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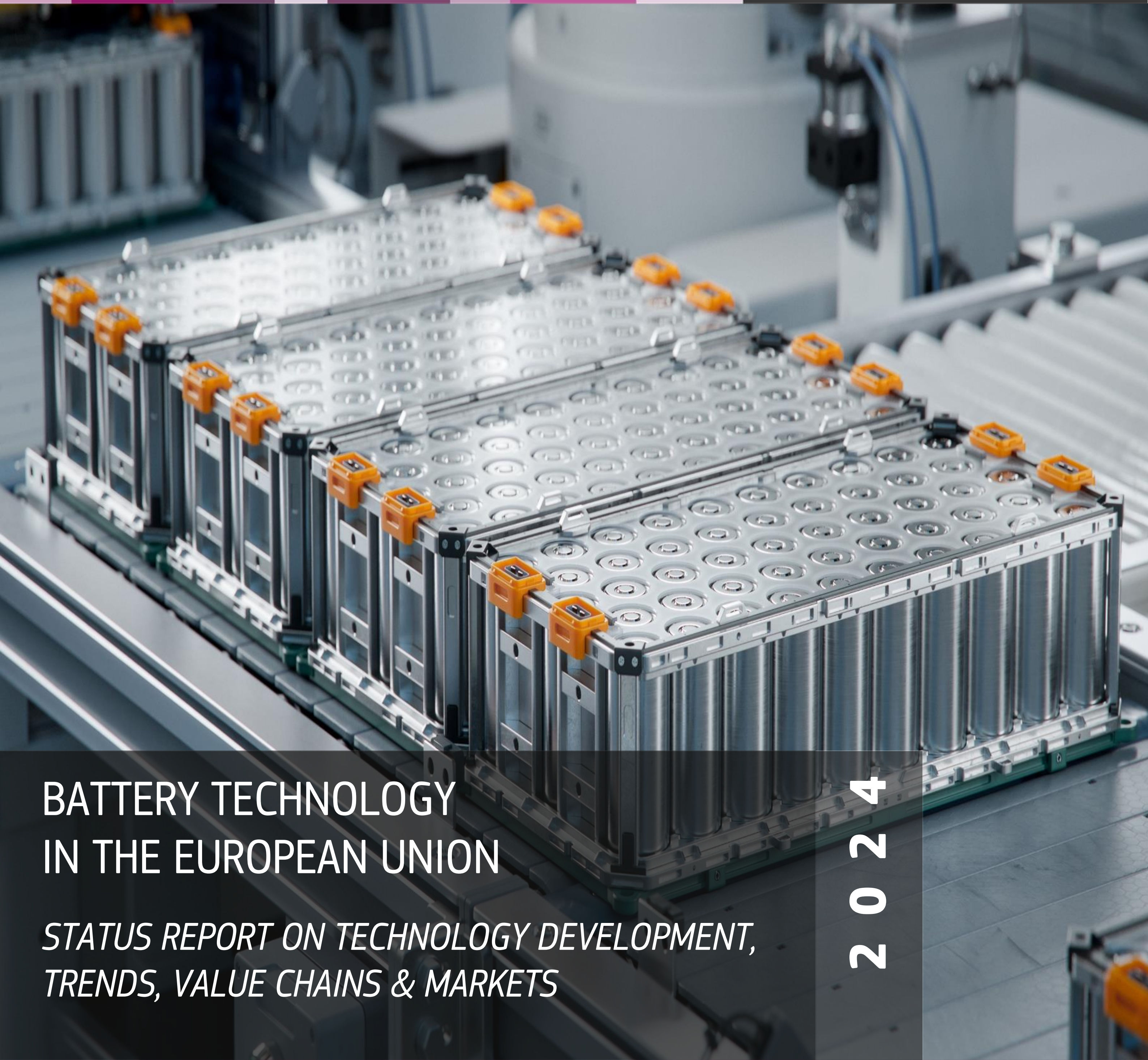

BATTERY TECHNOLOGY IN THE EUROPEAN UNION

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

2024

Joint Research Centre

EUR 40061

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Contents

Abstract

This report is an output of the Clean Energy Technology Observatory (CETO), and provides an evidence-based analysis of the overall battery landscape to support the EU policy making process. It is part of the series of reports on clean energy technologies needed for the delivery of the European Green Deal, and it is a continuation and extension of earlier editions of the CETO report on batteries. It addresses technology development, EU research and innovation activities, global and EU markets and market players and assesses the competitiveness of the EU battery sector and its positioning in the global battery market. Special attention is given to solid state and sodium-ion batteries. This report also contains an assessment of market developments, production, trade, patenting, and sustainability in the area of Li-ion batteries.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-facetted character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission's Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy technologies sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions, as well as the sustainable market uptake of both mature and innovative technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the development and implementation of the EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy systems, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web site.

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Executive Summary

Batteries are an enabling technology for reaching climate neutrality as stated in the Green Deal and the REPowerEU plan and to reduce dependency on fuel imports. E-mobility is still driving battery markets; lithium-ion batteries will dominate, at least until 2030, but other technologies develop in parallel. 55 million electric vehicles (>2 TWh of batteries) and 200 GWh of stationary batteries are expected in the EU by 2030. By 2050, the EU's entire car fleet of 270 million vehicles should be zero-emission. The report focuses on solid state (SSB), sodium-ion (Na-ion) batteries and updating indicators available for overall battery technologies. Looking at applications, focus lies on EV batteries and stationary battery energy storage systems (BESS).

General Technology Overview and Technology Readiness Level (TRL)

The dominating battery technology is lithium-ion (lithium iron phosphate (LFP), nickel manganese cobalt oxide (NMC) and nickel cobalt aluminium oxide (NCA)). In the future Li-ion will still dominate, but there will be a shift to low- or zero-cobalt chemistries (LFP, lithium manganese iron phosphate (LMFP), NMC811+). The role of sodium-ion batteries and other advanced technologies will increase significantly.

Sodium-ion batteries have reached the market (TRL 9). The leader is China, which advance quickly building the whole supply chain, scaling up production and testing first commercial products in real applications. The technology can be critical raw materials free, its specific energy is comparable to LFP, while power density, low temperature performance and safety are superior. It targets stationary and less-demanding mobility uses.

Technology Deployment

Mobility applications account for about 86% of all batteries in use, mainly in personal, light duty commercial vehicles and buses. Heavy trucks and other modes of transport are electrified only marginally. The capacity of Li-ion batteries installed in vehicles worldwide reached 750 GWh in 2023, 36% more than in 2022. Most of demand came from China which is continuing fast growth and Europe which experienced slower growth. Future global demand is expected to reach 4-6 TWh/y in 2030.

In 2023, global sales of electrified vehicles exceeded 14 million (+35% y/y), reaching 16% share of total vehicles sales (14% in 2022). China accounted for 8.3 million, the EU for 2.4 million, and US for 1.6 million of vehicles. The share of electrified vehicles in the domestic market in China was 34%, (+5 pp.) compared to 22% (+0.7 pp.) in the EU. Sales of electric buses reached 30 000 units in China, 13 000 in RoW and 8 000 in EU. Heavy duty EV registrations reached 38 000 units in China, 11 000 in Europe and 4 000 in US and RoW together.

Global installations of new battery energy stationary storage (BESS) systems exceeded 130 GWh in 2023, (+115%), and the cumulative installations approached 300 GWh. The market expects growth to about 490 GWh in 2030. The market leader was China, with 70 GWh and 60% of global market share. The US took second place with 28 GWh (20%) ahead of the EU with 16 GWh (12%).

Battery prices

In 2023, the average global battery price per kWh decreased by 14% returning to a long-term trend of decreasing prices and continuation of this trend is expected in future. It is also expected that in 2026-27 the average pack price should fall below 100 USD/kWh depending on raw materials costs, competition and pressure from alternative technologies, e.g. Na-ion batteries which might be about 30% cheaper than LFP when production is scaled up. The costs of solid state batteries were 300-500 USD/kWh in 2023, while future expectations narrow down to 100-150 USD/kWh by 2034.

RD&I Funding and Investments

The global public RD&D investments grew from 450 million EUR in 2021 to about 490 million EUR in 2022, the US, EU and Canada lead globally. The annual EU public RD&D investments reached 270 million EUR repeating the result from 2021. The EU leaders were France, Austria and Germany.

The global private RD&I funding and VC Investments in battery developers decreased to 7.5 billion EUR in 2023 (-27% y/y). This decrease was driven by China and the US, while the EU set a historic record. The biggest innovators were corporations, start-ups were active in all fields of batteries R&I. The global Top 5 innovation leaders are: Toyota, Bosch, LG Chem, Samsung and LG ES.

Patenting trends

Japan was a patenting leader since 2009, however since 2018 a strong decrease in patenting activity is observed moving it to the third place in 2021. Korea and China showed continued growth until 2020, in 2021, despite observed drop, they took first and second place respectively. Global top 10 companies are led by LG ES, Toyota and CATL while the only EU representative is Bosch at 10th position.

Scientific publication trends

Out of analysed battery chemistries, most scientific interest was observed for Na-ion, however solid state batteries attracted just a bit lower interest. In each of analysed chemistries China is a leader while the EU takes 2nd, 3rd or 4th place, depending on the chemistry. No strong international collaboration is observed, while for each analysed chemistry cooperation clusters began to form in Europe, cooperation between clusters is also observed.

Turnover

The turnover in the EU battery manufacturing sector is rising at increasing rate, almost tripling in the last seven years. This is in line with expanding production in the EU battery plants. The trend is expected to continue.

Gross value added

The fragmentary data available points at Germany as the EU leader contributing with almost 50% share to the EU gross value added. Hungary contributes 20% and France almost 7%.

Environmental and socio-economic sustainability

The EU Battery Regulation as well as the Critical Raw Materials Act aim to reduce the environmental and social impacts of batteries in their life cycle but they do not cover batteries use. However, the most positive impact of battery technologies comes from the phase of their use. Only the transport electrification led to 658 million of barrels of oil equivalent not burned in vehicles globally in 2010-22 period, equivalent to 280 million tonnes of CO_2 that was not emitted to the atmosphere. For the EU the batteries reduced need for oil imports by 120 million of barrels of oil equivalent and saved emissions of 51 million tonnes of CO_2.

Role of EU Companies

The global leader in Na-ion batteries is China, where big companies have been very quick in moving to mass production supported by a basic, but complete value chain and testing commercially produced batteries in real applications. In the EU Tiamat and Altris together with Northvolt are setting up production plants. Solid state batteries are still not commercialized for large scale applications. The EU is represented by Blue Solutions and Factorial. For mainstream Li-ion batteries, the EU started reducing distance to global leaders, the largest battery cells producers in the EU are LG, CATL and Samsung.

Employment

The number of direct jobs in the EU battery manufacturing is growing at an increasing rate. The leaders are Germany, Hungary and Poland; with by far highest growth observed in Hungary due to opening new battery production facilities. The sector hosted about 90 000 direct and 300 000 – 400 000 indirect jobs in 2023 in the EU. By 2030 this could increase to about 0.3 million of direct and 1.5 million of indirect jobs..

EU Production Data

The total value of batteries produced in the EU approached 35 billion EUR in 2023. The largest segment was production of accumulators with 85% share while non-rechargeable batteries contributed with 12% share. 70% of the accumulators were Li-ion batteries, while Pb-A batteries production accounted for 22%. The value of battery production is increasing fast, with a CAGR of 33 % over the last five years.

The structure of the battery production shows a clear shift from lead-acid batteries before 2020, to Li-ion batteries dominating after 2020, however in absolute terms production of lead-acid batteries remains stable.

Global and EU market leaders

Global leaders in Na-ion batteries production are Chinese companies: China Three Gorges Corporation (CN), operating the world's first Na-ion gigafactory; CATL (CN) and HiNa (CN). BYD (CN), Reliance (IN) and many other companies also plan mass production. The EU leaders are: Tiamat (FR) planning to start production in 2025 and to expand the plant to 6 GWh/y production capacity in 2030 and Altris (SE) developing together with Northvolt a production facility of Na-ion batteries based on proprietary cathode material.

Solid state batteries are not yet commercialized at a scale required for automotive market. The most advanced plans were presented by Toyota aiming to commercialize first vehicles powered by solid state batteries in 2027/28. Welion semi-SSBs are used in an automotive battery that debuted in 2024. The EU is represented by BlueSolutions (FR, CA) joint venture operating a 1.5 GWh/y production facility, and Factorial (US, DE, JP) testing their demo solution.

The global leaders in mainstream Li-ion battery manufacturing are: CATL, BYD, LG ES, Panasonic and SK Innovation, listed in order of annual production in 2023. The EU leaders are EU subsidiaries of the Korean and Chinese companies, the LG ES, CATL, SK Innovation.

Trade and trade balance

The global export of batteries is estimated at 260 billion EUR in 2021-23. The EU export to non-EU countries reached almost 18 billion EUR (9% of global market) in the same time. The EU satisfied 50% of its battery demand by imports from non-EU countries. In 2023, the EU export rose by 25%, while in the same time import rose by 22%. The deficit reached a record high of 18.6 billion EUR, 26% more than in 2022.

China remained the biggest global exporter, Poland and Hungary are listed second and third. Germany is the number one global importer, and is followed by the US and Hong Kong.

Resource efficiency and dependence in relation to EU competitiveness

The EU remains strong in the application field, holding above 25% of global EV production. In the field of stationary energy storage systems, the EU is not a strong player.

The production capacity of battery cells in Europe was estimated at 175 GWh/y in 2023. The production capacity of battery components reached: equivalent to 40 GWh/y of cells production for cathode active materials; equivalent to 120 GWh/y for separator and equivalent to 230 GWh/y for electrolyte.

The NZIA and CRMA limits set for 2030 on EU battery cell production capacity, anode active materials, separator and electrolyte should be easily met; for cathode active materials limits will not be met, but the production capacity will be close to the required limit. This is expected if all announced production projects are successfully executed.

All projects for production of cathode active materials focus on nickel-based chemistries.

The EU depends heavily on third countries for battery raw and processed materials and production equipment.

Recycling EoL batteries available in the EU is one of possible ways to reduce EU's dependence on the supply of battery raw materials. Details on recycling processes are available in the CETO 2023 report. [1]

The battery recycling capacity in the EU already is, and will remain at least until 2030 above the 45% limit set by CRMA. However, most recyclers offer only mechanical or pyrometallurgical recycling and black mass recovered in those plants is usually sold to recyclers in the Asia-Pacific region for hydrometallurgical processing.

Up to 25% of the EU demand for lithium in 2030 could potentially be covered from highly mineralized water extracted in geothermal systems, if technical and financial challenges are solved.

Significant reduction of EU's dependence from third country suppliers could be achieved by development and deployment of CRM-low or CRM-free batteries, like LFP, Na-ion or redox-flow batteries.

Finally, flexible management of grid loads could reduce needs for integration of energy storage systems into the electricity grid, reducing required investments and dependencies and relieve pressure on batteries production.

Due to high rate of Na-ion batteries commercialisation in China and much slower rate in the EU, it should be expected that the EU will develop a dependence on China for this technology.

A short Strength-Weakness-Opportunity-Threat (SWOT) analysis for the competitiveness of the EU battery sector is presented in **Table 1**.

Table 1. CETO SWOT analysis for the competitiveness of the EU battery sector.

Strengths	**Weaknesses**
– Strong automotive industry generates demand. – Policies promote technologies that support demand. – Strong EU support for batteries R&D, production and deployment. – Generally strong multidimensional R&D sector. – Well-educated work-force. – General awareness of the need to mitigate climate change and for high environmental standards.	– Competing with already well-developed battery producers. – Dependency on third countries for raw and processed materials and production machinery. – High energy prices and labour costs. – Complex EU legislation and bureaucracy makes investment approval process lengthy and costly. – Conflicts of interest between MS. – Shortage of workers specialised in battery manufacturing. – Regulations and standards are not developed enough. – Missing domestic production of cheap batteries and goods incorporating batteries. – Missing or weak links between R&D sector and industry, especially in east Europe. – Large uncertainty of business, no trust in new technologies causing break-down of producers bringing new products to the markets.
Opportunities	**Threats**
– Development of economy segments based on batteries use. – Synergies with other value chains, e.g. hydrogen, other forms of energy storage and grid services. – Enabler for a wide deployment of RES, energy grids stabilisation and reduction of energy costs. – Reduction / elimination of dependency from oil / gas / coal suppliers. – Reduction of emissions from use of fossil fuels. – Development of local value chains with reduced geopolitical risks for innovative, more sustainable or cheaper alternative battery chemistries. – Shape / contribute to the development of missing international regulations and standards on batteries. – Batteries recycling could partly cover demand for secondary raw materials, including CRMs.	– Continued dependence on external raw materials. – Increasing the demand for battery imports can worsen the EU's trade balance. – Emergence of third countries dominant in cheap, battery technologies. – Risks from toxic materials in batteries production, use and recycling need proper management. – Supply of cheap batteries from countries with low environmental standards. – Geopolitical issues can cause actions of disinformation targeting the EU citizens, limiting trust in battery technologies and promoting third countries as "proven" suppliers of oil, gas, etc. – Subsidies and politically based decisions in third countries pose a risk to EU competitiveness. – Customers might be unwilling to pay higher prices for EU-produced batteries (even if technically better).

Source: JRC, 2023

1 Introduction

1.1 Scope and context

The European Union is aiming in climate neutrality by 2050 and set a legal framework to achieve this goal. [2], [3], [4] Reaching this objective requires significant energy storage capability in the EU, as only then, intermittent renewable energy sources could cover demand of the European citizens and industries. Storage of energy in batteries is also a key for transport decarbonisation. Thus, a significant technological advancement in energy storage technologies as well as their deployment is needed. In Jul 2023 the EU regulation aiming at making batteries in the EU market more sustainable throughout all their lifecycle was adopted. [5]

The battery technology advancement is still driven by the automotive sector, however other industries became active and co-develop or set specific requirements for battery manufacturers to develop batteries and cells optimized for their specific applications. The automotive sector is focusing on high performance Li-ion batteries for higher class vehicles on one side, but also looking for cost-effective solutions for popular cars on the other. The automotive battery sector remains the leading segment of the battery market, with an 86% share of global capacity installed in batteries. Stationary storage systems account for another 12%, while consumer electronics make up 2% of battery demand only. [6] The stationary segment requires high durability batteries while energy density is not a priority. Also cost is an important factor for stationary applications.

