, hybrid and commercial vehicles. With the gravimetric energy density of 185 Wh/kg and the volumetric energy density of 430 Wh/l this battery is of similar performance to the BYD's blade battery. The battery is capable of fast charge at 2.2 – 4C (charge time of 15-25 min.). The company has increased the energy density of LFP cells by optimising the anode material, however it is not clear which kind of changes to the anode material is meant. The company plan a dedicated production facility for short-blade cells of 20 GWh, starting production in the third quarter of 2022.[131]

Freyr has announced a JV with Aleees to establish a European LFP cathode plant in the Nordics.[10]</td></tr>
<tr><td>NCA</td><td>C</td><td>Organic liquid</td><td>1</td><td>9</td></tr>
<tr><td colspan="5">The chemistry that compete with NMC and recently also with LFP in EV applications. NCA cells exhibit high energy and power densities, long shelf life, but degrade faster with use than NMC cells. Relatively expensive and less thermally stable.</td></tr>
<tr><td>NMC111</td><td>C</td><td>Organic liquid</td><td>2a</td><td>9</td></tr>
<tr><td colspan="5">First of the NMC family formulations. Blending nickel with manganese and cobalt oxide improves cathode durability. Combining all three results in good performance (energy density, power density, durability and safety). Now NMC111 is seen as already outdated formulation, leaving space for more Ni-reach and low-Co chemistries.</td></tr>
<tr><td>NMC532</td><td>C</td><td>Organic liquid</td><td>2b</td><td>9</td></tr>
</table>

[128] https://www.cnbc.com/2021/10/20/tesla-switching-to-lfp-batteries-in-all-standard-range-cars.html
[129] https://www.catl.com/en/news/684.html
[130] https://autonews.gasgoo.com/china_news/70019980.html
[131] https://www.electrive.com/2022/01/05/svolt-presents-new-lfp-battery-cell/

Currently (since approx. 2019), NMC532 and NMC622 are chemistries dominating Li-ion EV battery cell production. The trend shows that in few years this formulation will be replaced with NMC811, even lower cobalt containing NMC90505, or cobalt-free cathodes, mitigating cobalt dependency. During the International Battery Seminar (IBS), 28-31 Mar 2022, Orlando, Florida prof. Jeff Dahn from Dalhousie University presented an single crystal $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC532)/graphite cells that started cycling test (1C charge/1C discharge) in Oct. 2017 and are still running at room temperature, reaching 4.5 years of continuous cycling (c.a. 20 000 cycles) with ~5% degradation. This result was achieved after switching from polycrystalline NMC to single crystal NMC, the choice of quality artificial graphite and appropriate electrolyte additives.[132]				
NMC622	C	Organic liquid	2b	9
Together with NMC532 currently dominating chemistry, accounting for about 40% of EV batteries production. It is expected that within few years it will be replaced with low cobalt or cobalt-free cathodes.				
NMC622	C/Si (5-10% Si)	Organic liquid	3a	9
Together with NMC532 currently dominating chemistry, accounting for about 40% of EV batteries production. It is expected that within few years it will be replaced with low cobalt or cobalt-free cathodes. Small addition of silicon compounds to anode active material is already settled on the cell production market.				
NMC811	C/Si (5-10% Si)	Organic liquid	3a	9
NMC811 is entering the wide deployment phase with growing market share, especially in high-end EVs. In 2021 it accounted for ~15 % of the EV batteries production. NMC 811/graphite cells can significantly increase their lifetime when operated at a limited upper cut-off voltage (UCV) of 4.06 V, reaching decades-long lifetimes at 20–30 °C, if the best graphites are selected.[133] This finding may have an important impact on the stationary ESS where lifetime is a critical parameter and energy density less important. Si dominant anode –> 3a+In Mar 2022 the StoreDot, developer of extreme fast charging (XFC) battery technology for electric vehicles, reported achieving 1 250 cycles with silicon-dominant cells that were taken to 80% of SoC in 15 minutes and then discharged for one hour. The test is done using a specially designed testing form factor cells of 300 Wh/kg and 680 Wh/l energy density under real-world conditions at room temperature and with no additional pressure applied. The company is now advancing to the B-samples using larger cells that will be shipped to global automotive manufacturers still in 2022. The cells will be available in both pouch and the 4680 form factors. The company's target is to deliver 100 miles of range after two minutes of charge within a decade.[134]				
HE-NMC	Si/C (>10% Si)	Organic liquid	3b	2025
High-energy NMC with the general formula $xLi_2MnO_3 \cdot (1-x)LiMO_2$ (M=Ni, Mn, Co), is an alternative chemical formulation of the cathode material that will be developed in longer term. Those materials exhibit the highest specific energy (~900 Wh/kg) among known cathodes. In the HE-NMC composite structure, the layered $LiMO_2$ component is stabilized by the structurally compatible Li_2MnO_3 component. This allow for a much deeper delithiation than that normally possible in pure layer LCO ($Li_{1-x}CoO_2$, $x_{(max)}$=0.5). In the cut-off voltage range of 2.0-4.4 V vs. Li^+/Li, $LiMO_2$ is the only electrochemically active component. Li_2MnO_3 is inactive as the manganese ions are already tetravalent and cannot be further oxidized. In this situation, the main function of Li_2MnO_3 is to stabilize the $LiMO_2$ layered structure by providing Li^+ ions to the active $LiMO_2$ component. However, when the voltage is increased to 4.4-4.6 V, Li_2MnO_3 becomes active and capacities above 250 mAh/g can be reached. In the higher voltage range, the electrochemically active MnO_2 phase will be generated owing to the removal of Li_2O from Li_2MnO_3. Despite the favourably high capacity, HE-NMC still suffers from poor cycling stability, seriously limiting its practical application in the EVs. This is mainly attributed to the removal of Li_2O from Li_2MnO_3, resulting in damage to the electrode surface and increased impedance, especially at high current densities. The severe voltage fading is probably ascribed to the				

[132] https://nickelinstitute.org/en/blog/2022/march/four-million-mile-battery-is-now-a-reality/

[133] A. Eldesoky, E. R. Logan, A. J. Louli, W. Song, R. Weber, S. Hy, R. Petibon, J. E. Harlow, S. Azam, E. Zsoldos, J. R. Dahn, Impact of Graphite Materials on the Lifetime of NMC811/Graphite Pouch Cells: Part II. Long-Term Cycling, Stack Pressure Growth, Isothermal Microcalorimetry, and Lifetime Projection, *J. Electrochem. Soc.* (2022) **169** 010501, DOI: 10.1149/1945-7111/ac42f1