The R&D activities concentrate in two distinct streams: improving existing Li-ion battery technologies via incremental changes to the chemistry, design and/or production technology, and development of alternative chemical formulations, often requiring completely different battery design and/or development of new production processes. The diving force is always a combination of better performance, durability, safety and price, but also increasing sustainability and – with increasing priority – security of raw material supply.

This CETO report focuses on solid state batteries (SSB), commercialisation of sodium-ion batteries (Na-ion) and status of battery technologies in general. From battery applications perspective, EV batteries and stationary battery energy storage (BESS) are addressed in most detail.

The current work is a continuation and extension of earlier editions of the CETO report on batteries. [7], [1]

1.2 Methodology and Data Sources

The report follows the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU position

The report is focused on most up-do-date technology status and, where possible, reports changes wrt. a preceding period. Solid State Batteries (SSB) are targeted in the technology development section, while in the battery production and market chapters the focus is given to Li-ion batteries. In all chapters, information on alternative technologies is given where possible, to provide a more complete evaluation of the battery sector.

The term “electrified vehicle” refers to full EVs (BEV) and plug-in hybrid vehicles (PHEV) together. Hybrid (HEV), mild- or micro-hybrid vehicles are not included in the report due to their low battery capacities. Also the use of batteries in fuel cell vehicles is not covered due the relatively low number of such vehicles.

By “technology” we understand distinctive groups, like Li-ion, Pb-A, Ni-Cd etc., while chemistry refers to more detailed, fine distinction, e.g. LFP, NMC111, NCA.

Annex 1 provides a summary of the indicators for each aspect, together with the main data sources.

Annex 2 contain detailed sustainability assessment based on the Sustainability Assessment Framework.

The available statistical data, technical reports and scientific publications provide a rather complete picture of technology development, technology cost, patenting and scientific publications; however, statistics regarding other subjects are not readily available: this especially applies to gross value added, labour productivity (which are available for one year only), energy intensity and also partially to production data (where several member states provide limited access to their statistics). Some indicators are not available for battery technologies that did not reached the market yet, or which are still at their infancy stage.

2 Technology status and development trends

2.1 Technology development

Current electrical systems require flexibility, stability and reliability for customers across the electricity network, thus energy storage is one of the crucial technologies for the future. In particular the share of renewable energy in the EU is expected to reach 69% by 2030 and 80% by 2050 [8]. Batteries is one of the key technologies that can provide required flexibility to the energy grid. However, still the majority of batteries are developed for EV applications, as well as the most use come from the mobility sector.

2.1.1 General trends

The following general trends have been observed in the battery field during last years and are still intact:

- **Evolutionary changes to the existing battery technologies** in order to improve performance, durability, safety and/or cost of cells. Usually those are linked to changes in additives, modifications of active materials surface or grains size, small changes to cell design, changes to the production process or suppliers, etc. Such modifications are performed frequently, up to few times per year, and lead to incremental improvements of the technology and leaving major parameters unaltered.
- **New chemistries** are being developed – this covers major changes to the battery chemistry, involving new active materials (e.g. Si or metal Li for the anode, LMFP for the cathode), electrolyte (e.g. solid state electrolyte), or shuttle-ion (Na-ion). Such major changes are introduced much less frequently, once per few years and usually require major changes to the supply chain, design, production technology and sometimes facilitate new use cases.
- **Obsolete technologies leave the markets** and are replaced with newer, more suitable technologies (e.g. Ni-Cd replaced by Li-on in power tools; Li-ion is replacing Pb-A in data centres – especially during renovation when area released due to use of higher energy density storage system can be dedicated to data processing and increased computational power).
- **Increasing size of a single cell.** This trend is continued in all chemistries of traditional Li-ion batteries. As example, the case of Tesla can be taken, which initially used 18650 format of cells, later switched to 21700 and now is moving to 4680. In stationary applications cells of 280 Ah became a first choice of system designers, and the market is preparing for adoption of >300 Ah cells. Some companies are also deploying even larger formats, up to 1 000 Ah. Increasing cell size helps to reduce cost of energy storage, e.g. through improved energy density at cell level and cell-to-pack design. It however makes thermal management more difficult in high power applications.
- **New pack designs** including cell-to-pack design, where battery instead being one big block installed in especially dedicated place, start to play structural function also, utilizing its strong case. Another possibility is the battery system assembled directly from cells avoiding module integration level and reducing amount of passive materials, increasing volume filling, etc.
- **Specialization of cells design** is advancing. While few years ago practically all batteries were designed and optimized for use in vehicles (but used also in stationary applications as ready-to-use solution), now specific cells are being developed and optimized for a specific application. This facilitates optimum performance and increased service life.

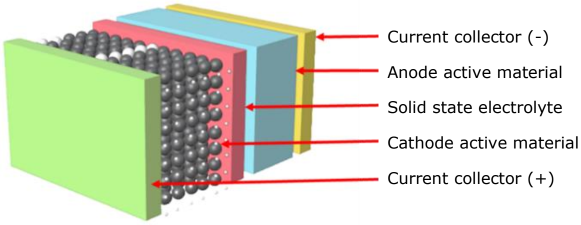
2.1.2 Solid state batteries

One of the most important upcoming battery chemistries is solid state batteries (SSB), also known as all solid state batteries (ASSB). It is classified as one of Generation IV chemistries. [9] SSBs can utilize low cost materials, have moderate to high performance and potentially improved safety. [10]

JRC reported on solid state batteries previously, in 2020. [11] This section will present the advances that the SSB technology made in the last years and the current technology trends.

Many architectures and characteristics of SSB are found in literature [12], [13], [14]. Unlike traditional Li-ion batteries, SSB employ a solid state electrolyte to provide mobility of Li^+ ions. At the same time, this solid state electrolyte functions as separator by electrically separating anode from a cathode. **Figure 1** shows a typical construction of a SSB.

Figure 1. Typical design of a solid state battery.



Source: JRC, 2024

The main characteristics of SSB:

- improved specific capacity and energy density (300 - 400 Wh/kg, 400 - 1 100 Wh/L) due to large capacity anode, lack of separator,
- wide temperature operation window of -40 °C to 100 °C,
- fast charging capability, reaching 10C in some batteries,
- improved safety due to lack of volatile organic solvents (reduced risk of fire or leakage),
- flexible design, allowing also bipolar stacking (enclosing stack of several anodes and cathodes in one enclosure, not possible for batteries with liquid electrolyte as the electrolyte would be in direct contact with voltage outside of electrolyte stability window; bipolar stacking would allow to reduce amount of passive materials in the battery (mainly cell casings, conductors, connectors, etc.) simplify battery design, and assembly process; overall, this would increase energy density and specific energy of battery and reduce its cost) [15],
- potentially reduced cost due to cheap materials use and reduction of passive materials (the technology is under development and currently is very costly, mainly due to high production cost),
- potentially consuming more Li per kWh of storage capacity due to use of Li excess in electrodes,
- production technology needs scale-up, including production equipment supply,
- calendar life needs to be proven in real life application
- new technology that require development of new battery management and other ancillary systems.

The current race for SSB is on the development of a battery that surpasses traditional Li-ion technologies on energy density, specific energy and safety for use in EVs. The cycle life is not the main priority anymore. Assuming that most of current SSBs can already deliver 700 – 1 000 of charging cycles, an average EV energy consumption is about 20 kWh/100 km (passenger cars) and EV battery storage capacity is about 80 kWh, this would be sufficient for 280 000 – 400 000 km of driving, more than average vehicle millage in the whole service life. This would give space for battery size reduction, which in combination with higher specific capacity and in line with fast charging capability of SSBs, would allow to significantly reduce weight of EV battery. Most of SSB research focuses on electrolyte as key component, but also a lot of attention is given to anode active materials. [14], [16], [17] The study of cathode materials is less intensive as a wide range of classic Li-ion cathode materials might be used.

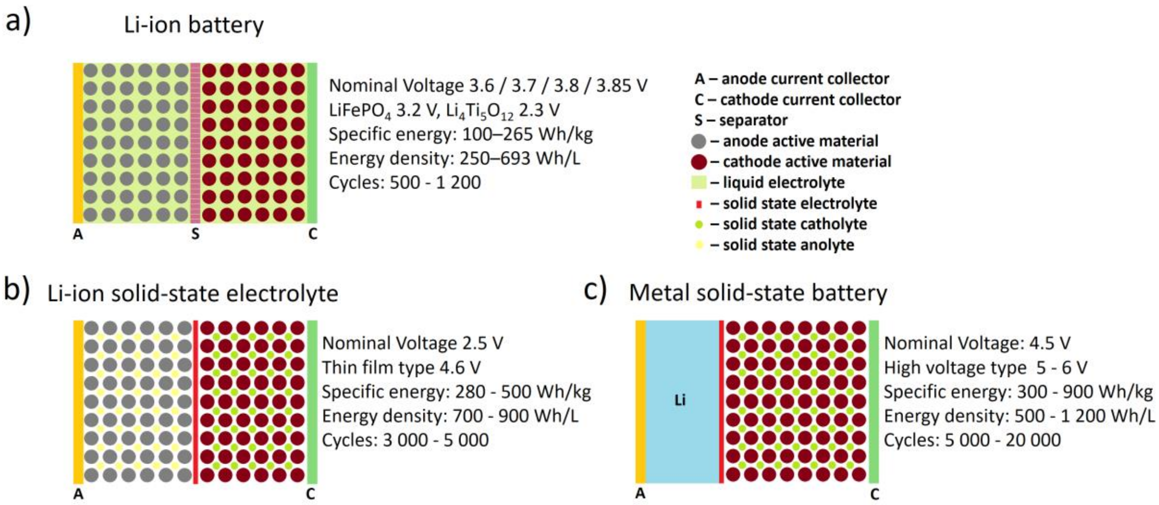
2.1.2.1 Comparison of SSB with liquid electrolyte Li-ion batteries

Li-ion batteries with liquid electrolyte are a SoA battery technology, despite this fact, they suffer from a number of dis-advantages. A number of those drawbacks could be avoided in solid state batteries.

The liquid organic electrolyte allows for mobility of Li^+ ions in relatively wide, but not very different from room temperature range, usually 0-60 °C. [18] However, the organic solvents tends to develop with use and time a highly resistive solid electrolyte interphase (SEI) at the electrodes surface that became a barrier for lithium ions. It also consume lithium that became permanently bound in SEI layer, leading to smaller availability of lithium ions and in consequence capacity loss. The electrolyte will also decompose at high potentials which limits the use of high voltage (>4.35 V) cathode materials. Finally, the liquid organic electrolyte pose a risk of leakage and forming harmful atmosphere after evaporation, is flammable leading to increased risk of fire and during thermal runaway harmful or toxic gases, such as e.g. hydrogen fluoride (HF) are formed. [19], [20], [21], [22]

In **Figure 2** a comparison between liquid electrolyte based Li-ion and SSBs is presented, including basic performance characteristics.

Figure 2. Comparison of design and performance of a traditional Li-ion battery with liquid electrolyte a), Li-ion SSB b) and lithium-metal anode SSB (Li-SSB) c).



Source: JRC, 2024

In contrast, cells with solid electrolyte do not exhibit these drawbacks: allow for higher operating temperatures due to better thermal stability, [23] higher electrochemical stability enables use of high potential cathodes, [24] metallic lithium as an anode and chloride based (e.g. lithium yttrium chloride) electrolytes, [25] resulting in a higher specific energy. **Table 2** present a comparison of a commercial SoA Li-ion battery and a SoA SSB.

Table 2. Comparison of Li-ion and SSB technology

	Liquid electrolyte Li-ion battery Commercial, TRL 9	**Solid-state Battery (SSB) Under development, TRL 6-8**
Perfor mance	• Limited by separator thickness. [26] • Compromised at low temperatures. [27] • High voltage cathodes are not compatible with liquid electrolytes. [28] • SEI growth reduces performance with ageing.	• A solid-state electrolyte reduce dendrite formation allowing large capacity anodes. [29] • Wide operation temperature window, -73-120 °C [30] • Fast cycling 10C (6 min. charge). [17] • Enhanced cycle life of 6 000 [31], potentially 20 000 [32] of charge cycles.
Typical design	• Cylindrical, pouch and prismatic. • Increasing energy density possible by increasing thickness of the electrodes, which compromise power. [33]	• Flexible design due to the absence of liquids. [34] • Electrodes stacking possible for increased specific energy, high (tuneable at design) cell voltage, or even several voltages from the same cell. [35]
Price	• 139 EUR/kWh, steadily decreasing [36], but approaching maturity level at which further reduction is slow. • Prone to price volatility of raw materials.	• Currently high, 300-500 EUR/kWh, due to small scale and slow production technology. • Technology under development, reduced use of passive materials and simple design offer potential costs reduction. [37]
Security of supply	• Li, Co, Ni, natural and artificial graphite are used in NMC cells. Those are CRMs and their supply is of concern, as well as sustainability of their extraction. [38] • Supply of graphite and other processed materials is controlled by China. [39] • Some chemistries allow reduced fractions of Co and Ni, e.g. in LFP, Co and Ni are substituted by Fe.	• Solid electrolyte allow using Li metal anode eliminating graphite but increasing use of Li, also some cathode materials uses excess of Li. • Some cathode chemistries allow for reduced fractions of Co and Ni, e.g. in LMP Co and Ni are substituted by Mn. • Market of SSBs is not mature yet and the supply chain of SSB materials still require deeper analysis to identify potential risks. [40]
Hazards	• Lithium plating/dendrite growth or abusive conditions can lead to thermal runaway. • Risk of fire in case of thermal runaway. [41] • Electrolyte leakage may cause harmful atmosphere and/or risk of fire. • HF (toxic, corrosive gas) can be formed during thermal runaway.	• Lithium plating/dendrite growth or abusive conditions can lead to thermal runaway, which however is much less severe as no flammable liquid is present. • No liquid components, thus reduced risk of leakages, harmful vapours and fire. [41] • Resistant to high temperatures. • Li-SSBs exhibits risks typical for metallic lithium if the cell casing is opened.

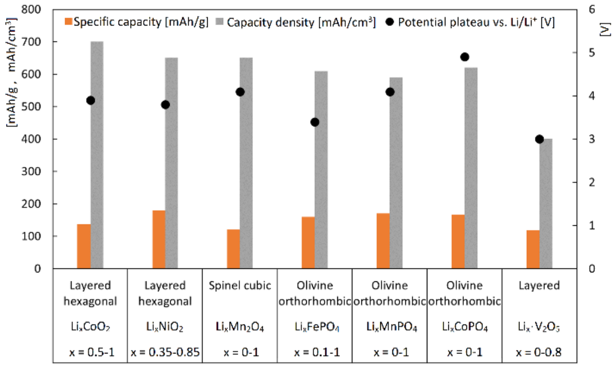
Source: JRC 2024

2.1.2.2 Cathode electrodes

The cathode active material act as a store of Li^+ ions, accepting them during discharge and providing during charge process. In SSB however, the cathode active materials often use large excess of lithium, so even discharged material contains a lots of lithium. [42] Increasing the content of cathode active material at cost of passive materials, e.g. decreasing separator thickness are considered most important to increase specific energy [43], [44] of battery. The positive electrode can be made with the same components used for Li-ion batteries such as LCO, NMC, NCA, LFP or others, like vanadium oxides and materials able to reach up to 5 V potential. Thus, there are two families of cathode materials: thin film cathodes with voltage similar to Li-ion batteries and high voltage cathodes potentially allowing for higher energy densities.

Figure 3 shows the theoretical characteristics of thin film cathode materials; the experimentally measured potentials are close to theoretical ones while specific capacity and capacity density are lower at current technology development stage. A thin film cathodes, despite using the same active materials like in traditional Li-ion batteries, require different structure of the material. The electrochemical potentials of thin film cathodes ranges from 3 to 4.8 V, similar to traditional Li-ion batteries, and exhibit a potential plateau, which cause challenges in SoC estimation. The highest capacity density and specific capacity is observed for the layered hexagonal materials, such as Li_xCoO_2 and Li_xNiO_2.

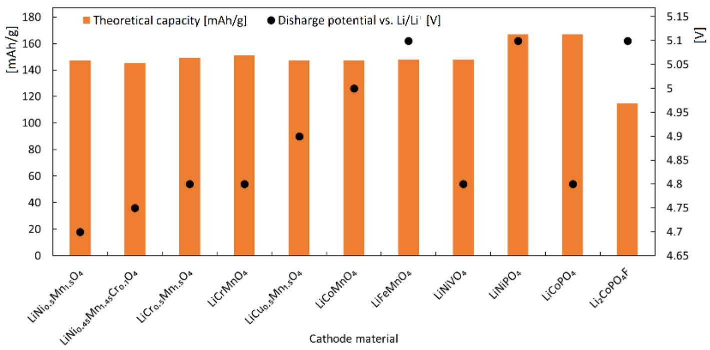
Figure 3. Theoretical characteristics of thin film cathode materials.



Source: JRC 2024

The materials with high electrochemical potential in the range of 4.7 V to 5.1 V, are shown in **Figure 4**. The experimentally measured potentials are close to theoretical ones while specific capacities are lower at current technology development stage. Often, blends of those materials are in focus of research. The material that offers the highest capacity (160 mAh/g) and voltage (5.1 V) is $LiNiPO_4$. Several other materials, e.g. $LiFeMnO_4$ and Li_2CoPO_4F offer similar electrochemical potential, but significantly smaller theoretical capacity (140 mAh and 120 mAh, respectively). Those differences may be related to the stability of the material. [45]

Figure 4. Theoretical characteristics of high voltage cathode materials



Source: JRC 2024

Selection of proper set of materials have an enormous impact on performance and durability improvements of Li batteries. More research is needed to develop stable electrode that can provide long cycle life under a range of temperature and mechanical conditions. The considered cathode materials have already been known for a longer time and no new cathode materials of relevant importance were found recently. Instead, the research is focussed on finding material blends with good characteristics. The existing cathode materials perform as expected in many commercial applications, although those applications create rather small market comparing to EV and BESS batteries. Thus, the SSB cathode materials still lack the assessment of their affordability, availability and environmental impact at scale, which should be tackled in near-future research.

2.1.2.3 Anode electrodes

The primary goal of SSB is to outperform Li–ion batteries in terms of energy density. In this context the material that is considered ideal for SSB anode is metallic lithium. However, Li is prone to side reactions and especially dendrites growth. The material can also passivate and stop working on the solid electrolyte interphase [46]. Other potential anode materials for SSB are also in the research interest. **Table 3** present general electrochemical characteristics of several anode materials compatible with solid electrolytes. Those materials have a voltage (vs. Li/Li^+) between 0.0 V and 1.7 V. The highest theoretical capacity is observed for silicon (4 200 mAh/g) and lithium (3 820 mAh/g) and most recent research has been focusing in those two [47]. Graphite, despite a lower theoretical capacity of 372 mAh/g, offers other advantages like low dendrite growth, low cost and good availability, however, or cells with voltages >3 V require special treatment to stabilise. [48] In this case a better choice would be either graphene or/and carbon nanotubes which have better stability and characteristics. [49]

Table 3. General characteristics of anode materials.

Material	Theoretical capacity [mAh/g]	Average voltage [V] vs. Li/Li^+
Silicon	4 200	0.4 [47]
Lithium	3 860	0
Germanium	1 600	0.3
Carbon nanotubes	1 115	0.7 [50]
Graphene	1 100	0.5-0.9 [51]
Transition metals	1 100	0-0.2
Phosphides	1 000	0.5-0.8 [52]
Tin	990	0.1
Antimony	661	0.23
Hard carbon	500	0.3 [53]
Bismuth	385	0.3
Graphite	372	0.1
$Li_4Ti_5O_{12}$	175	1.7 [52]

Source: JRC 2024

2.1.2.4 Solid electrolytes

Development of solid state battery (SSB) became possible after finding electronically isolating solids that allow for fast motion of ions at temperatures below 30 °C, i.e. in conditions compatible with most common use of batteries. Those solids became a candidate materials for solid state electrolyte (SSE) which were further optimised to obtain a workable solution. [54] SSE is in direct contact with both, the anode and cathode active materials, which are also solids. There are three major groups of materials for SSE: oxides, sulphides and polymers:

- Oxides: [55]
  - LATP (lithium aluminium titanium phosphate),
  - LiSICON (lithium superionic conductor),
  - LiPON (lithium phosphorus oxynitride).
- Sulphides: [56]
  - crystalline thio-LiSICON,
  - crystalline LGPS ($Li_{10}GeP_2 S_{12}$),
  - amorphous Li_2S-B_2S_3 composite,
  - amorphous Li_2S-SiS_2 composite.
- Polymers: [57], [58]
  - polymer salt complexes (PEO (Poly-(Ethylene Oxide)-based Electrolyte)-$LiBF_4$),
  - gel polymer electrolytes (PVDF (polyvinylidene fluoride) based),
  - composite polymer electrolyte (PEO-$LiAl_2O$).

Despite intensive research on SSE in recent years, challenges remain. The main two are SSE material incompatibility with lithium (or other electrode materials) and difficulties in integration of SSE with anode and cathode materials that are also solid. Although solid electrolytes have reached high ionic conductivity (e.g. 2×10^{-6} $S\cdot cm^{-1}$) at room temperature, they suffer from the interaction with the anode material, leading to side reactions and development of additional barrier for ions at interface of both solids. Ensuring obstacles-free movability of ions is extremely important for high performance, durability and safety of SSB. Furthermore, the materials need to prevent or at least reduce lithium dendrites growth. [59], [60], [61]

Out of the considered materials, the sulfides have the best compatibility with lithium composites, cathode materials and production processes, while the polymer electrolytes are more stable against metallic lithium, but they are sensitive to oxidation and offer lower conductivity at room temperature.

Those issues require further research focused on the reactions on the anode during lithiation and delithiation, using both, in-situ techniques (TEM, SEM, CT, cryo-techniques, structural studies, etc.) and traditional electrochemical methods.

In order to overcome the above mentioned difficulties, several hybrid solutions were proposed, e.g. gel electrolyte, solid state electrolyte combined with a small quantity of liquid electrolyte (to increase contact between solid phases), or combination of inorganic solid electrolyte with solid polymer electrolyte. Those solutions try to combine positive characteristics of both electrolytes used, in order to increase ionic conductivity, reduce interfacial impedance, and improve the stability of the electrolyte. Such hybrid solutions can significantly improve performance of batteries even if not being a “pure” SSBs.

There are number of companies working to commercialise SSB and an example of several most known, leading developers of this technology are presented in **Table 4**.

Table 4. Companies working on solid state batteries in 2023, references to the source data in text below the table.

	SSB type	specific energy [Wh/kg]	energy density [Wh/L]	cycle life	headquarter	customer OEM	TRL
QuantumScape	Li-ceramic-hybrid	330 - 400	800 - 1 100	900+	US	VW, Porsche, Mercedes	4-5
SolidPower	Sulfide	390	930	1 000+	US	Ford, Hyundai, BMW	
BlueSolutions	Li-polymer	300	380	800+	Fr, Ca	Mercedes, Bolloré	6-8
Ionic Materials	Polymer	350	800	750	US	Hyundai, Renault, Nissan, Mitsubishi	3-6
Toyota	Li-SSB*	310 - 400	900 - 1 200	1 000+	JP	Toyota	3-7
Gotion	SSB*	350	800		CN		
Sunwoda	SSB*	400			CN		4-5
Factorial	Hybrid-SSB*	310 - 380	900 - 1 100	1 000+	US, DE, JP	Mercedes-Benz, Hyundai, Stellantis, KIA	4-5
WeLion	Hybrid-SSB*	360	700 - 900	800+	CN	Nio	4-6
SES	Hybrid-SSB*	383	860	600+	US, CN, KR	Hyundai, SAIC	4-6

* type of SSB not disclosed

Source: JRC 2024

Quantum Scape (US) is developing a Li-metal SSB with a solid ceramic electrolyte and liquid organic catholyte. Their battery can deliver about 50% more energy than traditional batteries of similar size [62].

Solid Power (US) is developing a sulfide SSE and SSBs based on it. It is expected that their battery will improve driving range of EVs while battery life, safety and the cost will be significantly improved (compared to Li-ion batteries). They cooperate with Ford, BMW and Hyundai as customers. They plan to produce their batteries with a partner [63].

Blue Solutions (FR, CA) is focused on a lithium polymer based solid state battery. And solutions for EVs (panned debut of a commercial EV in 2028) and stationary storage. They already operate a production facility. [64]

Ionic materials (US) developed a polymer electrolyte supressing lithium dendrites growth. Their electrolyte is already in testing phase by automotive companies (Hyundai, Renault, Nissan and Mitsubishi). [65]. The latest news from June 2024 is that the company has closed its activity. [66]

Toyota (JP) have currently about 1 000 patents in SSBs, which represents the largest IP portfolio in this field. In Jan 2024 they confirmed the launch of an EV with 1 200 km range and 10 min fast charging capability by 2027-2028. [67], [68], [69]

Gotion (CN) is developing a SSB and plan to commercialize their product, but no details are available. [70]

Sunwoda (CN) is another company developing and planning commercialisation of its SSB batteries. Sunwoda is developing a SSB with Li-metal anode and the specific energy of 500 Wh/kg. The company has lab prototype samples available and expect to achieve lab samples of all-solid-state batteries with energy densities exceeding 700 Wh/kg by 2027. [70], [71]

Factorial (US, DE, JP) is developing a concept called FEST (Factorial Electrolyte System Technology), which is a combination of a metallic Li anode, quasi-solid electrolyte (solid electrolyte with small quantity of aqueous solution to increase conductivity), high-capacity cathode and a special cell design. They currently test their batteries (B samples) in demo projects for Mercedes Benz, Hyundai, Stellantis and KIA. The company plan to produce their batteries with a partner. [72]

WeLion (CN) has a production facility for Li-ion batteries, however they plan to fully shift to a hybrid (semi-solid state) battery with metallic Li anode and LFP cathode by 2030. Their cells reach 360 Wh/kg specific energy. The company started supply of their cells batteries to Nio in June 2023 [73], [74], [70]

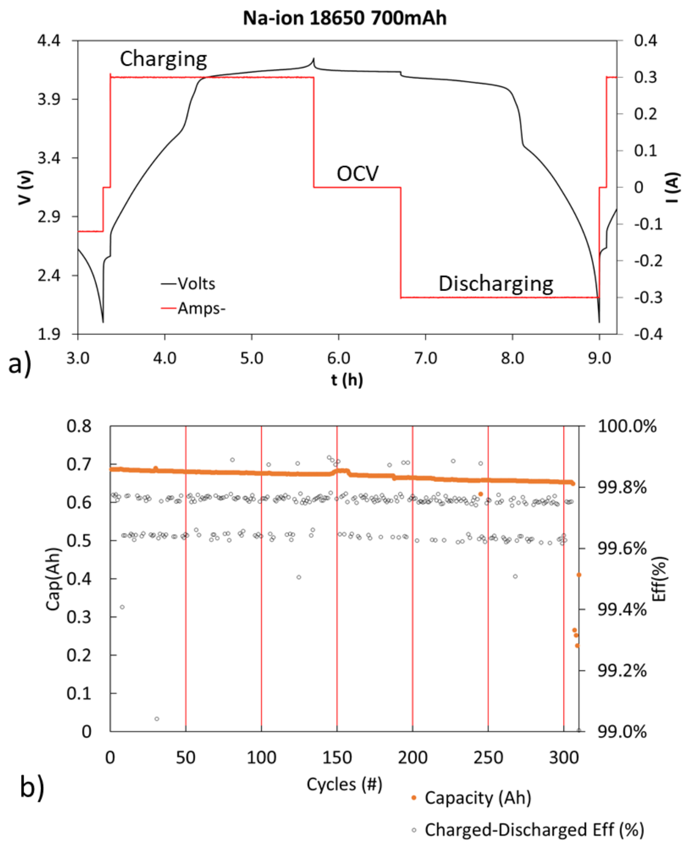
SES (US, CN, KR) is developing Li-metal SSBs and claim starting production by the end of 2024. Prototypes are already being tested by Hyundai and SAIC in China, the US and South Korea. [75]

Additionally, six large battery producers in China, CATL, BYD, FAW, SAIC, WeLion and Geely, will receive a total of 830 million USD support by the Chinese government to develop solid state batteries. [70]

2.1.3 Sodium-ion batteries (Na-ion) update

The detailed analysis of Na-ion battery technology can be found in [1], while in this chapter only a short update is given. The Na-ion battery chemistry is being commercialised and in 2024, for the first time, a regular EU consumer could commercially buy a product powered by Na-ion battery, a small cordless screwdriver. [74] The JRC has started research on performance of these batteries and preliminary experimental results are presented in **Figure 5**, where voltage-current profile is shown in a) and cyclic performance in b). The analysis was performed based on producer's charge-discharge characterisation method. [76] Three voltage changes were observed during battery charging (1.90-3.60 V, 3.60-4.00 V and 4.00-4.30 V), similarly, equivalent changes were observed also during discharge (4.20-3.98 V, 3.98-3.55 V and 3.55-1.90 V). During the rest period (0 A) the OCV was 4.25 V, while the overall round-trip efficiency of about 99.8% was observed during the test. The battery has failed after the 305th cycle and it was not possible to continue the cycling.

Figure 5. Performance test of first Na-ion battery commercially available on the EU market. a) voltage-current profile during the first charge-discharge cycle and b) cycle capacity and columbic efficiency.



Source: JRC 2024

Na-ion technology has reached parity with Li-ion LFP chemistry for energy density while for performance at low temperatures, power density, durability and potentially cost (at scaled production) keep advantage. [1] It should be expected that, similarly to LFP, Na-ion cells will find their path to wide adoption in selected mobility applications (entry-level BEVs, hybrids, micro-cars, micro-mobility) and stationary energy storage. **Table 5** lists companies developing Na-ion battery projects with applied cathode, anode and electrolyte.

Table 5. Technology summary and announced status from companies developing Na-ion battery production.

Company	Announcement	Cathode	Anode	Electrolyte
Northvolt (SE)	First cells expected in Aug 2024 [77]	Prussian White	Hard carbon	$Na_2Fe(Fe(CN)_6)$
Tiamat (FR) *[78]*	First commercial product powered by Na-ion battery [79]	Polyanions	Hard carbon	$Na_3V_2(PO_4)_2F_3$
Faradion (UK) *[80]*	Faradion has been bought by Reliance Industries (IN) for 135 million EUR [81]	Layered oxides	Hard carbon	Na-Ni-Mn-Mg-Ti-O
Natron Energy (US) *[82]*	Batteries for aeronautics and data centres [83]	Prussian White	Hard carbon	$Na_2Fe(Fe(CN)_6)$
CATL (CN) *[84]*	Commercial Na-ion battery by Aug 2024, 16 min. fast charge. [85]	Prussian White	Hard carbon	$Na_2Fe(Fe(CN)_6)$
HINA battery (CN) *[86]*	First EV and container size with Na-ion technology [87]	Layered oxides	Hard carbon	Na-Cu-Fe-Mn-O

Source: JRC 2024

2.1.4 TRL levels

In **Table 6** a summary of technology readiness levels of analysed SSB chemistries is presented. Dark violet indicates the TRL achieved by technology leaders, light violet the TRL achieved by other technology developers, blue represents the TRL achieved per sub-technology.

Table 6. Technology readiness levels of battery technologies

	TRL (Technology Readiness Level); strong colour = market leaders								
(Sub-)Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SSB*									
sulfide SSB									
ceramic SSB									
polymer SSB									
quasi-solid, hybrid SSB									

* *In some market segments (e.g. earbuds, small electronics) the technology is commercialized* *Source: JRC, 2024*

2.2 Installed Capacity and Production

The market of Li-ion batteries is dominated by mobility applications that currently are consuming 86% of production. Another 12% is utilized in stationary energy storage systems (residential, commercial and industrial), while consumer electronics is responsible for 2% of Li-ion battery demand. The lead-acid batteries sector is stable while new, “post-lithium” technologies are not yet produced in relevant quantities, maybe except sodium-ion, which quickly enters into production phase. [6]

2.2.1 EV applications

Sales of electrified vehicles

The statistical data presented in this chapter are in the vast majority cited from the IEA “Global EV outlook 2024” report [88] and EV Volumes [89], unless indicated otherwise.

Cars

Global sales of electrified vehicles[1] (BEV + PHEV; cars + vans) in 2023 were reported at 14.2 million (+35% y/y), out of which 10 million (70%) were BEVs and 4.2 million (30%) PHEVs. The general market of light vehicles grew in the same time by 10%. The share of electrified vehicles in total sales rose from 13% in 2022 to 16% in 2023. The global stock of electrified vehicles exceeded 41 million (3.0% of global fleet) in 2023 rising by about 60% from 2022. In this number, 29 million were BEVs (71% of whole electrified light vehicles stock). The IEA Stated Policy Scenario (STEPS) scenario foresees 22 million electrified vehicles sales in 2025, 43 million in 2030 and 61 in 2035. The Announced Pledges Scenario (APS) gives 23, 47 and 74 million markets, respectively. The stock of vehicles will reach about 80, 250 and above 500 million units in discussed years for both scenarios.

In China, sales of electrified vehicles exceeded 8.3 million (BEVs 5.6 million, +23%; PHEVs 2.7 million, +80%) in 2023, leaving other regions far behind. The share of electrified vehicles in the Chinese market reached 33.9% in 2023 compare to 29% in 2022, by far exceeding the 2025 target of 20% share of sales. China also targets a 50% share of NEVs sales by 2030 in highly polluted regions and a 40% share country wide. The stock of electrified vehicles in China reached almost 22.5 million, approaching 55% of the global electrified vehicles fleet and 7.4% of the national fleet of light vehicles.

It is expected that the Chinese Market of light electrified vehicles will grow until 2040, and then stabilise at about 40 million vehicles a year (corresponding to full electrification). The market of commercial vehicles is expected to reach full electrification by 2045. [90] On shorter term, the STEPS scenario foresees a market of electrified vehicles of 11.7 million in 2025, 18.7 million in 2030 and 23.4 million in 2035. The APS scenario projects 11.9, 18.3 and 23.1 million, respectively. The stock of light electrified vehicles will reach about 43, 120 and 230 million in 2025, 2030 and 2035, respectively, in both scenarios.

In Europe[2], sales of electrified vehicles reached 3.4 million (+26% y/y) in 2023. BEV sales rose by almost 40%, while PHEV sales remained stable over the last three years. The dynamics of the whole European car market was recorded at +14% relative to 2022. Europe kept its position of second largest market globally (22% of global market), behind China (60%) and before the US (11%). The stock reached 11.6 million EVs in 2023. The STEPS scenario foresees a market of electrified vehicles of 5.1 million in 2025, 9.9 million in 2030 and 15.2 million in 2035. The APS scenario projects 5.1, 10.2 and 15.8 million, respectively. The stock of light electrified vehicles will reach about 20, 55 and 120 million in 2025, 2030 and 2035, respectively, in both scenarios.