[134] https://www.greencarcongress.com/2022/03/20220323-storedot.html

transition towards a spinel phase when cycling at a cut-off window of 2.0 and 4.6 V. Besides cycling performance, low electronic conductivities and low tap densities need to be enhanced before HE-NMC could be considered as a battery technology for next-generation EV applications.				
HVS (LNMO)	Si/C (>10% Si)	Organic liquid	3b	2025
The high-voltage spinel $LiNi_{0.5}Mn_{1.5}O_4$ (HV-spinel) is a promising next-generation high-energy cathode material for EVs. It has a high operating voltage at 4.7 V and a specific capacity of 130 mAh/g, which leads to a specific energy of about 580 Wh/kg at the cathode-level. This is a modest energy improvement, but HV-spinel also has other advantages like a facile synthesis, low cost, good safety, environmental friendliness, and excellent rate capability owing to both high electron and ionic (Li^+) conductivity. In particular, the rate capability of disordered HV-spinel phase (space group Fd-3m) is several orders of magnitude higher than that of the ordered one (space group P4332). However, such material suffers from some drawbacks such as severe capacity fading at elevated temperature (60 °C) and the electrolyte decomposition owing to higher operating voltage. Therefore, a high-voltage electrolyte also need to be developed.				
LCO	C	Organic liquid	-	9
Lithium Cobalt Oxide chemistry is commonly used in small electronics. It is the highest energy density among commercial Li-ion chemistries, but using expensive raw material, the batteries are prone to thermal instability (safety issues), fast capacity fade (short life) and low power density. This cause that other Li-ion chemistries are preferred for EV and stationary energy storage.				
LMO	C	Organic liquid	-	9
In the past it was a chemistry of choice for EV battery producers. Using manganese in place of cobalt allow for higher power density and improved thermal stability (comparing to LCO). Lifetime however remains short and energy density is reduced.				
	LTO	Organic liquid	-	9
LTO chemistry uses LTO nanocrystals as anode active material. It shows excellent thermal stability and durability. They are expensive, but able to deliver stored energy over an extremely short period, which makes them competitive in high power applications. Low energy density make them unsuited to EV's, but suitable for grid frequency regulation, PV/wind farm smoothing and some city e-buses.				
BMLMP	NA	NA	-	6
C4V's LiSER technology is a patented battery cell design that allows to build the pack directly from cells. This platform includes super-fast charge and discharge capabilities without losing the energy density of 190 Wh/kg at the pack level (currently the highest available on the market), an energy density at cell level of up to 228 Wh/kg and a power density of up to 2 000 W/kg. By using the patented bio-mineralized lithium metal phosphate (BMLMP) technology LiSER enables the highest average voltage of any Li-ion cells at 3.9 V. The inherent oxygen deficient BMLMP not only augments battery safety but also delivers a voltage that is at least 20% higher than the LFP formulations currently widely being used in the market. The cell is tables, advanced prismatic cell that has an in-situ cooling loop allowing efficient operations at temperatures ranging from -40 °C to 90 °C. The chemical formulation is cobalt and nickel free. The company also claim that while burning nickel-rich NCA or NMC cells emit nickel oxide particles, the LiSER battery produce fumes that is non-carcinogenic, but still toxic. Their battery uses elements that are environmental-friendly, sourced with a robust local supply-chain and enable a significantly lower carbon footprint. In the US early partners of this technology would be C4V's own Gigafactory, iM3NY and C4V is closely working with a few OEMs to integrate this technology in various end applications starting from grid, EVs and electric aircrafts.[135]				
ASSB Li-ion				
LCO, NMC, LMO, NCA	Si/C (>10%)	Solid state	4a	5-6, 9*
In solid-state batteries not only electrodes and the electrolytes are solid state. They can potentially be made thinner, more flexible, and contain more energy per unit weight than conventional Li-ion batteries. They are also safer as do not containing liquid and flammable electrolyte.				

[135] https://www.chargecccv.com/innovation/li_ser_tech

In 2021 Ford and BMW has committed to testing Solid Power's cells for automotive qualification.[136] 20 Ah Silicon EV Cells successfully produced, qualification will start in 2022. Company is setting the production line for 100 Ah cells that will enter the automotive qualification in 2022.[137] Qing Tao started the first Chinese production line of solid-state batteries in 2018 supplying SSBs for "special equipment and high-end digital products". Reports from 2018 were already talking about an energy density of 400 Wh/kg. QingTao has a production line for solid-state lithium batteries with a capacity of one gigawatt-hour per year since 2020. Neta and BAIC have already used these pouch cells batteries in electric car prototypes. In 2022 QingTao Energy Development has begun constructing a solid-state battery production facility in Kunshan, with an annual capacity of 10 GWh and is the company's second battery plant. It is not yet known when construction will be completed.[138] Since 2019 Murata Manufacturing Co is commercially supplying 2-25 mAh solid state batteries with oxide ceramic electrolyte for small electronics (no more details on chemistry available).[139] In Jan 2022 ProLogium and Mercedes-Benz entered into a technology cooperation agreement to develop solid-state battery cells for electric vehicles. ProLogium's automated pilot production line has provided nearly 8 000 solid-state battery sample cells to global car manufacturers for testing and module development. By the end of 2022, ProLogium will complete the establishment of a GWh plant, followed by capacity expansion plans in major markets worldwide.[140]				
LCO, NMC, LMO, NCA	Li metal	Solid state	4b	5-6
From generation 4a differs in using metallic lithium anode, leading to increase of the energy density. In 2021 Solid Power produced also 20 Ah Lithium Metal EV Cells. QuantumScape has a joint venture with Volkswagen to produce solid-state battery cells, starting in 2024, for the German automaker's electric vehicles and eventually for other carmakers.[141] ProLogium developed also a lithium metal battery cell.				
ASSB Li-S				
Li_2S	Li metal	Solid state	4	4, 9**
OxisEnergy, a leader of Li-S technology development declared on spring 2021 that by the end of 2021 it will provide its partners with cells and battery systems by Autumn 2021 for use in trials, proof of concept and demonstrator battery systems for the Aviation, Marine, Defence and Heavy electric Vehicles (HEV) sectors.[142] Berlin-based Theion, a developer of lithium-sulfur cathode technology patented production process that combines sulfur's crystal material properties with carbon nanotubes, a proprietary solid polymer electrolyte and lithium metal foil as anodes. The targeted battery specification is: Gravimetric energy density ≥ 1 000 Wh/kg Volumetric energy density ≥ 1 500 Wh/l Power capability ≈ 12 000 W/kg Cycle life ≥1 000 at 1 C Operational temperature -20 °C to 60 °C The company will start the qualification process already in 2022 starting at material level. First customers from the aerospace field, then aircraft, air taxis, drones, mobile phones and laptops, before servicing the electric flight and automotive sectors in 2024. Theion operates three locations in Berlin, specializing in cell design, prototyping and testing. Theion is expanding by adding manufacturing facilities beginning in Berlin. Locations for later gigafactories are not				

[136] https://solidpowerbattery.com/road-to-auto-qualification/
[137] https://solidpowerbattery.com/solid-power-meets-all-2021-milestones/
[138] https://www.electrive.com/2022/03/01/chinese-startup-chingtao-to-build-solid-state-battery-plant/
[139] https://www.murata.com/en-global/news/batteries/solid_state/2019/0626
[140] https://prologium.com/prologium-and-mercedes-benz-entered-into-a-technology-cooperation-agreement-to-develop-solid-state-battery-cells-for-electric-vehicles/
[141] https://www.reuters.com/business/autos-transportation/quantumscape-partners-with-unidentified-large-automaker-test-battery-prototypes-2021-09-21/
[142] https://oxisenergy.com/wp-content-uploads-2020-11-press-release-nov-2020-final-pdf-2/

determined yet, but will be located close to the customers, thus, production sites are expected in Europe, Asia and the US.[143]				
Li-air				
O_2	Li metal	Different considered	5	4
Japanese consortium of National Institute for Materials Science and Softbank have developed a rechargeable lithium-air battery with potential applications in residential storage, electric vehicles, drones and Internet-of-Things devices. They claim it has an energy density of 500 Wh/kg that greatly exceeds that of conventional Li-ion batteries.[144]				
Na-ion				
PBA	HC	Organic liquid	-	9
Sodium-ion batteries is emerging commercialised alternative to other battery technologies.[145] It has been explored as a potential cheaper alternative to Li-ion, however, due to expected low specific energy, was not well accepted by OEMs and battery suppliers. In contrary, the recent developments showed that this scepticism was unjustified. Here several parameters analysed following the recent RhoMotion report[31] and newest announcement of CATL that commercialized Na-ion cells in 2021: • energy density 100 – 150 Wh/kg (for comparison, 120 – 180 Wh/kg for LFP), while in 2021 energy density reported by CATL for commercialized cells was 160 Wh/kg with perspective of 200 Wh/kg • cycle durability of >2 000 (LFP >3 000; but 12 000 reported by CATL) – this might be the key parameter defining the cost of stationary energy storage. • cell cost at $0.045/Wh ($0.066/W for LFP) [146] • capacity retention rate at -20 °C >90% (<70% for LFP), and fast charge to 80% SoC in 15 min. • safer and easier to transport than Li-ion • wide deployment of large-scale renewable energy sources (RES) drastically lifted the demand for energy storage, which can make more space on the market for Na-ion batteries. • To achieve large-scale commercialisation, sodium-ion batteries still have a long way to go, due to the high cost associated with building out a supply chain for a new technology – this might be an overestimation, China announced plans to build this supply chain before 2024. • Na-ion batteries do not relay on any critical raw material thus allow to avoid any geopolitical risk. • Na-ion batteries relay on abundant and widely used raw materials thus not subjected to price volatility – in contrary to Li-ion batteries exposed to price changes of lithium, cobalt and nickel. • development of Na-ion production technology is less challenging than development of any other new chemistry, as many Li-ion battery technologies are easily transferrable to Na-ion battery, including fast and relatively cheap adaptation of depreciated Li-ion production lines (not having enough production capacity to compete with new installations) that ideally fit to scale up the production of batteries for emerging Na-ion market. The sodium-ion batteries' thermal stability exceeds the national (China) safety requirements for traction batteries. The first generation of sodium-ion batteries will be used in various transportation electrification scenarios, especially in regions with extremely low temperatures.[147]In 2022 CATL and Reliance Industries acquired UK-based sodium-ion specialist Faradion.[148]				
Redox-Flow (RFB)				
Vanadium RFB (VRFB)			-	9