In the EU, the sales of electrified vehicles reached 2.45 million (+18%) in 2023. BEV sales rose by about 33%, while PHEV sales dropped by 6%. The dynamics of the whole EU market was +14% relative to 2022. The share of BEVs in total vehicles registrations in the EU in 2023 reached 14.6%, 2.5 percent points more than in 2022. The share of PHEVs has decreased by 1.7 percent point reaching 7.7%. Together, electrified vehicles correspond to 22.3% of the total new car registrations in EU, +0.7 pp. The EU stock of electrified light vehicles reached 8.4 million units.

In the US, sales of electrified vehicles approached 1.4 million (+40% y/y), 1.1 million of BEVs (+37%) and 0.29 million of PHEVs (+53%). The growth of general market was recorded at +12%, indicating that EV market grows faster than the whole car segment. The share of electrified vehicles in the market reached 9.5 pp (+2.1 pp y/y). The total stock of electrified light vehicles reached 4.8 million, almost 60% more than in 2022 and accounted for 12% of the overall stock. The EV stock is expected to expand and reach 9.7 million in 2025, 42 million in 2025 and 91 million in 2025 (according to STEPS, but APS project very similar numbers).

Summary of market growth of electrified vehicles in main global regions is presented in **Table 7.**

Table 7. Electrified vehicles market growth in selected regions

	Electrified vehicles market			total market of light vehicles change y/y [%]
	units sold [million]		change y/y [%]	
	2023	2022		
global	14.2	10.5	+35%	+10%
Europe	3.15	2.68	+18%	+14%
EU(27)	2.35	2.00	+18%	+14%
US	1.62	1.10	+46%	+12%
China	8.41	6.18	+36%	+6%
RoW	1.00	0.56	+81%	+12%

Source: JRC based on EVvolumes data.

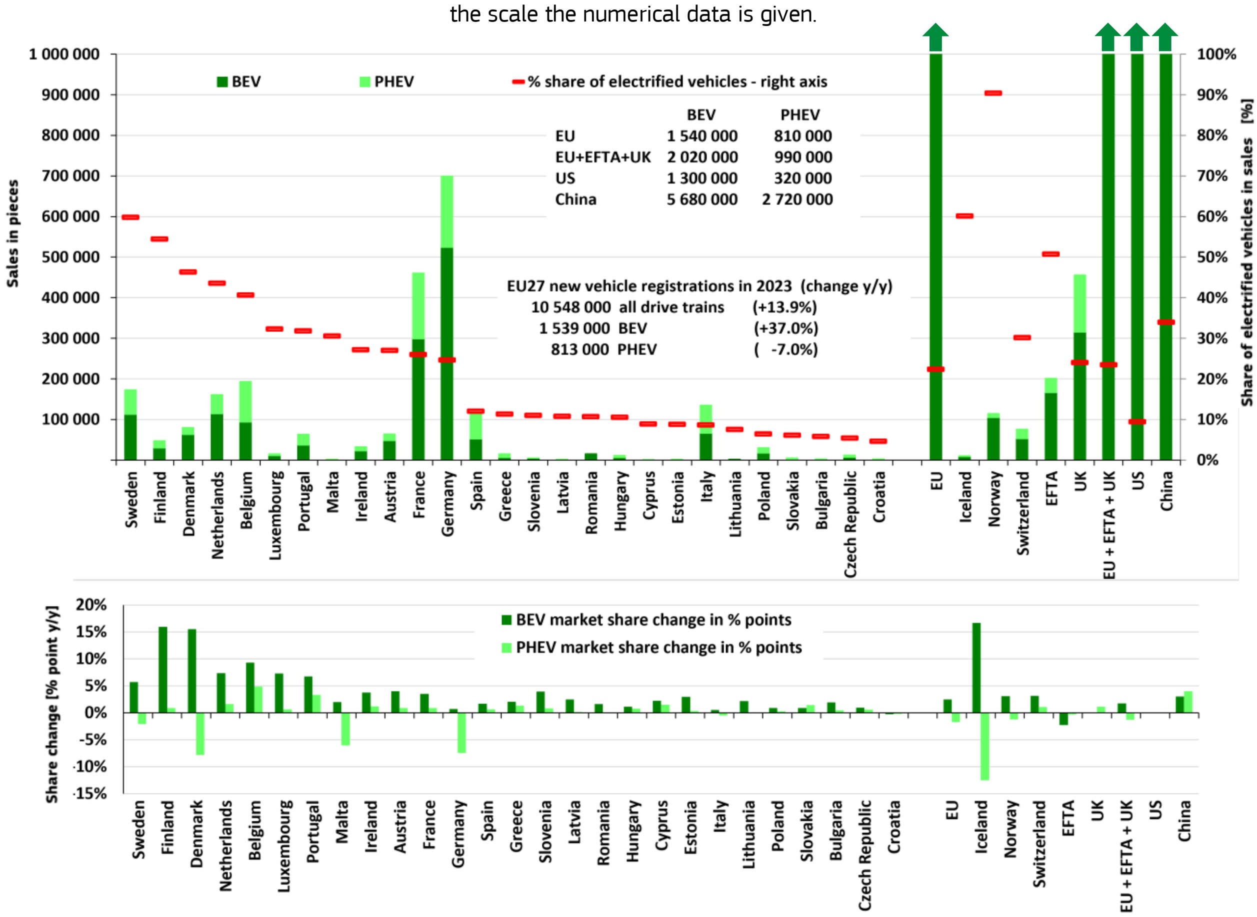
[1] IEA provide statistics for combined category, personal cars + light duty vans.
[2] IEA methodology include EU countries, Iceland, Israel, Norway, Switzerland, Turkey and UK

The EU 2023 new vehicle registrations [91] are shown in **Figure 6**. This data indicates that the trend of mobility electrification is continued, especially for BEVs (+37% y/y), while PHEV vehicles noted some decrease (-7%).

In terms of absolute numbers, DE remain the EU leader, despite total number of electrified vehicles registrations decreased from above 800 000 pieces to ca. 700 000 due to decrease in PHEV registrations, while BEVs noted a moderate increase. DE is followed by FR (the same rank, but solid increase), BE (3 ranks higher), SE (1 rank lower) and NL (the same position). In market share terms, the leader is SE, followed by Fi (+1), DK (-1), NL (0) and BE (+1). The preference of BEVs over PHEVs is stronger pronounced in 2023 (65% of electrified vehicles registration) than in 2022 (56%). This trend is observed in most MSs, especially those with more developed markets. Only in BE, ES, GR, IT and SK, PHEVs are preferred over BEVs in terms of registration numbers. Together, these are 5 MS, as compared to 7 in 2022, and also in 4 out of these 5 countries the ratio became more favourable for BEVs.

The EU advances in direction of meeting the 2025 expectations regarding electrified passenger cars (M1) and light duty vehicles (N1) sales, which is 3.5 million vehicles, corresponding to 31% of all vehicles in this class sold in 2025. However, if the advancement rate observed in 2022/23 (0.35 million vehicles more in each year) is kept, the goal of 3.5 million electrified vehicles sales will be reached one year later, in 2026, while the goal of reaching 31% of total sales will be reached significantly later. This is due to a faster than expected growth of the whole market in 2023 (+13.9% for all drive trains). The goals for 2030 and 2040 are at 7 million (55% of total sales) and about 11 million (85%), respectively. [92]

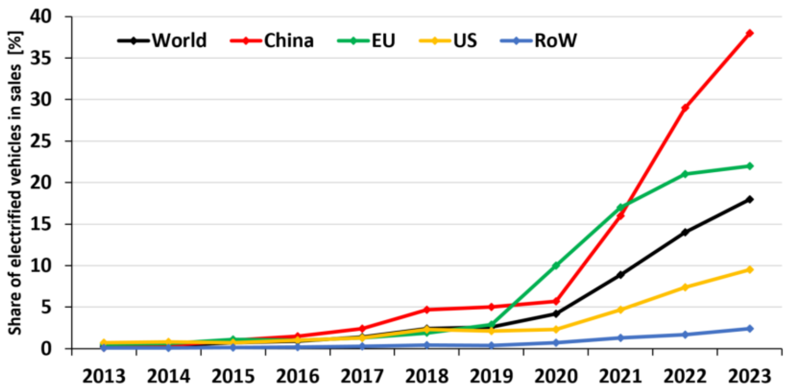
Figure 6. 2023 sales of electrified vehicles in the EU member states and selected world markets. For regions exceeding the scale the numerical data is given.



Source: JRC based on ACEA and IEA EV outlook data.

The evolution of the share of electrified vehicles in passenger car sales in main regions is presented in **Figure 7**. It shows a dynamic growth since 2019 in the EU and since 2020 in China (pulling the global figure) and US (at lower pace). Since 2022 the region with highest share of electrified vehicles in the sales is China. The EU takes second rank, however it should be noted, that since 2022 and also very clearly in 2023 the growth in the EU has lost dynamics, while outside the EU the growth rate remains rather stable.

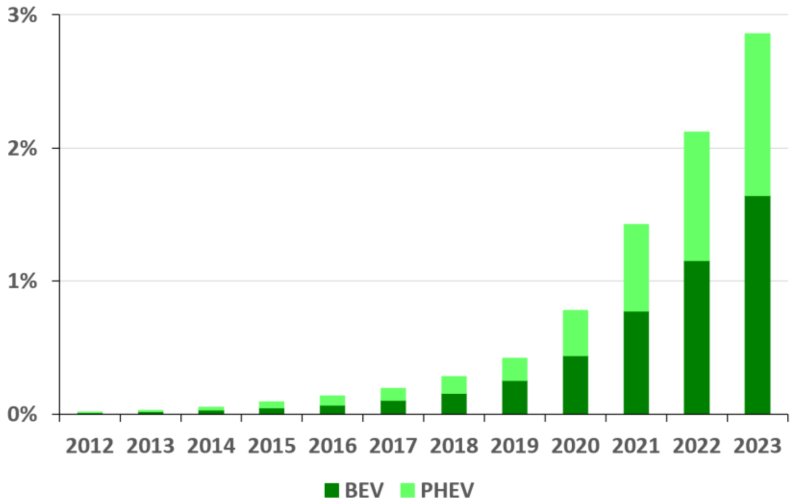
Figure 7. Share of electrified vehicles in passenger cars sales in main regions.



Source: JRC based on IEA EV outlook data

Considering vehicle fleets, the European Alternative Fuels Observatory (EAFO) reports 286 million [93] registered passenger cars (M1 and N1 vehicle categories [94]) in the EU in 2023; out of this, 4.69 million BEVs and 3.47 million PHEVs, which correspond to 1.64% and 1.21% of the total number of registered M1 and N1 cars in the EU, respectively. [93] The evolution of this number since 2012 is shown in **Figure 8**.

Figure 8. Evolution of BEV and PHEV share in M1+N1 vehicles stock in the EU



Source: JRC based on EAFO data.

The global demand for EV batteries is expected to reach 1.5 TWh in 2025 and 3.4 TWh in 2030. [95]

In 2023[3], the sales weighted average battery capacity of BEVs sold globally was 62.5 kWh, while for PHEVs it reached 21.8 kWh. [96] This is +14% and +56%, respectively, relative to capacities presented for 2022. Assuming those numbers and the EU sales of EVs, the overall capacity of batteries of all electrified cars registered in 2023 in the EU reached about 200 GWh. By 2030, this number is expected to reach at least 1.5 TWh in more than 50 million cars according to the "Central MIX" scenario of the Fit for 55 package. [97]

Buses

In 2023 the global market of electric buses was about 49 000 units (-17% y/y) representing 3.1% of the total bus market. In vast majority they were BEV, less than 1 over 30 sold electrified buses was a PHEV. The global fleet of e-buses exceeded 690 000 units and 3.6% (+0.3 pp) of the total bus fleet. Thus, the bus sector remain the most electrified segment of the road transport. The global electric bus market is expected to reach 260 000 – 290 000 in 2025 according to STEPS and APS scenarios. Reaching this level in only two years seems to be extremely challenging taking into account that current market is about 50 000 units and the trend was slightly decreasing over last four years. The scenarios project 380 000 – 540 000 and 710 000 – 970 000 electrified bus sales in 2030 and 2035, respectively. It is also projected that the fleet of electric buses will reach 1.1 million in 2025, 2.3 million in 2030 and 4.1 million in 2035 (in STEPS scenario, about 6%, 11% and 20% of the total bus fleet, respectively). APS scenario project 1.1 million (6.0%), 2.8 million (13%) and 5.5 million (25%) in those years, respectively.

[3] Aug 2023 – last available data

China remained on first position with about 30 000 sold units (61% of global e-bus market, 50% of total bus market in China). Almost all PHEV buses sold globally entered the Chinese market. The IEA (STEPS model) expect challenging about 190 000 electric buses in 2025 (strong increase due to replacement of the ICE fleet with EVs), while for 2030 it is "only" about 110 000 and 85 000 for 2035. This downtrend reflects completion of replacement of majority of fleet and return to "stabilised" market where only actual replacements of vehicles are made. In 2023 the share of EVs in the bus fleet in China was 25% (+3 pp y/y), and it is expected to reach 32%, 50% and 58% in 2025, 2030 and 2035 respectively.

Europe[4] accounted for 8 500 sold units (+70% y/y and 14% of the European bus market). Future expectations are around 25 000 sold units in 2025, 60 000 in 2030 and 70 000 in 2035, equivalent to 23%, 43% and 65% of the European bus market. In 2023 the share of EVs in the bus fleet in Europe was 1.6% (+0.5 pp y/y), and it is expected to reach 4%, 14% and 27% in 2025, 2030 and 2035 respectively.

Based on EAFO data, [98] in the EU in 2023 new bus registrations (M2&M3) reached 5 140 units, (+37% y/y, 96% of those were BEV) and accounting for 15.8% of the bus market (13.6% in 2022). The EU stock of e-buses reached 17 776 units, (+42% y/y), which represents 2.7% of the total EU bus fleet. In absolute terms, the leading member states were: DE (2 829, 15.9% of the EU fleet), FR (2 474, 13.9%), NL (1 560, 8.8%), DK (1 386, 7.8%) and IT (1 196, 6.7%).

The US accounted for 750 units in 2023, 0.8% of the US market. Extremely fast growth is expected, the US market reaching about 15 000 units in 2025, about 50 000 in 2030 and 100 000 in 2035, corresponding to 11%, 35% and 60% of the US bus market. In 2023 the share of EVs in the bus fleet in the US was 0.9% (+0.15 pp y/y), and it is expected to reach 4%, 20% and 45% in 2025, 2030 and 2035 respectively.

The RoW accounted for almost 13 000 units, of which about 3 000 units in India. The IEA (STEPS model) expect about 45 000 units (14 000 in India) in 2025, 180 000 units (60 000 in India) in 2030 and 450 000 units (100 000 in India) in 2035.

Trucks

In 2023, the global market of electric trucks was about 53 000 units, which is about 0.9% of all truck sales. The fleet of e-trucks reached about 330 000 vehicles (0.4% of all trucks). It is expected that the market will grow to about 250 000 by 2025, about 1 million by 2030 and about 2.5 million by 2035. The share of electrified vehicles in stock of the truck fleet will be around 0.7%, 4% and 10%, respectively.

China continues to dominate production and sales of electric trucks. The Chinese market accounted for sales of about 38 000 of electric trucks (72% of the global market, and 2.8% of total truck sales in China). Sales in Europe were estimated at 11 000 units (1.6% share in the European trucks market). The US data are not available. The US together with RoW sum up to about 4 000 units.

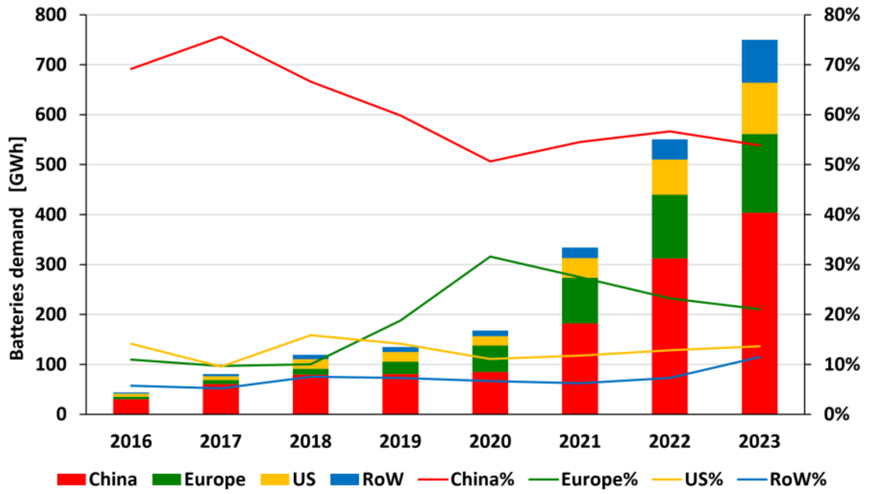
The EU electric heavy duty (N2+N3,) vehicle registrations reached 5 362 units in 2023 (+220% y/y, 1.5% market share). The EU stock of heavy duty vehicles reached about 6.5 million units, out of those 9 049 (0.28%) were electrified. Germany runs the biggest fleet of electrified N2&N3 trucks in the EU with 4 378 units (48% of the EU fleet), followed by Netherlands (1 532 units, 17%), France (801 units, 8.9%), Spain (541 units, 6.0%) and Sweden (511 units, 5.6%). [98]

Batteries for EVs

During 2023 a total of 750 GWh of Li-ion batteries was installed in vehicles globally, 36% more than n 2022 (550 GWh). China has biggest share in global demand, about 54% in 2023, which decreased 3 percent points in last year. Europe is scored second (21%, -2 percentage points, pp), the US is third (14%, +0.6 pp) followed by RoW (411%, +4.2 pp) - see **Figure 9**. Europe had been gaining market share from China and the US in 2019-20, however in last three years this trend was reversed. The US is following a steady trend of slow increase in demand share since 2021. RoW was gaining market share fast in 2023, after a limited increase in 2022. It might be a beginning of a new trend, but needs confirmation through future data.

[4] IEA methodology include EU countries, Iceland, Israel, Norway, Switzerland, Turkey and UK

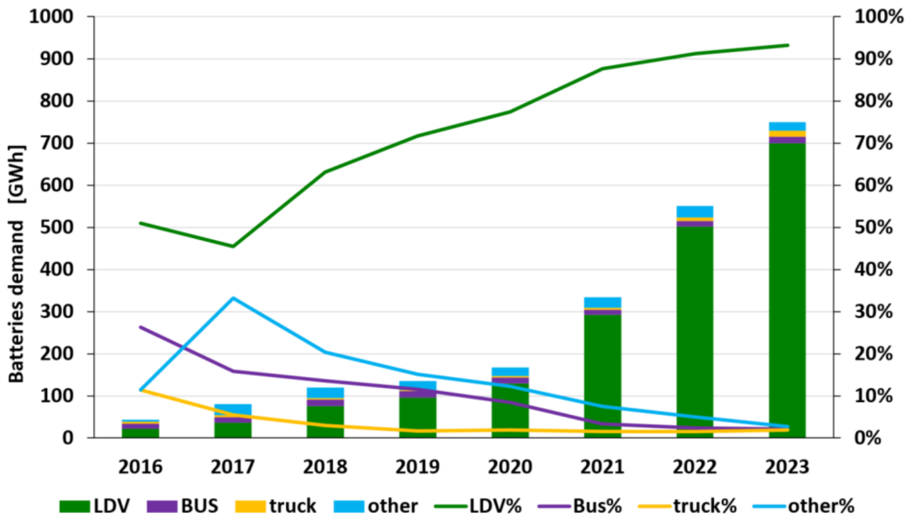
Figure 9. Li-ion batteries demand for EVs per region (bars, left axis), and share in global demand (lines, right axis).



Source: JRC based on IEA, EAFO and EVvolumes data.

The growth of global EV batteries demand was driven by the increase of light electric vehicles market, mainly the passenger cars segment, as well as a growing average battery size installed in a vehicle (see **Figure 10**).

Figure 10. Global batteries demand per application (bars, left axis), and share in global demand (lines, right axis).

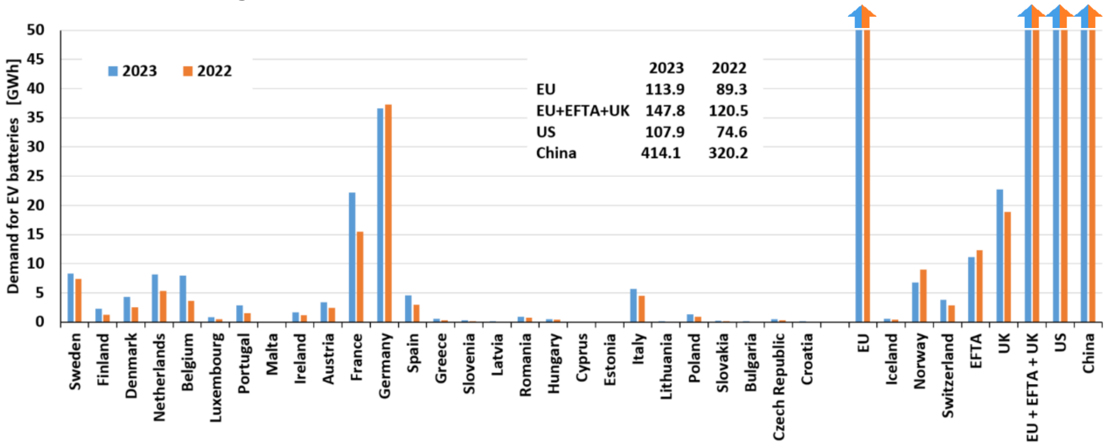


Source: JRC based on IEA, EAFO and EVvolumes data.

The internal demand[5] for batteries in the EU member states is presented in **Figure 11**. Belgium, France and Netherlands significantly increased their demand, while Germany was as the only Member State in which decrease was observed, even though at high level. The relatively weak EV battery demand in East- and Central Europe should also be noted. This data also shows decreasing advantage of the EU over the US and increasing domination of China.

[5] Demand from internal needs only, without exports; summary capacity of batteries installed in EVs new registered in the Member State.

Figure 11. The EU Member State's internal demand for EV batteries.



Source: JRC based on ACEA and IEA EV outlook data.

The future battery demand of 3.7 TWh/y in 2030 in the *Global CETO 2°C scenario 2024*[6], (similar to almost 4 TWh/y in 2030 in STEPS scenario and 6 TWh/y in Net Zero Emission (NZE) scenario in the same year). The demand increases substantially to 15 TWh/y in 2040 and to almost 25 TWh/y in 2050. The main application will still be in passenger cars, accounting for about 78-85% of overall demand followed by light commercial vehicles, buses and heavy-duty trucks. [99]

The regional split shows continued leadership of China, [100] while their market share will decrease from more than 50% to 31% in 2030. At the same time the EU and US will follow similar paths and are expected to reach 24% and 12% in 2030, respectively. [99]

As regarding solid state batteries, very limited data is available. 482.9 MWh of semi-solid-state batteries were installed in China in May 2024, (369.0 MWh in April, +30.9%) with WeLion being the sole technology provider. Since begin of 2024 the cumulative installations amounted to 1.622 GWh, WeLion was the sole provider again. Those batteries were installed in vehicles. [101]

2.2.2 Stationary applications

Global situation

Global installations of new BESS systems exceeded 134 GWh in 2023 (+115%). The cumulative capacity of installed BESS approached 300 GWh. [102], [103] Further fast growth of the market is also awaited in 2024. The expectations of market evolution were updated to 240 GWh in 2025 (no change), 486 GWh (+18%) in 2030 and 927 (+8%) GWh in 2040. [104] Other sources, however, provide higher expectations, 750 GWh in 2030 and 1.6 TWh in 2035. [103]

In 2023, the most frequently installed BESS technology was Li-ion with a market share of 90% (+9 pp), Pb-A took 8% (-8 pp), while flow batteries and sodium based shared the remaining 2% in almost equal parts, exhibiting no significant changes. An increase of the shares of Na-ion and redox-flow technologies at cost of Pb-A and Li-ion is expected. [104]

China was the leading market in 2023 with almost 70 GWh (43 GWh in 2022, +63%) of new installations and accounted for about 60% of the global market. The US with about 28 GWh (15 GWh, +87%) of new installations and a 20% share in global market took second place. The EU new installations reached 16 GWh (9 GWh in 2022, +78%) and accounted for 12% of global market. [104]

Grid BESS market

In 2023, grid systems (front of the meter) accounted for about 72% (+10 pp) of the global BESS market. Li-ion technology was applied in 98% (95% in 2022) of grid BESS installations and the LFP chemistry share among Li-ion chemistries reached 92 % (85% in 2022). Redox-flow batteries accounted for 1% (-1 pp) of the total BESS market, while the share of Pb-A batteries dropped to ~0% from 2% in 2022 and practically is not present in the market anymore. The drop for RFBs resulted from year-to-year fluctuations due to completing of larger projects in some years, while for the Pb-A batteries the reason is phasing out this chemistry from the grid market and replacing it with Li-ion, especially LFP chemistry that dominate the market due to price and

[6] The *Global CETO 2°C scenario 2024* was calculated with the POLES-JRC model. For this scenario a single global carbon price for all regions is applied to limit global temperature increase to 2°C at the end of the century.

durability performance. The role of RFBs, Na-ion and other Na-based chemistries (Na-S, ZEBRA) is expected to increase in the future, reducing the domination of Li-ion technology. Na-ion chemistry is projected to reach 7% share in 2030 and 14% in 2040, while flow batteries share will contribute 6% in 2030 and 10% in 2040. Other sodium-based chemistries will contribute with 2% in 2030 and 4% in 2040. [104]

The average duration[7] of grid BESS systems installed in 2023 slightly increased to 2.2 h (2.1h in 2022), and it is expected to further slowly increase in the future. In 2023, longest average duration systems were installed in the US (2.2 h), in China (2.1 h) and shortest in the EU (1.4 h). [104] This difference mainly reflect higher installation costs in Europe and demand for larger systems from grid side in the US and China.

The storage capacity of grid BESS were increasing, as well as the number of connected installations. 335 systems larger than 100 MWh were connected to the grid in 2023, compared to 120 in 2022. [102]

The grid BESS market projections increased to 382 GWh (from 283 GWh projected in 2022, +35%) in 2030 and 698 GWh (from 594 GWh, +18%) in 2040. [104]

The grid BESS market continuously looks to employ ever bigger cell formats and cells of 280 Ah of capacity or larger became a first choice solution. Still larger cells are expected to dominate this market in the future. [102]

Behind the meter (BTM) BESS market

In 2023, the share of behind the meter (BTM) system installations in all BESS market fell to 28 % (-10 pp). Li-ion technology was applied in 71% (59% in 2022) of BTM BESS installations, while the share of Pb-A batteries dropped to 28% (from 40% in 2022). The role of other chemistries remained marginal in 2023 at ~1% together. The largest fraction of this share was taken by Na-ion batteries, despite this technology is very fresh in the market. Na-ion chemistry is projected to reach 5% share in 2030 and 11% in 2040, while flow batteries will play no significant role before 2040. Pb-A batteries will be present on the market at least until 2040, however the share of this technology will decrease. Other sodium-based chemistries will slowly increase their share and reach 3% in 2040. [104]

Among Li-ion chemistries, the LFP share was 65%, the NMC family took 31% (mostly NMC 622, followed by NMC 811+, NMC 532 and NMC 111) and NCA 2%. [104]

The evolution of the BTM market projections points at 104 GWh (down from 127 GWh projected in 2022) in 2030 and 229 GWh (from 265 GWh) in 2040. [104]

Europe

In 2023, the market of BESS installations reached 10 GW / 16 GWh (**Table 8**). In this, 2.8 GW / 4.1 GWh were front of the meter installation and 7.3 GW / 12 GWh of BTM systems, mainly residential. Europe's contribution to the global market of energy storage was 10% in 2023. In the long term, the EU share is expected to increase to about 15% in 2040.

Table 8. The EU new and cumulative installations.

power [MW] / energy [MWh]		
	annual	cumulative
2020	907 / 1 606	2 408 / 3 951
2021	2 182 / 3 738	4 590 / 7 688
2022	4 500 / 7 500	9 100 / 13 200
2023	10 100 / 16 000	19 200 / 29 000

Source: EASE/EMMES 7.0, JRC

The EU electricity grids depends on energy storage only to a limited, but increasing, extent. The required rebuilding of the EU energy systems in context of limiting climate change and dependence on external energy carriers are drivers to increase EU's grid storage capabilities. However, it is still projected, that the most of future global BESS installations will be done in non-EU regions.

In the EU, Germany and Italy are the two largest markets for home storage systems, growing in 2023 by 180% and 200%, respectively. [102] In Germany, 500 000 combined photovoltaics and BTM BESS systems were installed in 2023.

[7] Despite the market uses term "duration", it rather reflects discharge time of the system, e.g. 1 MW system with 2 h storage time means that it can provide 1 MW over period of 2 hours (hence having storage capacity of 2 MWh).

2.2.3 Production capacity

The overall global manufacturing capacity for Li-ion battery cells reached 2.5 TWh/y in 2023, up from about 1.7 TWh (+50%) in 2022. The average utilisation rate of this production capacity dropped to below 33% from 35% in 2022. About 83% of global production capacity is located in China, 8% in the EU, 5% in the US and about 4% in RoW, mainly Korea and Japan. [100], [103]

The global top 10 companies ranked according to their production capacity in 2023 are presented in **Table 9**. More than 200 new gigafactories are expected before 2030, which means by average 5 new plants would need to go online every two months until 2030.

Table 9. Global top 10 battery producers (cell production capacity) and distribution of their production capacity in regions.

		Production capacity (2023)		Distribution of production capacity			
		[GWh]	% of global	EU	US	China	RoW
1.	BYD	391	21.1%	-	-	100.0%	-
2.	CATL	234	12.6%	3.4%	-	96.6%	-
3.	LG ES	205	11.1%	33.2%	6.8%	45.4%	14.6%
4.	CALB	128	6.9%	-	-	100.0%	-
5.	GOTION	93	5.0%	1.1%	-	98.9%	-
6.	SK Innovation	83	4.5%	27.7%	12.0%	54.2%	7.2%
7.	Svolt	65	3.5%	-	-	100.0%	-
8.	LISHEN	63	3.4%	-	-	100.0%	-
9.	TESLA	54	2.9%	9.3%	90.7%	-	-
10.	SAMSUNG	46	2.5%	65.2%	-	19.6%	15.2%

Source: CRU. [103]

2.3 Technology Costs

According to the *BloombergNEF's annual battery price survey,* [105] the average price of Li-ion batteries fell from 161 USD/kWh in 2022 by 14% in real terms to 139 USD/kWh in 2023, as presented in **Figure 12**. These prices represent a global volume-weighted average across all applications, including different types of EVs, buses and stationary storage, including differences in geographical regions and are expressed in real 2023 US Dollars. The observed cost reduction was mainly driven by an increase of production capacity in all segments of the battery value chain, while demand growth was smaller than expected by industry players and decreasing cost of battery materials. It also reflects increased use of cheaper, lithium iron phosphate (LFP) batteries. The prices are expected to continue decreasing in 2024.

For BEV packs, the 2023 volume-weighted average price was 128 USD/kWh (-12.9%), while at cell level it was 99 USD/kWh (-18.9%). Thus in 2023 cells accounted for 78% (-5 pp) of the total pack price.

The stationary energy storage system costs stayed above 300 USD/kWh for a four-hour duration system.

BloombergNEF report also the regional price differences: battery packs were cheapest in China, at 126 USD/kWh, while in the US and Europe the cost was 11% and 20% higher, respectively. The prices, however, are converging and the differences between China, US and Europe have been decreasing in recent years. In 2022, the China-US and China-Europe price differences reached 24% and 33%, respectively, compared to 40% and 60% in 2021.

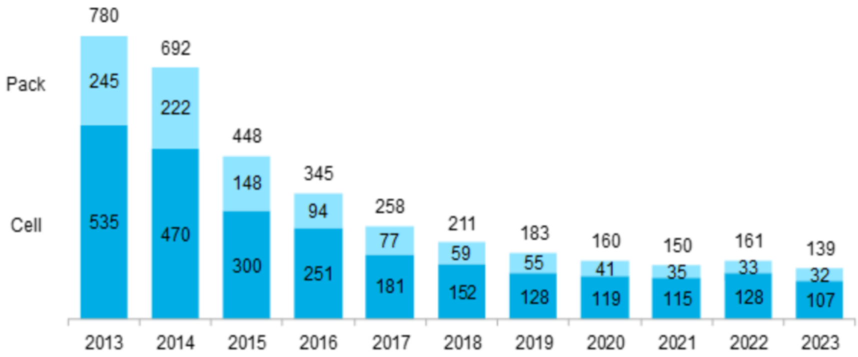
In 2023, the global weighted-average price of lithium iron phosphate (LFP) batteries reached 130 USD/kWh at pack level and 95 USD/kWh at cell level, the first time that BNEF's analysis found an LFP average cell price below 100 USD/kWh. On average, LFP cells were 32% cheaper than lithium nickel manganese cobalt oxide (NMC) cells.

An increased supply of raw materials could contribute to price reduction in 2024 and beyond, while geo-political frictions and trade issues remain the main source of uncertainty in the short-term. Market entry of non Li-ion batteries, especially Na-ion and redox-flow technologies, could alleviate price pressures. IRENA estimates cost of Na-ion battery cells at 40-80 USD/kWh depending on chemical formulation, equivalent to 30-60% of cost of Li-ion cells and about 30% lower than a cost of LFP battery. [106][8]

[8] This estimation was published in Sep 2023, since that time Li-ion battery prices have visibly decreased.

IDTechEx estimate the Na-ion battery cells average price (for different chemistries) at 87 USD/kWh in 2024. They expect also a Na-ion cells price reduction to about 40 USD/kWh (for chemistries using primarily Fe and Mn) by 2030. This would result in cost of about 50 USD/kWh at pack level [107]

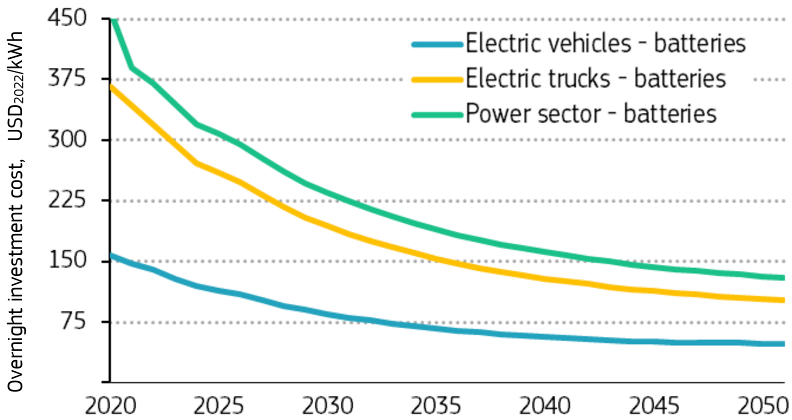
Figure 12. Volume-weighted average Li-ion battery pack and cell price split (real terms 2023 USD/kWh, based on 303 data points from EVs, buses, commercial vehicles and stationary storage).