[143] https://www.greencarcongress.com/2022/03/20220330-theion.html
[144] https://www.pv-magazine.com/2022/01/11/japanese-consortium-builds-lithium-air-battery-with-energy-density-of-500-wh-kg/
[145] Brand Essence Research, Sodium Ion Battery Market by Product Type, By End Use, Forecast to 2027 and Analysis 2019-2025, 2021.
[146] RONG Xiaohui, LU Yaxiang, QI Xingguo, ZHOU Quan, KONG Weihe, TANG Kun, CHEN Liquan, HU Yongsheng. Na-ion batteries: From fundamental research to engineering exploration, Energy Storage Science and Technology, 2020, 9 (2): 515-522
[147] https://www.catl.com/en/news/665.html
[148] https://www.pv-magazine.com/magazine-archive/sodium-ion-batteries-go-mainstream/

A 2021 study presented a novel hybrid membrane for VRFB using tungsten trioxide nanoparticles grown on the surface of graphene oxide sheets. Sheets are embedded into a sandwich structured PFSA membrane reinforced with polytetrafluoroethylene (PTFE). This membrane offer high Coulombic and energy efficiencies of more than 98.1 percent and 88.9 percent, respectively.[149] China is continuing construction of largest-to-date, 200 MW / 800 MWh VRFB energy storage installation in Dalian. According to the 2021 information, the first half of the system capacity is expected to be available by the end of 2021, the second half coming online in 2022. The design foresee the use of waste heat from the ESS for district heating (used with heat pumps).[150] In September 2021, VRB Energy, the vanadium redox battery manufacturer, started the construction of a battery energy storage system with 100 MW / 500 MWh capacity in Xiangyang, in China's Hubei province. It is installed for the Automobile Industrial Park of the Xiangyang high-tech development zone. The project is expected to be completed by late 2022.[151,152]		
Iron RFB	-	9
A technology developed under ARPA-E funding, Oregon-based ESS, whose batteries can store energy for between 4 and 12 hours, launched its first grid-scale projects in 2021. Massachusetts-based Form Energy, which raised $240 million in 2021, has batteries that store power for up to 100 hours. Its first installation will be a one-megawatt pilot plant in Minnesota, slated to be completed in 2023.[153] ESS Inc. is expanding into Europe with its first deployments on the continent later 2022 and local manufacturing capability expected by 2024/25[154] ESS Inc. will install a 300 kW / 2 MWh iron RFB BESS) for the micro grid in Patagonia, Chile[155]		
Zinc-bromine RFB (ZBRFB)	-	9
It is a rechargeable battery chemistry that uses a reaction between zinc metal and bromine to produce electric current, with an aqueous electrolyte, a solution of zinc bromide. Developed as an alternative to Li-ion batteries for stationary applications ranging from domestic to grid-scale. The water-based electrolyte makes the battery safer, less prone to overheating and fire. Zinc-bromine batteries show a number of advantages: 100% DoD capability on a daily basis, durability (>5 000 cycles), low risk of fire, no need for cooling, use of low cost and readily available raw materials, easy recycling using existing processes; but also some drawbacks: energy density lower than that of Li-ion batteries, lower round trip efficiency, need for 100% discharge every few cycles to prevent zinc dendrites growth that can puncture the separator, low charge and discharge rates. This characteristics make ZBRFB not suitable for mobility applications (high charge, discharge rates and low weight) but suitable for stationary applications such daily cycling to support solar power generation, off-grid systems and load shifting. The typical ZBRFB design: a water solution of zinc bromide is stored in two tanks. When the battery is charged or discharged, the solutions (electrolytes) are pumped through a stack and directed back into the tanks. One tank store the electrolyte for the positive electrode, and the other for the negative. During charge, metallic zinc is plated on the negative (carbon felt in older designs, titanium mesh in modern) electrode. Bromide is converted to bromine at the positive electrode and is stored in a complexed organic phase in the electrolyte tank. Older ZBRFB cells used polymer membranes (microporous polymers, Nafion), recent designs are membrane-less. It can be left fully discharged indefinitely without damage, also there is no self-discharge in a fully charged state, (in dry stack). The energy densities of available solutions range from 60 to 85 Wh/kg; round trip efficiency70-80%. The technology is commercially available for remote telecom sites, In Dec 2021 Redflow completed a 2 MWh system supporting a 2.0 MW biogas-fuelled cogeneration unit, and a micro-grid system in California, USA.[156]		

[149] https://newatlas.com/energy/hybrid-membrane-battery-grid-scale-energy-storage/
[150] https://www.en-former.com/en/china-builds-the-worlds-largest-lithium-free-battery/
[151] https://www.mordorintelligence.com/industry-reports/flow-battery-market
[152] https://www.greencarcongress.com/2022/01/20220101-reliance.html
[153] https://www.technologyreview.com/2022/02/23/1044962/grid-battery-iron-clean-energy/
[154] https://www.energy-storage.news/iron-electrolyte-flow-battery-player-ess-inc-expands-into-europe/
[155] https://www.energy-storage.news/ess-incs-all-iron-flow-battery-will-add-long-duration-storage-to-microgrid-in-patagonia-chile/
[156] https://redflow.com/project/redflow-completes-2-mwh-installation-in-california

<table>
<tr><td colspan="3">In Nov 2021 EOS Energy Enterprises announced a 300 MWh order from Pine Gate Renewables with installation planned for 2022.[157]</td></tr>
<tr><td>Zinc-bromine non-RFB</td><td>-</td><td>9</td></tr>
<tr><td colspan="3">Zinc-bromine non-RFB involve the same chemical reactions and active materials as zinc-bromine RFB batteries, but the design and passive materials are different. For the reason of this chemical equality it is described next to its RFB counterpart.
Gelion gel zinc-bromine battery
Gelion was launched in 2016 as a spin-off company of Sydney University, to develop the battery for commercial use. The company was boosted by an $11 million investment from UK renewables group Armstrong Energy. In 2021 after an IPO listed on the AIM London Stock Exchange.
In its battery liquid electrolyte was replaced with a gel. Gel is neither a liquid nor a solid, but combine the advantages of both. The company plans to commercialise a 1.2 kWh mono-block battery for use in commercial and grid scale applications. The battery characteristics (compared to ZBRFB):
- higher energy density of 120 Wh/kg
- higher efficiency, RTE >87%
- can be discharged to 0 V without damage
- can be operated in temperatures up to 50 °C without cooling
- cheaper to produce, no moving parts
- manufacturing scalable to gigawatt factory capacity by utilising existing lead-acid battery factories
In Feb 2022 Gelion signed an agreement with Acciona Energy to trial its Endure gel zinc-bromine batteries for potential grid applications. The trial is due to commence July 2022 and run for 6-12 months.[158]
EOS Energy Enterprise zinc-hybrid cathode battery
In Nov 2021 the company has commercialised Zyneth® “zinc hybrid cathode” battery. This is a non-flow battery design that uses zinc-bromine chemistry. They claim a RTE of 80%, but not many details on the design or performance of the battery is publicly available.</td></tr>
<tr><td>Organic RFB</td><td>-</td><td>4-5</td></tr>
<tr><td colspan="3">The organic redox flow batteries concept emerged in 2009 and many chemical formulations is possible, water or organic solvent based. Usually offer a voltage (single cell level) in range 1.2-1.6 V, 10-100 A/cm^2 current density and up to about 10 Wh/L energy density. Currently industries lead some projects to test the technology in the larger scale, e.g. brine4power.[159]</td></tr>
<tr><td colspan="3" align="center">molten salt batteries</td></tr>
<tr><td>sodium-sulfur battery</td><td>-</td><td>9</td></tr>
<tr><td colspan="3">In typical designs, a cylinder of ceramic solid electrolyte separates molten sodium inside from also molten sulphur on the outside, allowing for exchange of charge between them. When the sodium release an electron, it can move through the solid electrolyte barrier to combine with the sulphur outside. For operation the battery require temperature above the melting point of sulphur at 119 °C. This presents a serious safety concern as sodium can be spontaneously inflammable in air, and sulphur is highly flammable, several incidents were observed.</td></tr>
<tr><td>sodium–nickel–chloride battery / sodium–metal–halide / ZEBRA battery</td><td>-</td><td>9</td></tr>
<tr><td colspan="3">Technology developed in 1978 – 1999, based on domestically sourced raw materials (except for nickel), applicable for stationary energy storage.
The nickel-coated stainless steel case is the anode and is in the direct contact with sodium metal, which is separated by ceramic solid state electrolyte from a mixture of $NiCl_2$ and $NaAlCl_4$ that is in direct contact with the positive terminal.
The battery require minimum 154 °C, usually 300 °C to operate. It takes about two days to bring the battery to operation from room temperature. Materials in contact with liquid sodium cause degradation issues, and the hot materials and molten sodium metal remains a safety issue.</td></tr>
</table>