Source: BloombergNEF, Nov 2023

According to the *Global CETO 2°C scenario 2024*, which was calculated with the POLES-JRC model, the cost of EV car batteries, truck batteries and stationary BESS systems will be about 85, 195 and 235 USD_{2022}/kWh respectively in 2030 (see **Figure 13**). In the long term, the cost of EV car batteries is expected to fall to about 50 USD_{2022}/kWh by 2045 and stabilise at that level. The cost of truck batteries will also decrease and reach about 100 USD_{2022}/kWh by 2050, but it will continue a slowly decreasing trend beyond 2050, diminishing the distance to EV batteries. The cost of stationary systems will also decrease following a trend similar to that of truck batteries, but at about 20-30% higher level. They will reach 130 USD_{2022}/kWh by 2050 still following a slowly decreasing trend.[9] [99]

Figure 13. Overnight investment cost of batteries in mobile and stationary applications.



Source: JRC-POLES model

BNEF expects average battery pack prices to continue decreasing due to increasing supply of raw materials, technological innovation and manufacturing improvement. They expect battery pack prices at 113 USD/kWh in 2025 and 80 USD/kWh in 2030 (in real 2023 US dollars, and in agreement with the *Global CETO 2°C scenario 2024*. [99]

Ramping up local battery manufacturing in Europe and the US could increase pressure on battery pack prices due to higher local energy, equipment, land and labour costs compared to Asia. In the US, the Inflation Reduction Act, resulting in 45 USD/kWh production tax credit for cells and packs could act in direction of price decrease. The currently observed manufacturing process improvements, capacity expansion across the supply chain and new technologies, such as silicon and lithium metal anodes, solid-state electrolytes, new cathode materials, new pack and cell designs will act in direction of technology costs reduction. The cumulative impact of all those circumstances on pricing is not yet clear.

[9] Please note the unit is USD_{2022} in contrast to prices presented in the **Figure 12**. While BNEF uses actual year USD real value (updating past prices with inflation rate each year) the POLES-JRC model uses real value of USD fixed to 2022 for the future estimates.

The SSB market is still in its infancy and therefore prices are generally high due to low production volumes and technological difficulties during production; they are expected to depend on many factors, vary between different SSB technologies and exhibit volatility.

In 2023 the costs of SSBs were about 300-500 USD/kWh, depending on materials and technology used. The future estimates expect the cost of 100-150 USD/kWh by 2034 if expected advancement in materials and production technology are made. [108]

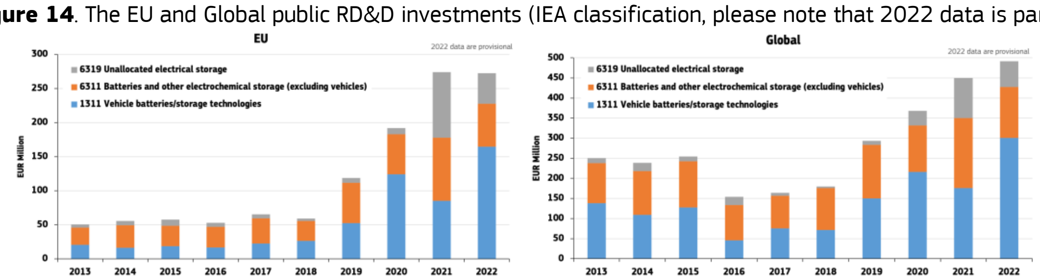
For example, the current cost of the 150 kWh semi-solid-state battery pack for Nio vehicles is about RMB 298 000, or 41 000 USD. This is about 275 USD/kWh, [71] while Sunwoda, a Chinese manufacturer of Li-ion batteries, expects to reduce the cost of polymer-based all SSB to about 275 EUR/kWh by 2026, close to the current cost of semi-solid-state batteries. [71]

2.4 Public RD&I Funding and Investments

The analysis is based on IEA data and is limited to a country's national investments. [109] The code numbering follows IEA classification[10]. There are many gaps in the available data set, as some countries do not publish data with sufficient level of details, especially for optional 4-digit codes used here. All values are converted from a country's national currency to EUR, based on the OECD annual currency average exchange rate. Data for the US is available up to 2015 only.

The EU and global public RD&D investments are presented in **Figure 14**. The EU investments have been increasing dynamically since 2019, boosting from stable 50-70 million EUR to almost 300 million EUR in three years. 2022 showed the same level of investments as 2021. Global investments follow similar trends, increasing from (please note US data discontinuity as of 2015, visible as global investments shrink in 2016 to 150 million EUR from 250 million EUR in 2015) about 150 million EUR before 2019 to almost 500 million EUR in 2022. Global leaders are the US (data missing since 2016, but older data of about 100 million EUR suggest this with high level of probability), EU and CA. Japan was also very active in the field of general use batteries before 2018, limiting its activity after this year. The EU MS with highest public RD&D investment is FR, followed by AT and DE.

Figure 14. The EU and Global public RD&D investments (IEA classification, please note that 2022 data is partial)



Source: JRC based on IEA data

Source: JRC based on IEA data

2.5 Private RD&I Funding and Investments

Private investments or 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 methodology are available in the footnote.[11]

In 2023, global VC investments (**Figure 15**) in battery developers decreased to 7.5 billion EUR (-27%) after a decrease of 21% in 2022. A drop was observed mainly for China, and to lower extent for the US. The EU, after a 31% drop in 2022, exceeded the previous record figure registered in 2021 setting a new historic record in 2023 and taking the position of global leader in VC investment. In general, investments at later stages are larger as compared to earlier stage investment per investment, but a dominance of later stage investment can also be observed when accumulating all investments. The early stage investments in the EU decreased by 35%

[10] IEA Guide to Re IEA Guide to Reporting Energy RD&D Budget/ Expenditure Statistics porting Energy RD&D Budget/ Expenditure Statistics, https://iea.blob.core.windows.net/assets/a2f370cf-873e-486f-935d-c2a117e14ba6/IEAGuidetoReportingEnergyRDDBudget-ExpenditureStatistics.pdf

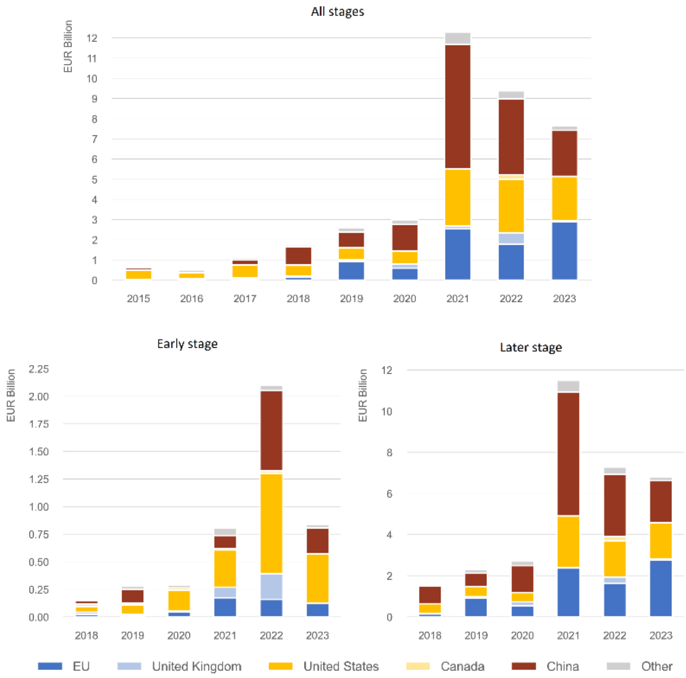
[11] *Venture Capital investment consist of early-stage and later-stage deals. Early-stage deals include accelerator/incubator, angel, seed, Series A and Series B deals; it also includes grants. Later-stage deals include all later series and private equity growth. Undisclosed series, deals occurring more than 5 years after the company's founding date and very large early-stage deals are re-classified as later-stage deals.*

to 0.1 billion EUR, however this was overcompensated by an increase of later stage investments by 80% to 2.8 billion EUR. For China, the early stage investments rose significantly in 2023, which however did not compensate a massive decrease in later stage investments. The US strongly decreased activity for early stage partly compensating this loss through later stages.

Overall, the EU share in the period 2018-23 in all-stages investments increased to 24.4% (from 20.2% in 2017-22), 15.2% (13.2%) in early-stage and 25.4% (21.1%) in later-stages investments.

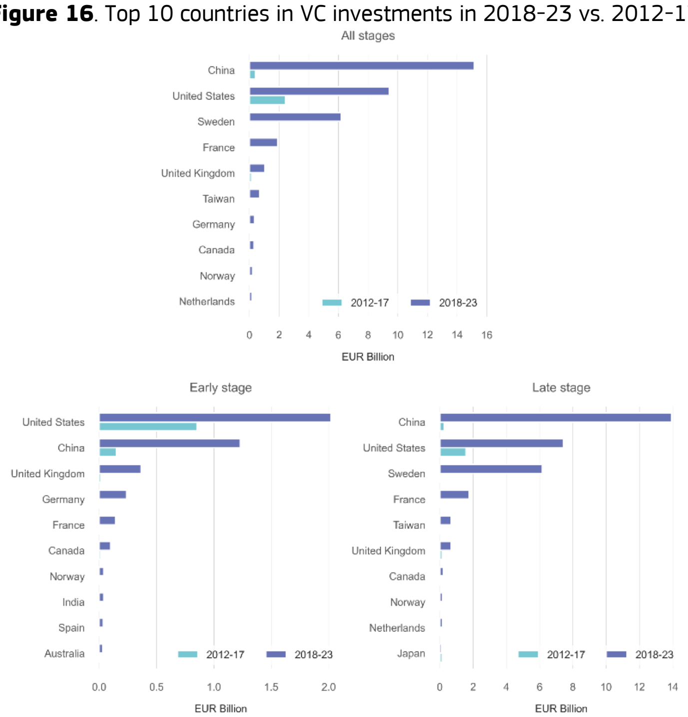
On the list of top 10 countries regarding all-stages VC investments China is leading and is followed by the US and Sweden. Three other EU MS are also listed there: France (4), Germany (7) and Netherlands (10). For more details see **Figure 16**.

Figure 15. Total VC investment by region and stage



Source: JRC based on PitchBook data

Figure 16. Top 10 countries in VC investments in 2018-23 vs. 2012-17



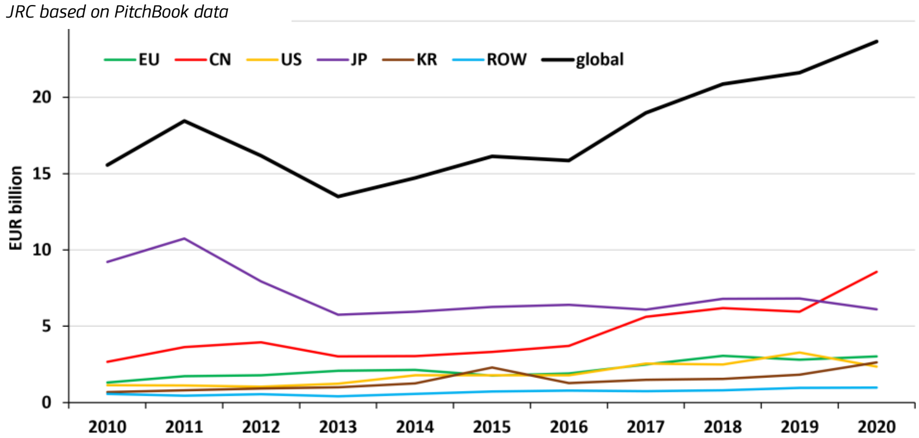
Source: JRC based on PitchBook data

JRC has also developed a methodology to estimate private R&I expenses using patenting output as a proxy [110], [111]. Its results however, should be interpreted with caution and serve as an indication of a trend rather than reflecting absolute expenditures. It also takes 3-4 years before patent data are available for analysis, as patents processing takes several years. [110] Thus only the 2020 data are close to final, while 2021 data is still incomplete and provisional only at the time of drafting this report. The data is also subjected to periodical revisions each year, to assure coherence with the EU R&I Industrial Scoreboard.

The global private R&I expenditures calculated according to this methodology (see **Figure 17.** *R&I expenditures estimation from patenting activity by region*) have been steadily increasing since 2013 with a CAGR of about 8%. The leader is China, which overpassed Japan in 2020 following slightly increasing steady trend. The EU takes third position in front of Korea and the US; all following slightly increasing trends.

Figure 17. R&I expenditures estimation from patenting activity by region.

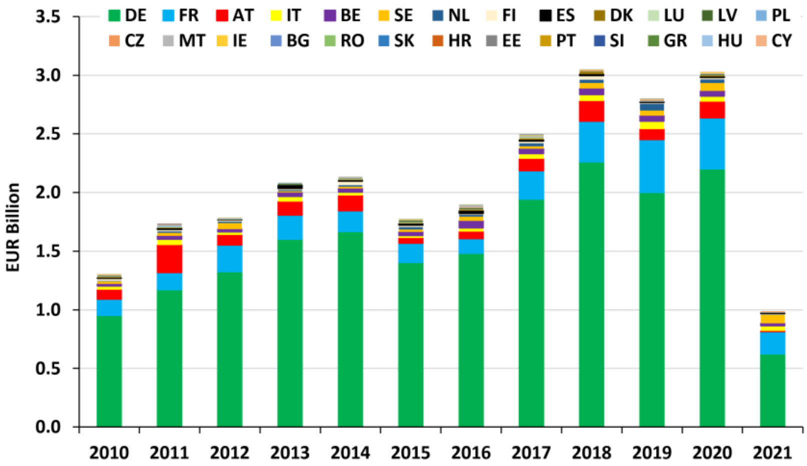
JRC based on PitchBook data



Source: JRC based on EPO Patstat

In the EU (see **Figure 18**) Germany is leading with about 73% contribution to the total EU expenditures in 2020. It is followed by France and Austria accounting for 14% and 5% respectively. Contributions from all other member states sum up to remaining 8%.

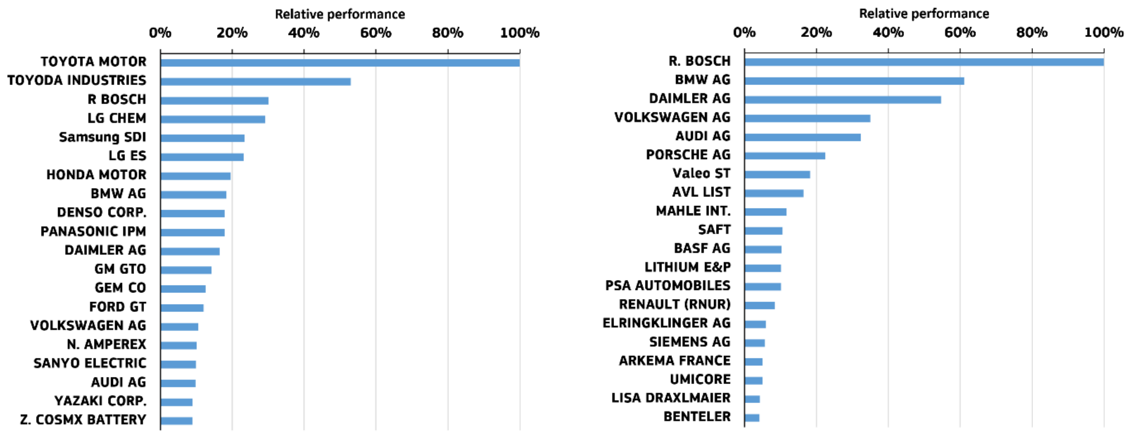
Figure 18. Estimation of the EU MS expenditures on R&I using their patenting activity.



Source: JRC based on EPO Patstat

The global Top 10 innovators (see **Figure 19**) are mostly Asian companies, with only two EU representatives: Bosch at place 3 and BMW at place 8. Another three takes places in the second 10.

Figure 19. Top 20 global (left) and EU (right) innovating companies based on their patenting activity.



Source: JRC based on EPO Patstat

In addition to the analysis above: start-ups actively develop batteries, from incremental improvements of existing technologies to new chemistries. The battery Important Projects of Common European Interest (IPCEI) from 2020-21 brought 14 billion EUR of private money added to the public funding. The European industry invest regularly in integration of batteries in their products. The summary investments in the EU's battery sector were 180 billion EUR until end of 2022. [112]

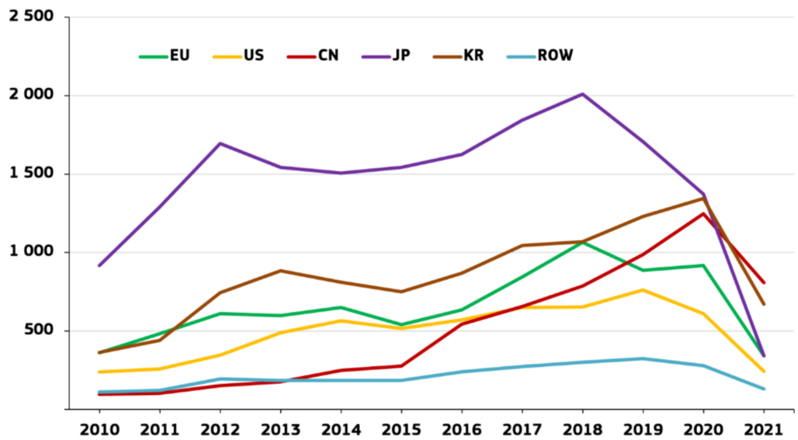
2.6 Patenting trends

The analysis is based on European Patent Office PATSTAT [113] data,[12] 2023a. The analysis considers only patent applicants. A patent family was used as a proxy of invention and thus the number of patent families measures inventive activity. A patent family includes all documents relevant to a distinct invention, e.g. applications to multiple authorities, thus preventing multiple counting. An equal fraction of the family is allocated to each applicant and technology. High-value inventions refer to patent families with applications filed in more than one patent office, independent of number of the offices. The 2021 data are partial only.

The battery specialisation index (SI) represents patenting intensity in a battery technology for a given country (region) relative to geographical area taken as reference, e.g. global. If the battery SI = 0, the patenting intensity is equal to the global average; SI < 0 means patenting intensity is lower than the global average (e.g. SI = -0.5 means patenting activity is half of the reference one), SI > 0 means that the country patenting effort is higher than the global average. [114] More details are available in the literature. [110], [111], [115], [116], [117]

The number of high-value inventions per region is presented in **Figure 20**. Japan recorded the highest number of the high-value inventions over most of the analysed period, followed by Korea. The EU was overpassed by China in 2019 and occupy fourth position. The significant drop of most regions and especially Japan in 2021 is reflecting incompleteness of the data due to patent processing time and potentially some effects of the Cov-19 crisis. Interpretation of data trends in this period require special care.

Figure 20. Number of high-value inventions by region.

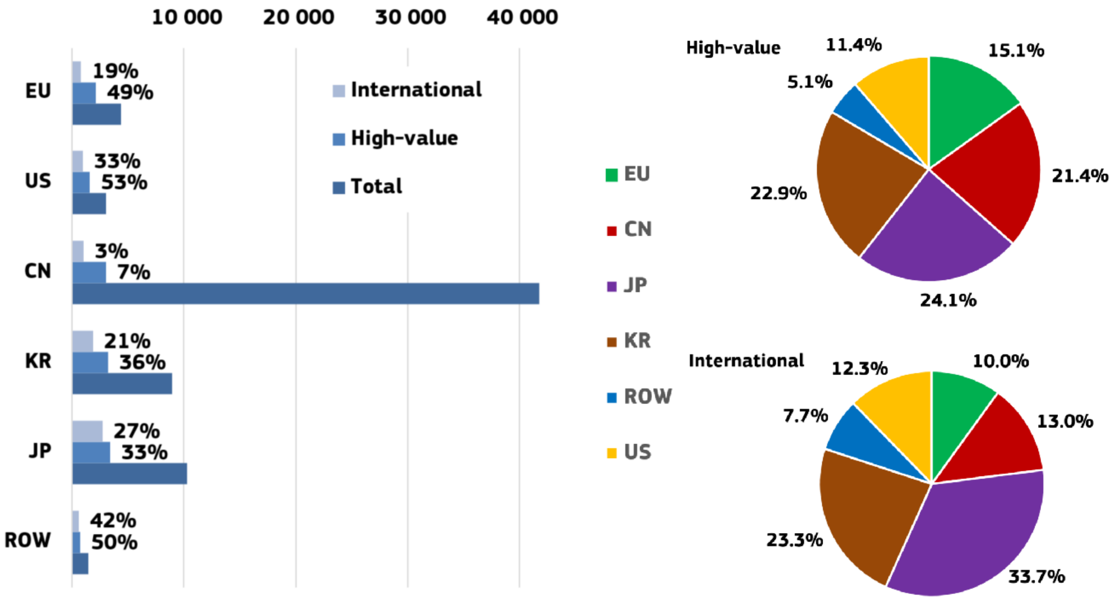


Source: JRC based on EPO Patstat

[12] The following CPC codes were considered: Y02E 60/10, Y02T 10/70, Y02W 30/84, Y04S 10/14.

As presented in **Figure 21**, in the 2019-21 period, the total number of inventions (dark-blue bars, left side), was highest for China (41 733, 60% share, +7 pp relative to 2018-20), followed by Japan (10 286, 15%, -3 pp) and Korea (8 977, 13%, -1 pp). The EU (4 363, 6%, -2 pp) is ranked fourth, before the US (3 058, 4%, -1 pp). The shares of international and high-value inventions for a region is marked with light- and mid-intensity blue, respectively. While China is leading in total inventions, the fractions of international and high-value categories are lowest of all regions (3% and 7%, respectively, both not changed) indicating that China has been mostly protecting its own market. The highest number of high-value and international inventions are reported for Japan, Korea and China, followed by the EU and US (high-value) or US and EU (international patents).

Figure 21. Number and type of inventions by region (left, percentages indicate fractions of high-value and international inventions) and inventions distribution among regions (right) in 2019-21.



Source: JRC based on EPO Patstat

The international protection of high value inventions in 2019-21 period – see also **Figure 22**:

The **EU** applied 650 times (979 in 2018-20, -34%) to other countries for protection of its inventions: 260 (40%, -4 pp) to the US, 245 (38%, no change) to China, 75 (11%, +2 pp) to RoW; while in the same time received 1 464 applications (1 855 in 2018-20, -21%) from other countries: 480 (30%, +2 pp) from Korea, 420 (26%, -2 pp) from Japan, 349 (22%, +2 pp) from China, 303 (19%, -1 pp) from the US and 51 (3.2%, -0.3 pp) from RoW.

The **US** applied 708 times (905 in 2018-20, -22%) to other countries, 303 (43%, +1 pp) to the EU, 219 (31%, -4 pp) to China and 117 (16%, +1 pp) to RoW; while received 2 111 applications (2 743 in 2018-20, -23%) from other countries: 716 (34%, -1 pp) from Japan, 608 (29%, +3 pp) from Korea, 384 (18%, +2 pp) from China, 260 (12%, 4 pp) from the EU and 143 (6.8% +0.1 pp) from RoW.

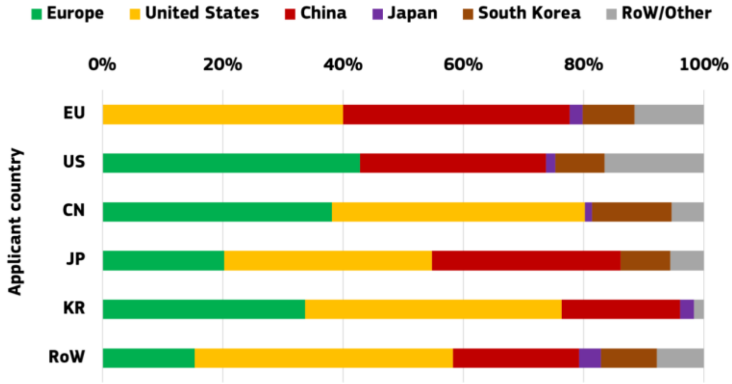
China applied 914 times (949 in 2018-20, -4%), 384 (42%, -4 pp) to the US, 349 (38%, -1 pp) to the EU and 121 (13%, +6 pp) to Korea; while received 1 464 applications (2 196 in 2018-20, +33%) from other countries: 650 (44%, +1 pp) from Japan, 280 (19%, -2 pp) from Korea, 245 (17%, no change) from the EU, 219 (15%, +1 pp) from the US and 70 (4.8%, +0.3 pp) from RoW.

Japan applied 2 073 times (2 821 in 2018-20, -27%), 713 (34%, -1 pp) to the US, 650 (31%, -12 pp) to China and 420 (20%, -8 pp) to the EU; while received only 81 applications (112 in 2018-20, -28%) from other countries: 33 (41%, +5 pp) from Korea, 14 (17%, -5 pp) from the EU, 12 (15%, +1 pp) from Row, 11 (14%, +1 pp) from the US and 11 (14%, -1 pp) from China.

Korea applied 1 425 times (1 779 in 2018-20, -20%), 608 (43%, +2 pp) to the US, 480 (34%, +4 pp) to the EU and 280 (20%, -6 pp) to China; while received 437 applications (430 in 2018-20, +2%) from other countries: 171 (39%, -10 pp) from Japan, 121 (28%, +13 pp) from China, 58 (13%, no change) from the US, 56 (13%, -3 pp) from EU and 31 (7.1%, -0.2 pp) from RoW.

RoW countries applied 333 times (421 in 2018-20, -21%), 143 (43%, -1 pp) to the US, 70 (21%, -2 pp) to China and 51 (15%, no change) to the EU; while received 407 applications (517 in 2018-20, -21%), from other countries: 117 (29%, +2 pp) from the US, 116 (28%, -8 pp) from Japan, 75 (18%, +1 pp) from the EU, 49 (12%, +1 pp) from China, 26 (6.4%, +1.4 pp) from other RoW countries and 24 (5.9%, +0.8 pp) from Korea.

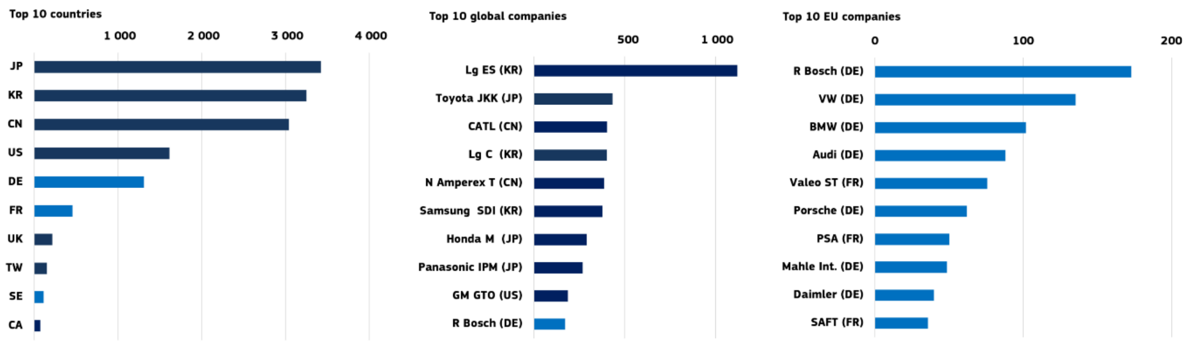
Figure 22. International protection of high-value inventions (2019-21).



Source: JRC based on EPO Patstat.

The top 10 countries high value invention, global companies and EU companies are present in **Figure 23**. On the top 10 countries regarding high-value inventions in 2019-21, three EU MS were ranked: Germany (5th place), France (6th) and Sweden (9th). No changes to the order of Top 10 was observed, however it is worth to notice that Korea and China significantly reduced distance to preceding countries. Among the global Top 10 companies Lg Energy Solutions is leading (+1 position), followed by Toyota (+4), CATL (no change), Lg Chem (-3) and Amperex (+2). There is only one EU based company on the list, Bosch (DE, 10th, -2 positions). On the Top 10 EU innovators Volkswagen (+1) replaced BMW (-1) on second position, PSA appeared on position 7 moving Mahle (-1) and Daimler (-1) down. Arkema and Renault went off the list (from positions 9 and 10) while SAFT appeared on place 10. The top 10 EU innovators list is fully occupied by companies from Germany (7) and France (3).

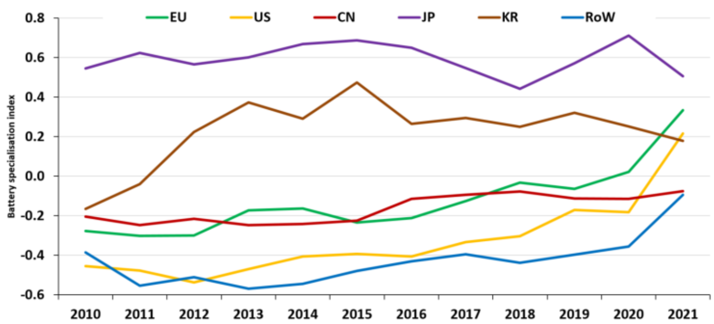
Figure 23. 2019-21 high-value inventions: top 10 countries, global and EU companies.



Source: JRC based on EPO Patstat.

A battery specialisation index (**Figure 24**) shows continuous leadership of Japan in the battery technology development since at least 2010. It seems the strong increase of Japan in 2019-20 was a statistical fluctuation only and in 2021 it decreased even steeper. This period, however, was especially affected by economies shutdown due to COV-19 and should be interpreted with special care. The long term trend for Japan can be described as stable. Korea suffered from a moderate decrease and moved to the fourth rank, overpassed by the EU and US, both recording fast growth to second and third position, respectively. China continued a slow increase, however was overpassed by US and recorded fifth rank.

Figure 24. Battery specialisation index, (global average taken as reference).



Source: JRC based on EPO Patstat

2.7 Scientific publication trends

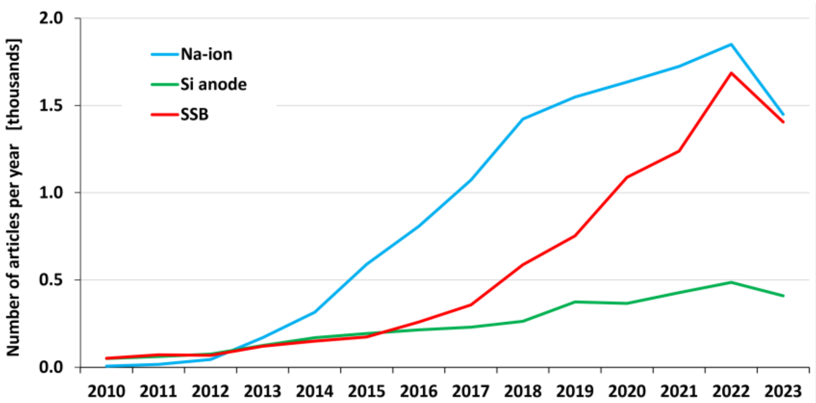
The analysis is based on JRC Tools for Innovation Monitoring (TIM) [118] system fed with data from Scopus database and includes global, regional and MS statistics.[13]

Analysis of links between countries in Europe include all European countries (defined as geographical location) and is not limited to the EU member states only. TIM was also applied to assess collaborations between global regions and countries. Those assessments are based on analysis of affiliations of authors of scientific publications. The size of the nodes in the cooperation graphs represent number of documents assigned to a country, lines between two nodes mark co-publications or co-occurrence in the same document. Line thickness is relative to the number of common publications. Colours mark groups of nodes that appear together more often than with other nodes, thus creating clusters. All publications from the 2010-22 period were analysed.

For benchmarking regions and countries regarding citation numbers, a Field Weighted Citation Impact (FWCI) index was used. FWCI is the ratio of the actual and “expected” number of citations. “Expected” means average citations over the last three years for all Scopus outputs of the same age, type and field. An FWCI = 1 means that a publication has “world average impact”, a FWCI > 1 indicates higher impact, e.g. FWCI of 1.5 indicates 50% more citations than the global average for similar publications.

Global bibliometric trends for Na-ion, Si-rich anode, and solid state (SSB) batteries (**Figure 25**) show continuously increasing interest in those technologies, except for 2023, when all of them recorded some drops. More time is needed to judge, if this is a trend-breaking behaviour or just a short-time deviation. Na-ion batteries experienced the fastest growth of publishing activity between 2012 and 2018, reaching more than 200 publications·y^{-2}. After that period, the rate of increase of the publications number slightly decreased, but the publication numbers continued to grow at a rate of about 100 publications·y^{-2} until 2022. Publishing activity for batteries with Si-rich anodes exhibited a steady increase of about 45 publications·y^{-2}. Publishing activity for SSBs increases at growing pace, reaching about 440 publications·y^{-2} increase from 2021 to 2022. Those trends represents well the relative interest in the assessed technologies and indicate that Na-ion and SSBs are very close to wide entrance to the markets (Na-ion is already present).

Figure 25. Global publishing activity trends for Na-ion, Si-rich anode, and solid state battery technologies.



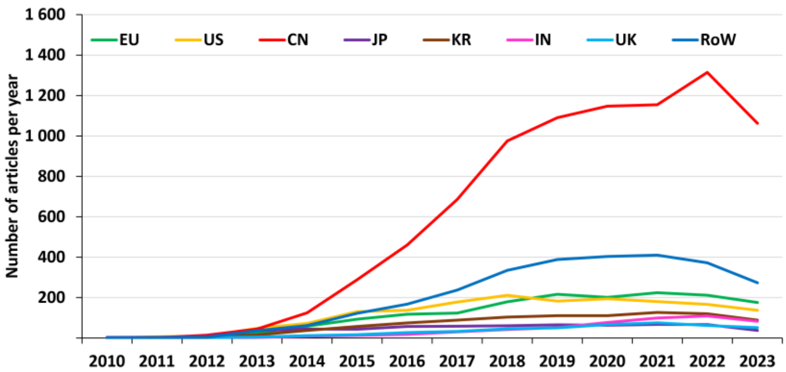
Source: JRC based on TIM data

Na-ion batteries

China, after booming its interest in the 2013-18 period followed by stabilisation at about 1 100 publications·y^{-1} remains a global leader. **Figure 26** It is followed by the RoW (300 publications·y^{-1}), EU and US. In 2023, all analysed regions exhibited reduced number of publications.

[13] The following search queries were used in TIM:
Na-ion - topic:("sodium ion battery"~2 OR "Na ion battery"~2) AND class:article
Si-based anodes - topic:(("Si anode"~2 OR "silicon anode"~2 OR "silica anode"~2) AND battery NOT LiySiTON) AND class:article
SSB - topic:("solid state battery"~2 OR "solid state batteries"~2 OR "solid electrolyte battery"~2 OR "solid electrolyte batteries"~2 OR "polymer electrolyte battery"~2 OR "polymer electrolyte batteries"~2) AND class:article

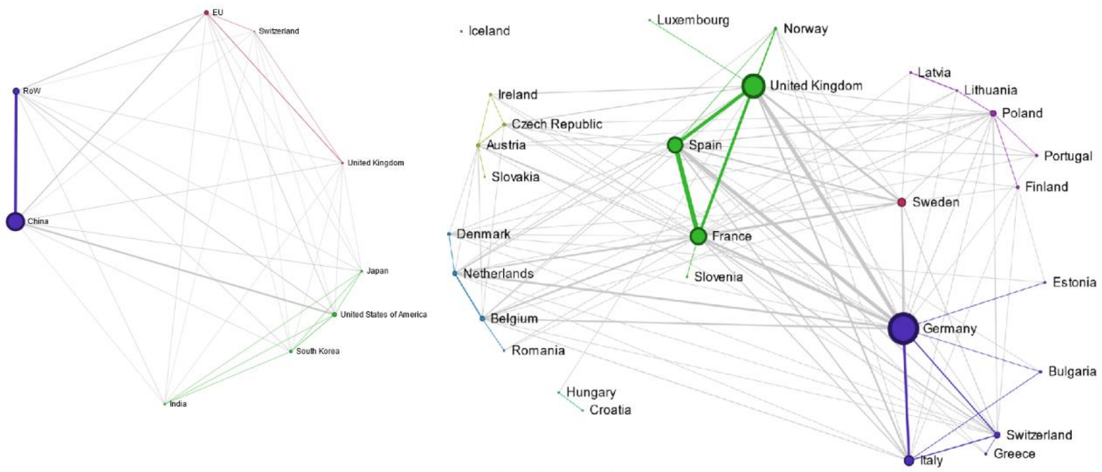
Figure 26. Na-ion technology publishing trends activity per region.