[157] https://renewablesnow.com/news/eos-energy-secures-order-for-300-mwh-of-battery-storage-systems-760723/
[158] https://reneweconomy.com.au/gelion-to-trial-its-zinc-bromide-batteries-with-spanish-solar-farm/
[159] https://www.ewe-gasspeicher.de/x_backup/presse/presseinfo-22062017

Liquid metal / liquid calcium (Ambri) battery	-	6-7
Technology based on liquid calcium alloy anode, molten salt ($CaCl_2$ based) electrolyte and solid, antimony based cathode. The antimony cathode create also solid $CaSb_x$ intermetallic alloy during battery discharging, while the anode is completely consumed. High temperature battery, designed to work at 500 °C, tolerant of over-(dis-)charging, not prone to thermal runaway, electrolyte decomposition, or electrolyte off-gassing. At room temperature not active (not conductive, 0 V voltage). The battery should be cheaper than Li-ion equivalent battery (25% of cost of Li-ion 4h system) and more durable (20+ years of service). Developed by US Ambri, spin-off from Massachusetts Institute of Technology, co-funded by Bill Gates and TOTAL S.A but it seems now TOTAL is not among the main investors.		

TRL 9* - the TRL 9 is achieved for some market segments (e.g. earbud, wearables) or special operation conditions (e.g. BlueSolution by Bolloré)

TRL 9** - the TRL 9 is achieved for some niche applications (e.g. space, military)

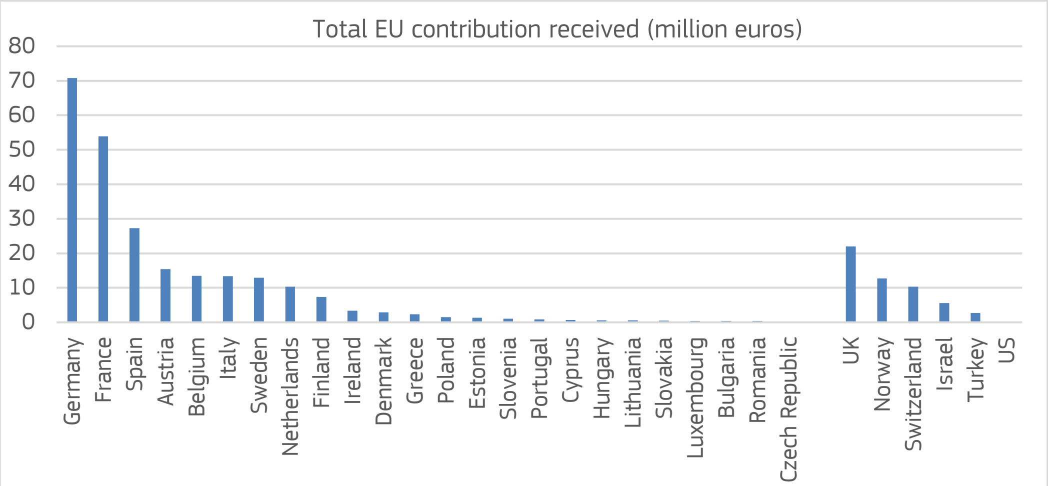
Source: JRC analysis.

Annex II Data on EU Horizon 2020 funding for selected battery technologies

Distribution of the EU support to the H2020 projects among selected battery technologies and applications over 2014-2021 period.

Li-ion, general

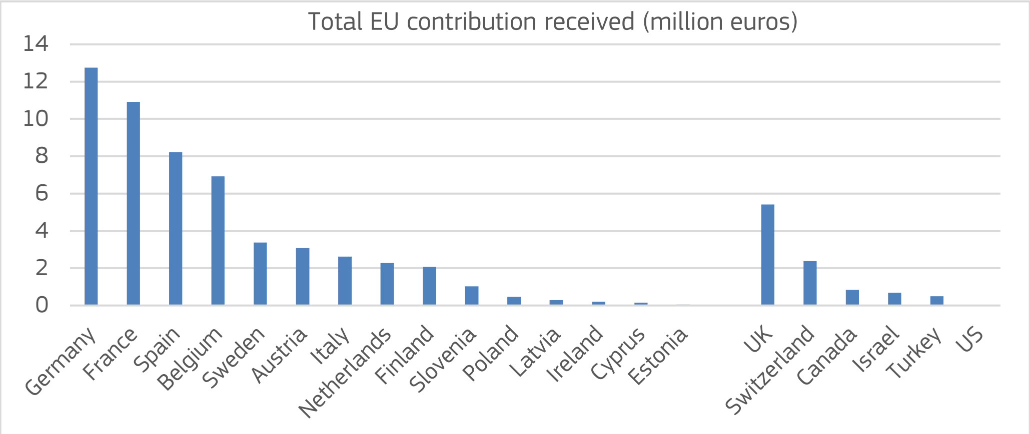
Figure 30. EU support to the Li-ion projects in period 2014-21.



Source: JRC based on CORDIS data.

Li-ion with metallic Li anode

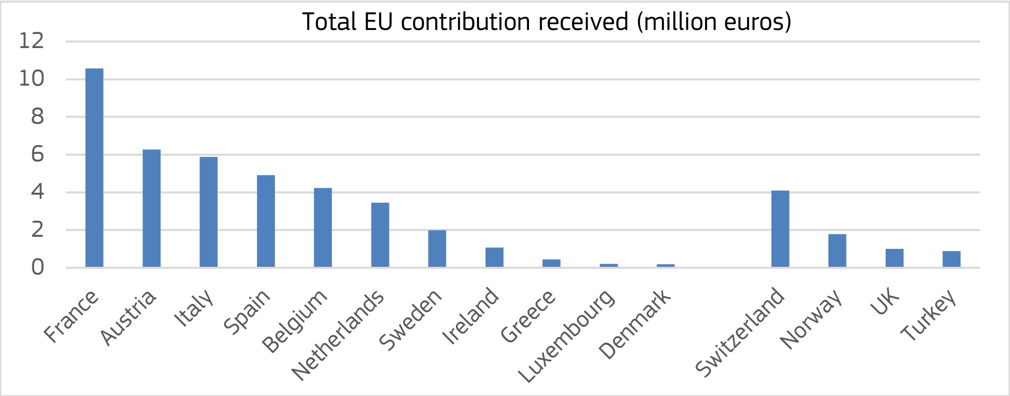
Figure 31. EU support to the projects on Li-ion with metallic Li anode in period 2014-21.



Source: JRC based on CORDIS data.

Li-ion with Si dominant anode

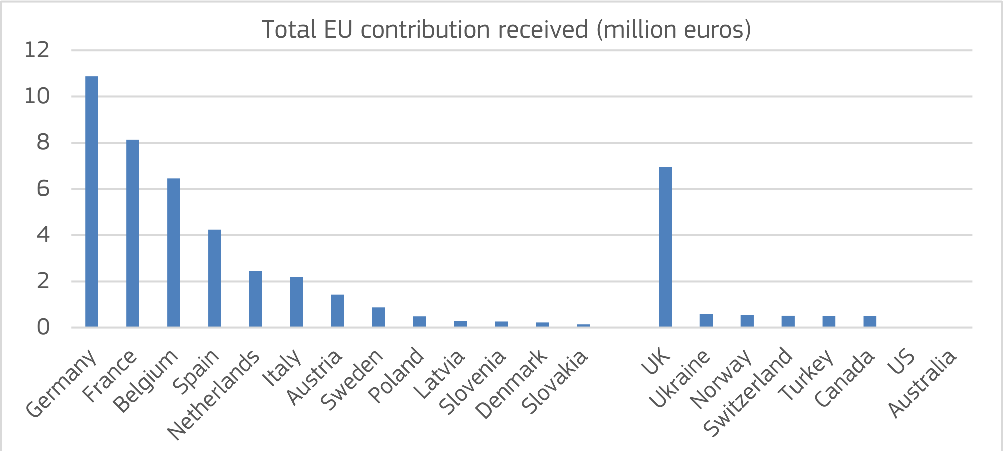
Figure 32. EU support to the projects on Li-ion with Si dominant anode in period 2014-21.



Source: JRC based on CORDIS data.

All solid state batteries

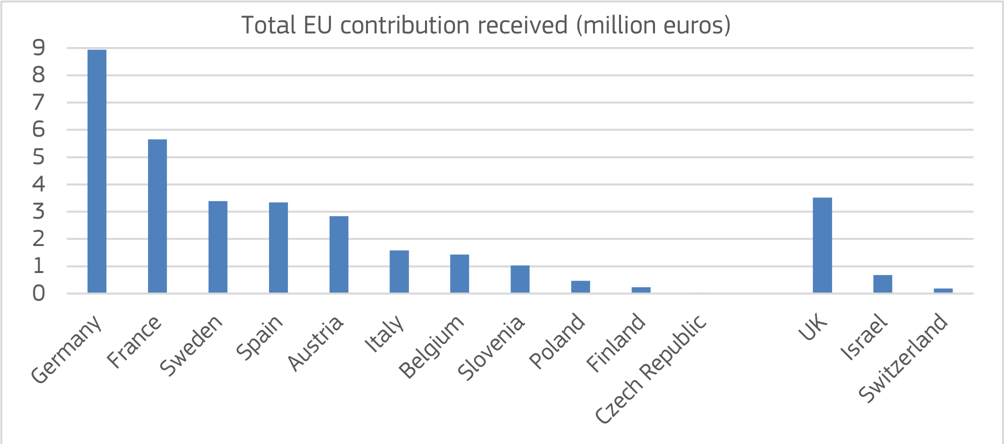
Figure 33. EU support to the projects developing solid state batteries in period 2014-21.



Source: JRC based on CORDIS data.

Li-S batteries

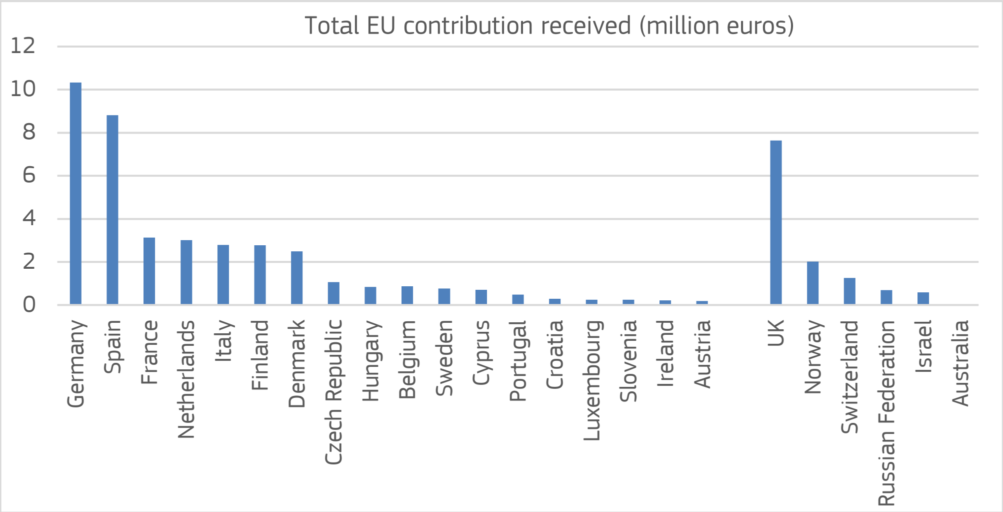
Figure 34. EU support to the projects developing Li-S batteries in period 2014-21.



Source: JRC based on CORDIS data.

Redox-flow batteries

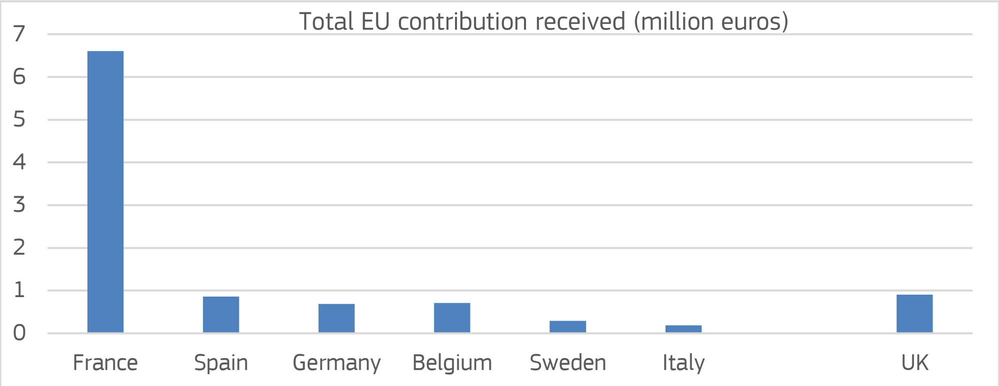
Figure 35. EU support to the projects developing redox-flow batteries in period 2014-21.



Source: JRC based on CORDIS data.

Redox-flow batteries

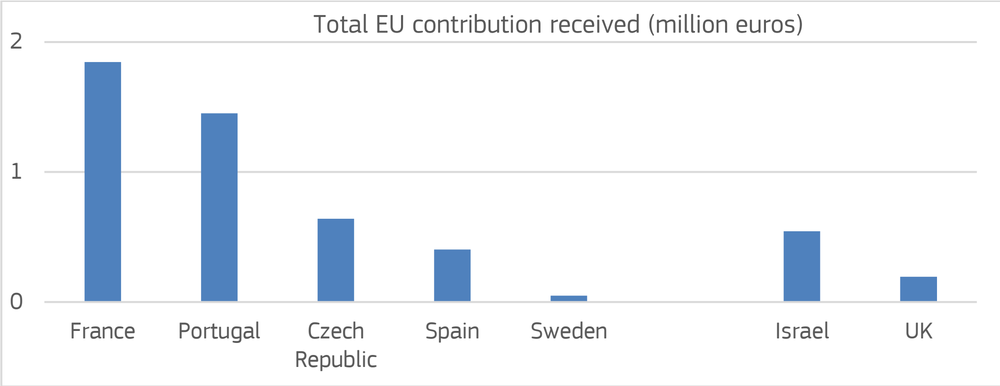
Figure 36. EU support to the projects developing Na-ion batteries in period 2014-21.



Source: JRC based on CORDIS data.

Pb-A batteries

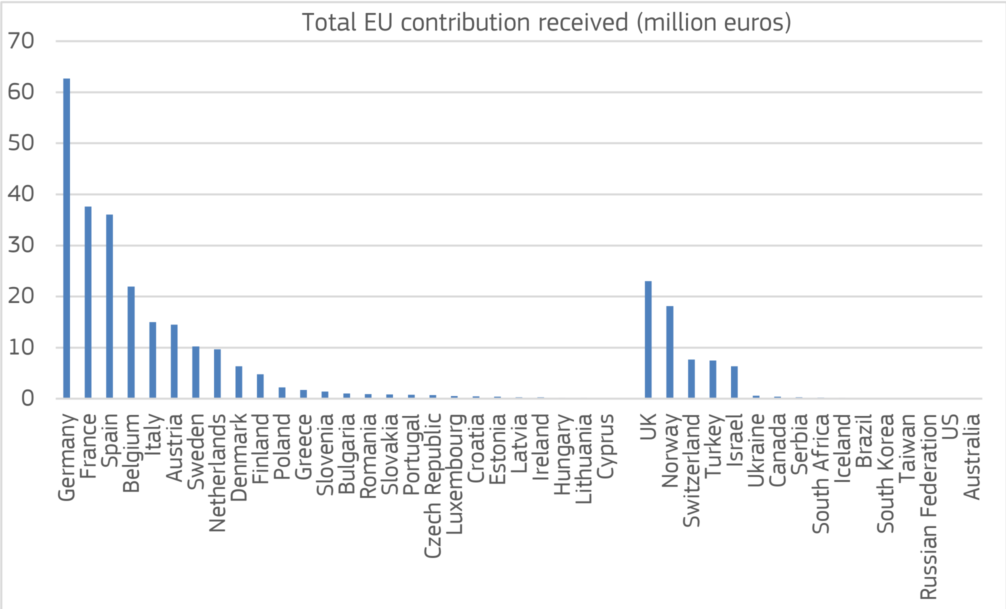
Figure 37. EU support to the projects developing Pb-A batteries in period 2014-21.



Source: JRC based on CORDIS data.

Mobility applications

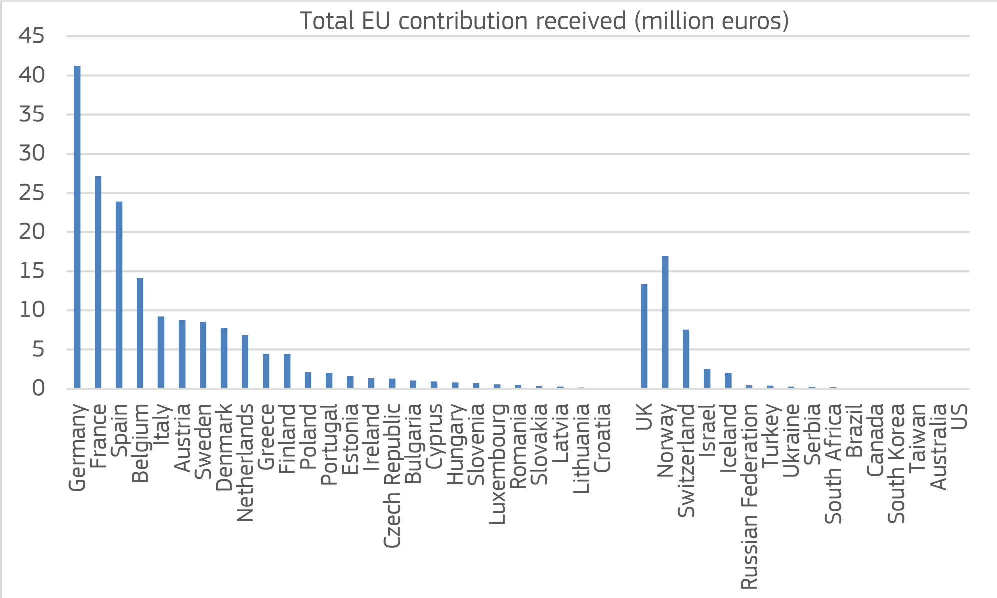
Figure 38. EU support to the projects developing batteries for mobility applications in period 2014-21.



Source: JRC based on CORDIS data.

Stationary applications

Figure 39. EU support to the projects developing batteries for stationary applications in period 2014-21.



Source: JRC based on CORDIS data.

Annex III CETO Environmental and Socio-Economic Sustainability Analysis

Table 5. Details of the Environmental and Socio-economic Sustainability analysis.

Parameter/Indicator	Input
Environmental	
LCA standards, PEFCR or best practice, LCI databases	LCA is a standardized methodology to estimate the environmental impacts of products/services, and various LCAs of both batteries and their adoption in different applications are already available. In the framework on the Product Environmental Footprint (PEF)[160], the "Product Environmental Footprint Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications"[161] were published back in 2018. This rules provide the necessary information to develop reproducible, comparable and verifiable LCA of different types of batteries. Currently, in the framework of the Battery Regulation, Article 7 states that "e*lectric vehicle batteries and rechargeable industrial batteries with internal storage and a capacity above 2 kWh shall be accompanied by technical documentation that includes, for each battery model and batch per manufacturing plant, a carbon footprint declaration drawn up in accordance with the delegated act*"; JRC is currently tailoring PEF Category Rules developed by industries, adapting to the ambition of the Battery Regulation to develop clear rules and high-quality data for robust and comparable assessments of batteries put in the EU market.
GHG emissions	Based on the PEFCR of batteries[162], the benchmark Climate Change (kg $CO_{2eq.}$) values for four different representative batteries are the following: • 0.95 kg $CO_{2eq.}$/kWh for CPT-Li-ion batteries (excluding the use phase) • 0.57 kg $CO_{2eq.}$/kWh for ICT-Li-ion batteries (excluding the use phase) • 0.80 kg $CO_{2eq.}$/kWh for ICT-NiMH batteries (excluding the use phase) • 0.42 kg $CO_{2eq.}$/kWh for e-mobility Li-ion batteries (excluding the use phase) Such values are now under revision to support Article 7 of the Battery regulation proposal which foresees the declaration of the carbon footprint of batteries that are put in the EU market, to promote the adoption of More environmentally-friendly batteries.
Energy balance	Energy (electricity mix) is used in manufacturing cells/assembly the battery pack are reported below according to the PEFCR (2018): • 41.20 MJ/kg of battery for CPT-Li-ion batteries • 12.90 MJ/kg of battery for ICT-Li-ion batteries • 41.20 MJ/kg of battery for ICT-NiMH batteries • 41.20 MJ/kg of battery for e-mobility Li-ion batteries For the use phase, the losses of energy are considered in the PEFCR: • 6.9 kWh/kg of battery for CPT-Li-ion batteries • 11.7 kWh /kg of battery for ICT-Li-ion batteries • 11.6 kWh /kg of battery for ICT-NiMH batteries • 9.6 kWh /kg of battery for e-mobility Li-ion batteries Similarly, some energy is also used for the EoL treatment (in this case recycling is considered): • 0.3 $MJ_{electricity}$/kg of battery and 0.9 MJ from natural gas/ kg of battery for CPT-Li-ion batteries • 0.42 $MJ_{electricity}$/kg of battery and 1.24 MJ from natural gas/ kg of battery for ICT-Li-ion batteries • 0.41 $MJ_{electricity}$/kg of battery and 1.23 MJ from natural gas/ kg of battery for ICT-NiMH batteries

[160] https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html
[161] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf
[162] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

	• 0.69 $MJ_{electricity}$/kg of battery and 2.07 MJ from natural gas/ kg of battery for e-mobility Li-ion batteries
Ecosystem and biodiversity impact	Impacts of biodiversity mainly relates site-based practices. Supporting studies to the PEFRC have not identified specific hotspots therefore the impact of batteries on ecosystem and biodiversity "is not at the moment of concern".
Water use	Water is used in manufacturing processes of batteries. Default water quantities used in cells and battery pack manufacturing are reported in the PEFCR of batteries. For instance, the amount of water needed in manufacturing the battery is: • 11 kg/kg of battery for CPT-Li-ion batteries • 11 kg/kg of battery for ICT-Li-ion batteries • 5.5 kg/kg of battery for ICT-NiMH batteries • 11 kg/kg of battery for e-mobility Li-ion batteries
Air quality	
Land use	No significant impacts on land use have been identified by the supporting PEFCR. Main concerns derives from the size of manufacturing plants and the possible increase of such an industrial sector.
Soil health	
Hazardous materials	The Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, already prohibited to put into the EU market batteries and accumulator containing hazardous materials, with specific reference to mercury and cadmium above specific thresholds. Also in case of mercury, cadmium and lead content, this needs to be reflected through labelling[163]. It is also noticed that Li-ion cells and batteries belong to "Class 9: Miscellaneous - Hazardous Materials" according to the International Carriage of Dangerous Goods by Road (ADR)[164].
Economic	
LCC standards or best practices	Life Cycle Costing (LCC) is a methodology that can be used to estimate the total costs of batteries along their life-cycle. LCC on batteries are already available for different type of applications; among others, a LCC analysis is provided by the Preparatory Study on Ecodesign and Energy Labelling of Batteries (Hettesheimer et al., 2019) [165].
Cost of energy	An LCC analysis was developed for the Ecodesign Preparatory study (Hettesheimer et al., 2019). The study provide the Capital Expenditure (CAPEX), the Operational Expenditure (OPEX) and the Levelized Cost Of Energy (LCOE) for batteries used in BEV, PHEV, truck and ESS applications (residential and commercial).
Critical raw materials	Several materials belonging to the Critical Raw Materials List for the EU[166] are used in manufacturing batteries that are currently used in the EU; the demand of such batteries is expected to rapidly increase in the next decade following the trend of the batteries demand in various sectors (e.g. mobility, energy storage, portable devices)[167]. Among the used CRMs, cobalt and lithium are mainly used in cathodes (e.g. nickel-manganese-cobalt cathodes) and natural graphite in anodes ([168]). Currently, the EU is highly dependent on imports of primary and processed materials for batteries, and the situation is not expected to change in a short term, even though global supply of these materials will be increasingly diversified[169].

[163] https://echa.europa.eu/legislation-profile/-/legislationprofile/EU-BATTERIES
[164] https://adrbook.com/en/2017/ADR/3.3.1
[165] https://www.eceee.org/static/media/uploads/site-2/ecodesign/products/Batteries/ed_battery_study_task5_v3_20190823.pdf
[166] https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6
[167] https://rmis.jrc.ec.europa.eu/?page=analysis-of-supply-chain-challenges-49b749
[168] https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf
[169] https://rmis.jrc.ec.europa.eu/?page=analysis-of-supply-chain-challenges-49b749

	Enhanced Circular Economy strategies, aiming at maximizing the value of materials extending the lifespan of products in which they are embedded (e.g. through reuse and second-use) and recirculating secondary materials (e.g. through recycling) is key to decrease the EU dependency from third Countries.
Resource efficiency and recycling	The adoption of more resource-efficient batteries and the increased flows of secondary materials obtained from batteries recycling has potential to maximize the value of materials and to keep them within the EU, hence decreasing the EU dependency from imports. The new Battery Regulation proposal foresees progressive minimum recycling efficiencies for lead-acid, Li-based and other waste batteries. In addition, specific materials recovery levels needs to be achieved for cobalt, copper, lead, lithium and nickel. JRC is currently leading the work related to the definition of measurement rules and related targets to maximize the collection of waste batteries. Moreover, JRC is revising the calculation rules of recycling efficiency and material recovery levels (Article 57). Recent analysis shows that, starting from 2030, the flow of materials available for recycling is expected to be quite important in terms of secondary supply[170]. Key aspects to promote circularity are: 'design for circularity', traceability of batteries along their value-chain, development of business cases related to circular economy strategies, maximisation of waste batteries collection and development of high-quality recycling technologies.
Industry viability and expansion potential	*Yes, see markets section*
Trade impacts	*Yes, see markets section for volume and import/export balance*
Market demand	*Yes, see markets section*
Technology lock-in/innovation lock-out	*Comment if dominant technology or technology provider*
Tech-specific permitting requirements	*Comment*
Sustainability certification schemes	The Social LCA methodology can be used to identify social hotspots and impacts along the batteries supply chain. However, comprehensive life cycle-based studies on social impacts of batteries are scarce and the methodology is still under development (Batteries Europe, 2021)[171]. Concerning data, uncertainties are high also due to the lack of primary data, the low granularity of available secondary data, and the limited possibility to generalize results from specific case studies/assessments. Hence, interpretation of results can be challenging (Batteries Europe, 2021). Analyses identifying social hotspots along the battery value chain are provided by (Bobba et al., 2018) and (Eynard et al., 2018). Moreover, an analysis of social risk in battery raw materials supply is provided in (Mancini et al., 2020) while (Mancini et al., 2021) investigates the social impacts of responsible sourcing initiatives in artisanal cobalt mining sites in the Democratic Republic of the Congo.
Social	
S-LCA standard or best practice	The Social LCA methodology can be used to identify social hotspots along the batteries supply chain. However, information on social aspects are lacking and the methodology is still under development (Batteries Europe, 2021)[172]. Concerning data, uncertainties are high also due to the lack of data, and hence interpretation of results is complicated (Batteries Europe, 2021). Analyses identifying social hotspots along the battery value chain are provided by (Bobba et al., 2018) and (Eynard et al., 2018). Moreover, a focus on battery raw materials is provided in (Mancini et al., 2020) and (Mancini et al., 2021).
Health	Few information on health effects of batteries are available, even though some considerations can be provided by S-LCA studies (e.g. (Bobba et al.,

[170] https://rmis.jrc.ec.europa.eu/?page=analysis-of-supply-chain-challenges-49b749
[171] https://ec.europa.eu/energy/sites/default/files/documents/sustainability_task_force_position_paper.pdf
[172] https://ec.europa.eu/energy/sites/default/files/documents/sustainability_task_force_position_paper.pdf

	2018)(Mancini et al., 2020)). It is noticed that studies on health effects on specific battery raw materials are already available in the literature, e.g. on specific risks of artisanal mining of cobalt (Mancini et al., 2021).
Public acceptance	Few information on social acceptance is available on public acceptance of batteries, even though study addressing the topic are ongoing (e.g. (Baur et al., 2022)).
Education opportunities and needs	Few information on education opportunities is available, even though some considerations can be provided by S-LCA studies (e.g. (Batteries Europe, 2021)).
Employment and conditions	Several studies have been published on the working conditions of the mining sector, especially in the case of cobalt extraction in the DRC. Additional information can be derived by S-LCA studies (e.g. (Batteries Europe, 2021)(Eynard et al., 2018; Mancini et al., 2021, 2020)).
Contribution to GDP	*see VC analysis section*
Rural development impact	Few data are available on the effect of the impact of batteries in rural development even though projects on the adoption of batteries in energy storage systems in rural areas (including second-used EV batteries) already exist to increase energy self-sufficiency and the share of renewable energy (e.g. battery storing solar or wind energy). E.g. (Ambrose et al., 2014)(Kessels et al., 2017).
Industrial transition impact	The industrial battery sector is a strategic sector for the EU, with a significant potential on both short and long term to decarbonize the EU (e.g. mobility sector and increasing the share of renewable energies). The battery technology is rapidly evolving and both R&D&I activities as well as industrial initiatives are currently engaged to build a more competitive and sustainable European battery industry (EBA250, BatteriesEurope, Battery2030+, etc.).
Affordable energy access (SDG7)	The battery industry development can have a key role in "ensuring the access to affordable, reliable, sustainable and modern energy for all (SDG 7)". Chemistries and type of batteries can be used in multiple applications, increasing the consumption of renewable energy (e.g. in combination with PV panels), decreasing the life-cycle impacts of the mobility sector, supporting the transition towards a climate-neutral Europe.[173]
Safety and (cyber)security	
Energy security	Cost-effective batteries (including second-used EV batteries) can contribute in increasing the self-consumption and self-sufficiency, especially in rural areas. They hence contribute to energy security and quality[174].
Food security	
Responsible material sourcing	The Battery Regulation proposal states that rechargeable industrial batteries and EV batteries with a capacity above 2 kWh are accompanied by a documentation reporting the due diligence policies adopted along the batteries value chain. Information on specific materials related risk embedded in batteries are available in (Mancini et al., 2020)

Source: JRC analysis.

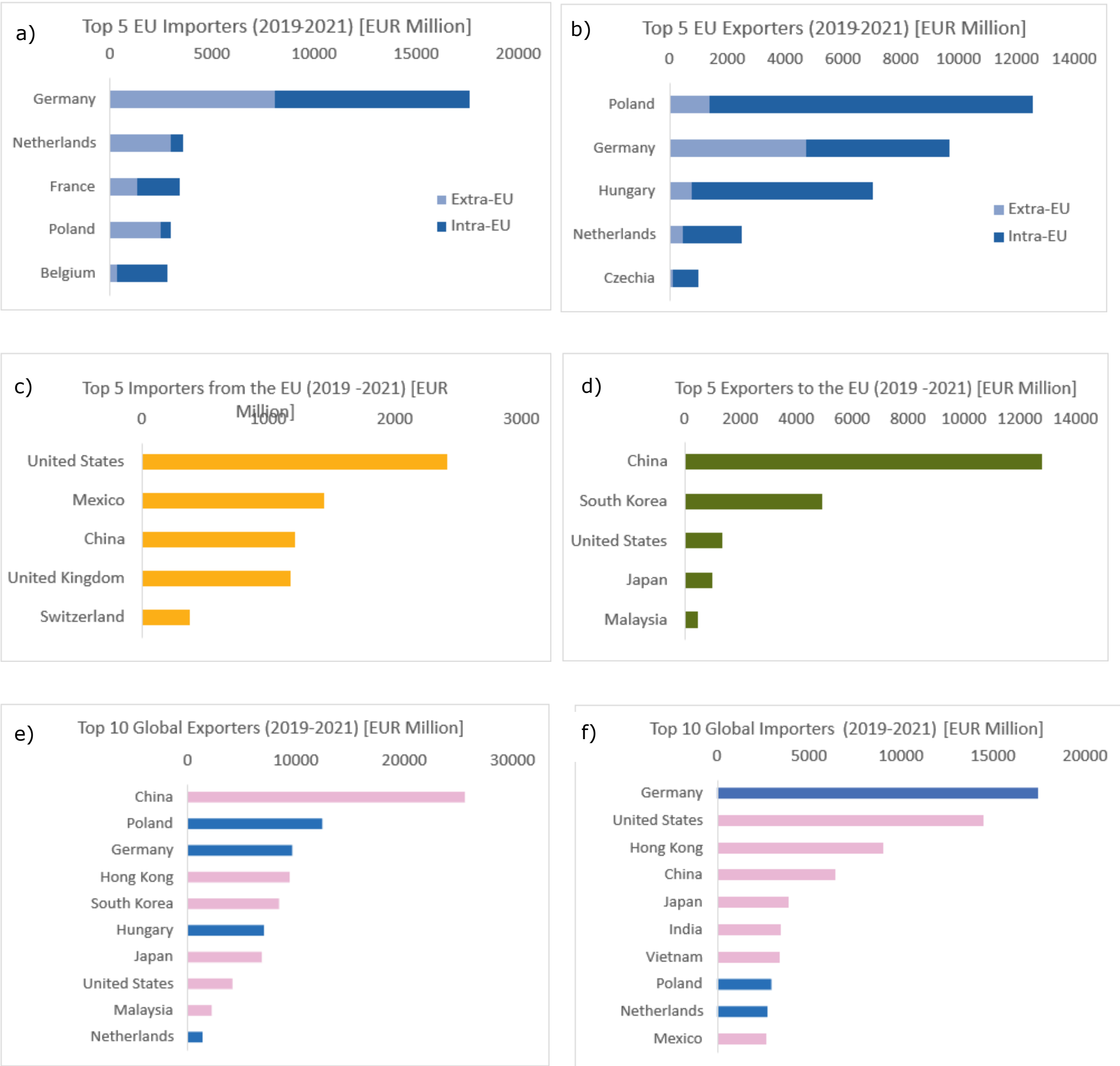
[173] https://bepassociation.eu/wp-content/uploads/2021/07/BATT4EU_Draft_SRIA_June_2021.pdf, https://www.ipcei-batteries.eu/fileadmin/Files/accompanying-research/media/download/2022-01-BZF_Nachhaltigkeitsmetrik-ENG.pdf

[174] https://bepassociation.eu/wp-content/uploads/2021/07/BATT4EU_Draft_SRIA_June_2021.pdf

Annex IV EU positioning in the global battery market

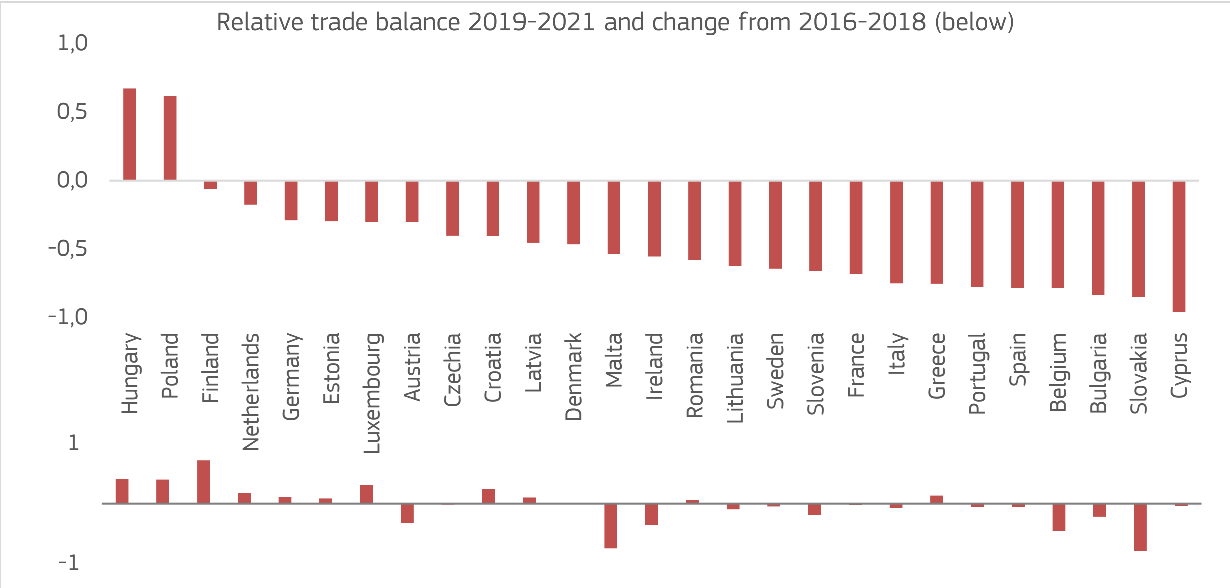
Details of the EU position on the global battery market

Figure 40. *Position of EU on the global battery market: a) top 5 EU importers, b) top 5 EU importers, c) top 5 importers of EU made batteries, d) top 5 exporters of batteries to EU, e) global top 10 exporters, f) global top 10 importers.*



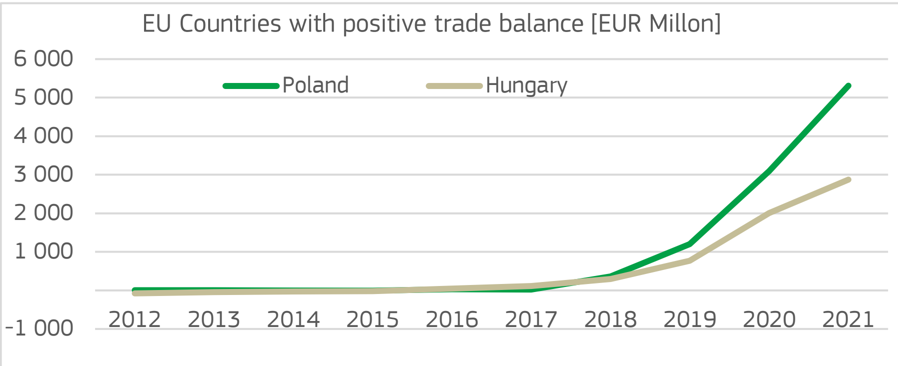
Source: JRC based on Eurostat data

Figure 41. Relative trade balance of EU countries in 2019-21 period and its change relative to 2016-18.



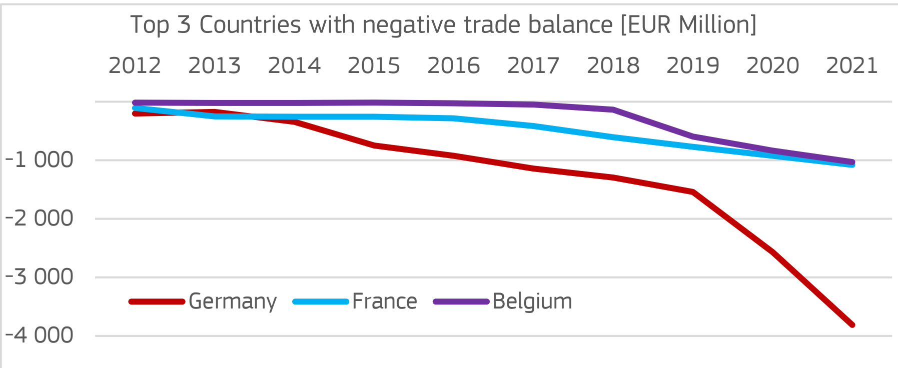
Source: JRC based on Eurostat data.

Figure 42. Trade balance trends for EU countries with positive trade balance in 2019-21 period.



Source: JRC based on COMEXT data.

Figure 43. Trade balance trends for EU countries with most negative trade balance in 2019-21 period.



Source: JRC based on COMEXT data.

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