Source: JRC based on TIM data

Globally, the strongest collaboration is observed between China and RoW, while two other clusters grouping EU, Switzerland, UK and US, Japan, Korea and India are observed. Among European countries the strongest link is observed between UK, France and Spain, which together with Norway, Luxembourg and Slovenia formed largest cluster. Germany is leader of second cluster (together with Italy, Switzerland, Greece, Bulgaria and Estonia) and remains strongly linked with leaders of the first cluster. Poland seems to be a leader of a smaller cluster formed with Finland, Portugal, Lithuania and Latvia. Another cluster is created by Belgium Netherland, Denmark and Romania and one more by Austria, Czech Republic, Slovakia and Ireland. Sweden remains alone, but bound to few clusters, see **Figure 27**.

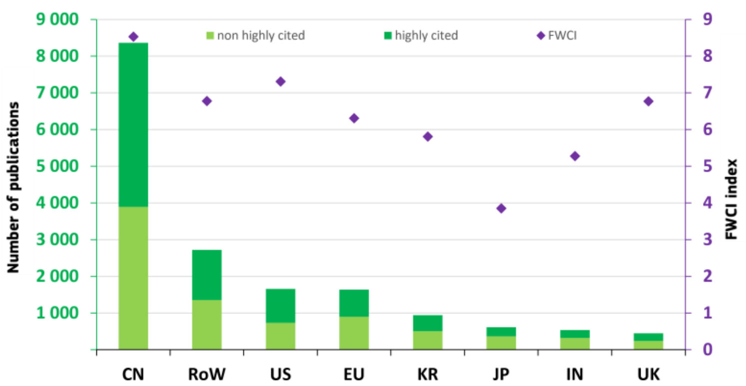
Figure 27. Na-ion batteries inter-regional (left) and intra-Europe (right) links.



Source: JRC based on TIM data

China is a global leader in publication activity including highly cited publications followed by the RoW, US, EU and Korea. The highest share of highly cited publications is observed for China and the US (see **Figure 28**). The EU is fourth in this category, after RoW. The FWCI rank gives similar order, high values of this index indicate high interest in Na-ion technology in all regions.

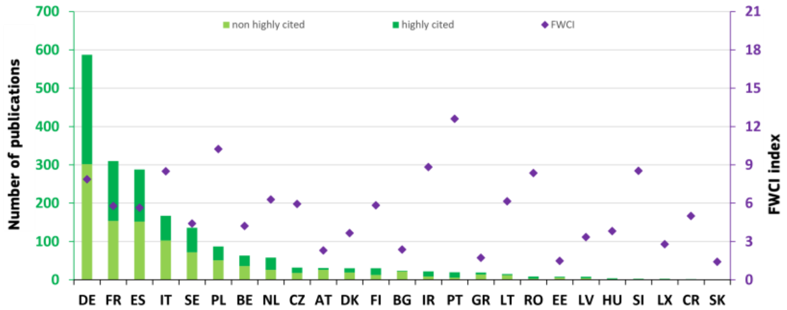
Figure 28. Number of publications and FWCI index for regions.



Source: JRC based on TIM data

In the EU, the leading MS is Germany, followed by France and Spain. The values of FWCI ranges between 1.5 and 13, with average around 6 (**Figure 29**). For lower ranked countries, the FWCI needs to be interpreted with caution, as due to low number of publications the influence of a single one or a few highly cited publications might distort the picture.

Figure 29. Na-ion batteries publications and FWCI index for the EU MS.

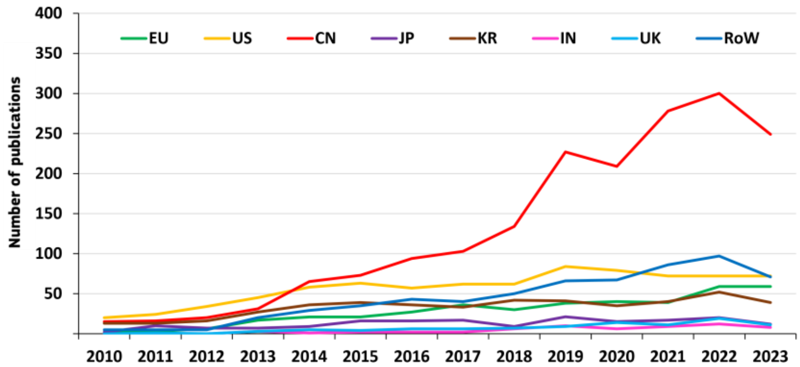


Source: JRC based on TIM data

Si-rich anode batteries

China is the current leader of publishing activity (250 publications·y^{-1}, see **Figure 30**) and is far ahead of the RoW and US (both 70 publications·y^{-1}), which in turn are in front of the EU (60 publications·y^{-1}) and Korea. In 2023 China exhibited a significant drop of publishing activity, however, this is not cancelling yet its long term increasing trend. The growth rate of the trend is faster than the RoW, while the US reached stabilisation. The EU keeps increasing at slow pace. In 2023, all countries experienced a decrease except for US and EU (both kept publishing rates equal to 2022).

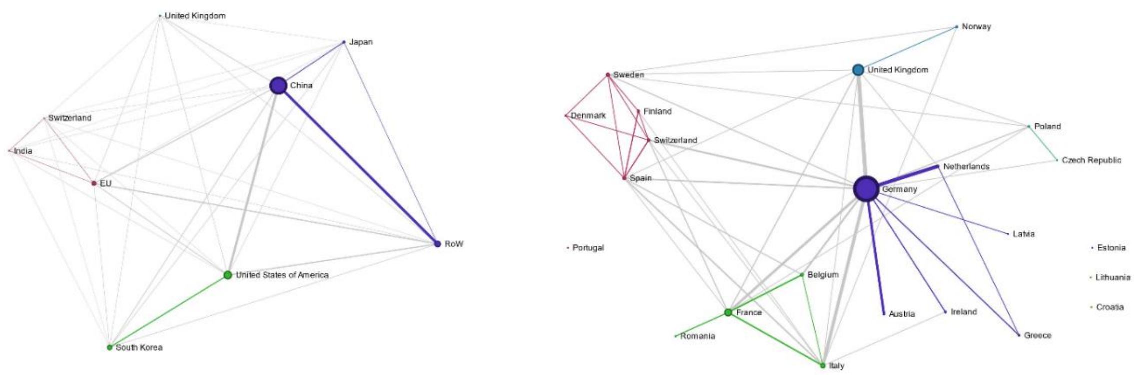
Figure 30. Si-rich technology publishing activity trends per region.



Source: JRC based on TIM data

Globally, the strongest links are observed between China and RoW, which together with Japan create a cluster. Another cluster links the EU, Switzerland and India, while US is grouped with Korea. (**Figure 31**). Among European countries, the strongest links are observed between Germany and Netherlands, which together with Austria, Greece, Ireland and Latvia developed the strongest cluster. France together with Italy, Belgium and Romania created a second cluster. Another clear cluster is formed by Spain, Switzerland, Finland, Sweden and Denmark. Except for those three clusters, the UK is grouped with Norway and Poland with Czech Republic. Portugal, Estonia, Lithuania and Croatia remain rather isolated.

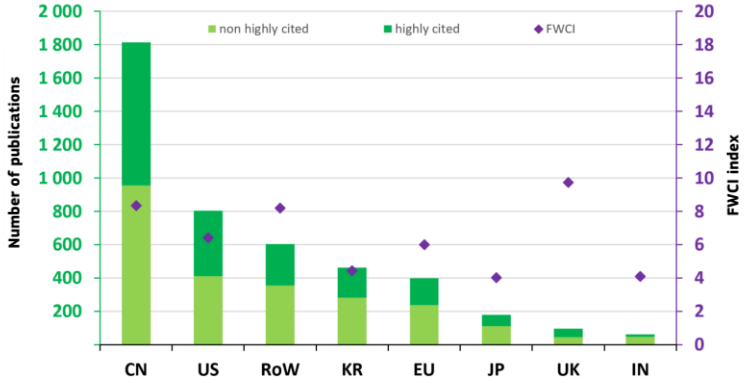
Figure 31. Si-rich anode batteries inter-regional (left) and intra-Europe (right) links.



Source: JRC based on TIM data

China is a global leader in publication activity including highly cited publications, followed by the US, RoW, Korea and the EU. The highest share of highly cited publications is observed for China, while US is second (**Figure 32**).

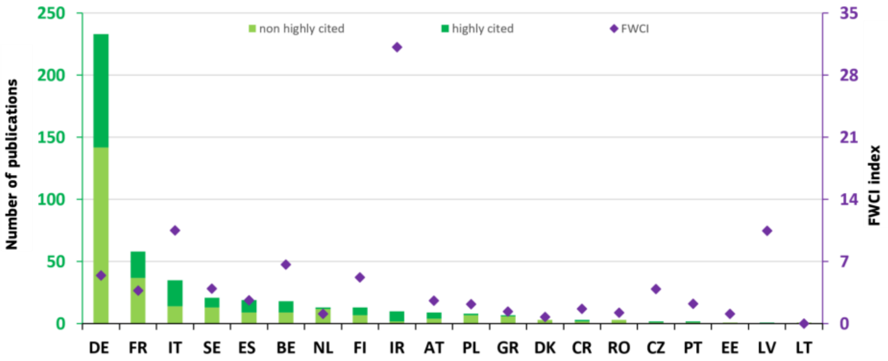
Figure 32. Si-rich anode publications and FWCI index for regions.



Source: JRC based on TIM data

The EU leader is Germany, followed by France and Italy, the highest share of highly cited publications is reported for Latvia (only one, highly cited) Ireland and Italy. (**Figure 33**).

Figure 33. Si-rich anode publications and FWCI index for the EU MS.

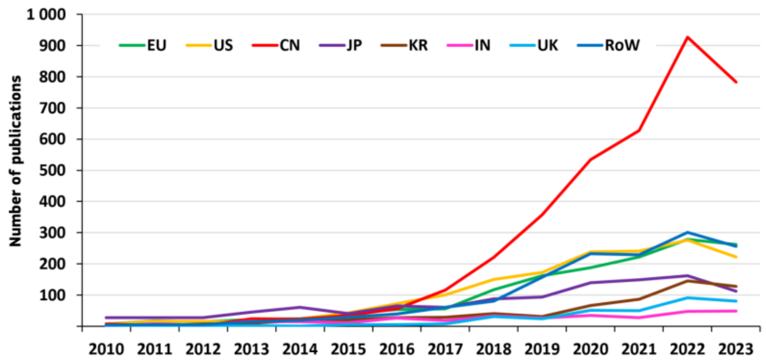


Source: JRC based on TIM data

Solid state batteries

China is a current leader of publishing activity (780 publications·y^{-1}, see **Figure 34**). Second is the EU, closely followed by RoW (both at about 270 publications·y^{-1}), and by the US (220 publications·y^{-1}). The interest of China is growing at increasing rate. In 2023, however, like for all counties except India, publication activity decreased.

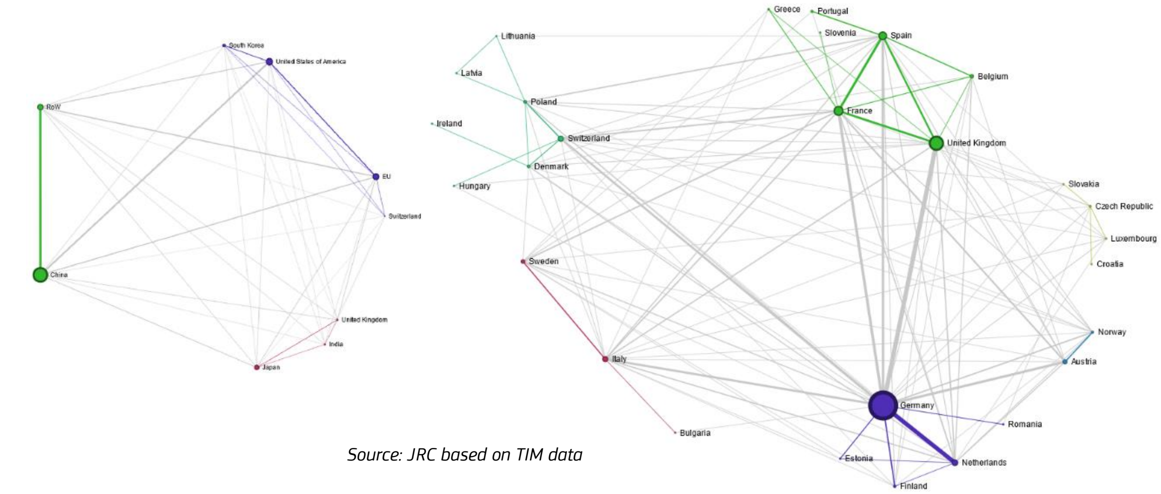
Figure 34. Solid state battery technology publishing activity trends per region.



Source: JRC based on TIM data

As shown in **Figure 35**, globally, the strongest collaboration is observed between China and RoW forming a cluster. Another cluster links the EU, US, Korea and Switzerland, while a third one connects Japan, India and UK. Among European countries, the strongest links are observed between France, Spain and the UK, which together with Belgium, Greece, Slovenia and Portugal constitute the best developed European cluster. Germany is strongly linked with Netherlands and together with Finland, Estonia and Romania creates a second one. Switzerland, Poland, Denmark, Lithuania, Latvia, Hungary and Ireland form a third cluster. Czech Republic, Slovakia, Luxembourg and Croatia; Italy, Sweden and Bulgaria; Austria and Norway create another three clusters.

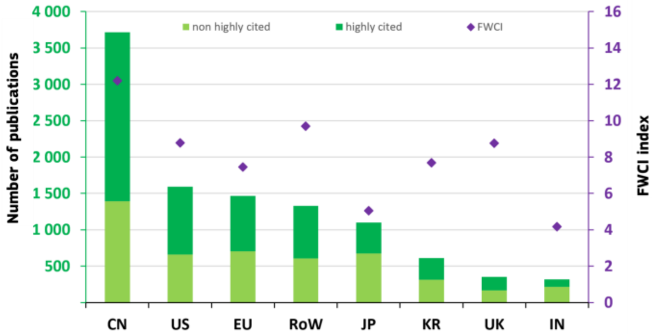
Figure 35. SSB inter-regional (left) and intra-Europe (right) links.



Source: JRC based on TIM data

Global leader in publication activity including highly cited publications is China followed by the US, EU, RoW and Japan. The highest share of highly cited publications is noted for China, while US is the second. (**Figure 36**).

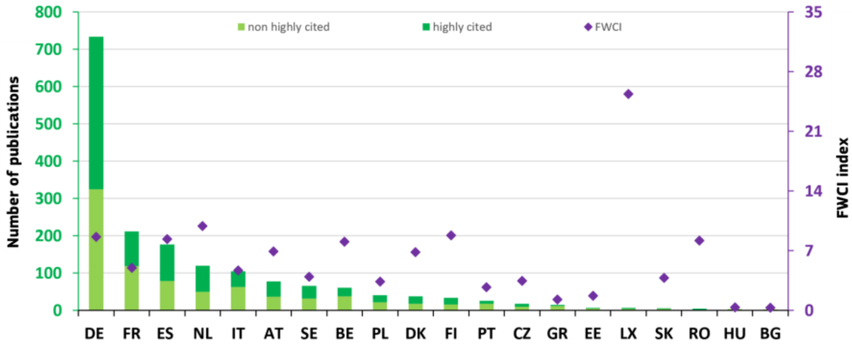
Figure 36. Solid state battery publications and FWCI index for regions.



Source: JRC based on TIM data

The EU leader is Germany, followed by France and Spain, the highest share of highly cited publications is reported for Germany, Spain and Netherlands, as presented in **Figure 37**.

Figure 37. Solid state battery publications and FWCI index for the EU MS.



Source: JRC based on TIM data

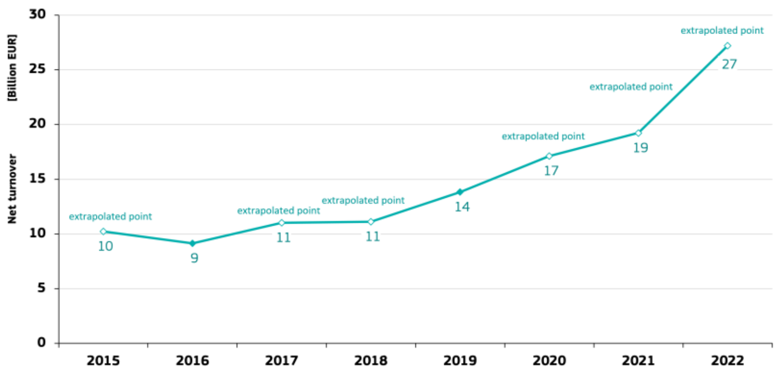
3 Value Chain Analysis

3.1 Turnover

Statistical data on turnover in the battery manufacturing sector is not readily available nor complete. Numerous countries do not disclose their statistics. Where possible, the not disclosed numbers were approximated using available data points and trends observed over longer periods. This approach may lead to substantial underestimations, especially for countries that dynamically increased their batteries production over the last years, but did not disclosed their statistical data, e.g. Poland (last available data from 2019). The analysed statistical data were reported under NACE Rev. 2 [119] category "Manufacture of batteries and accumulators" and include combined data from all battery and accumulators related activities, including non-rechargeable and re-chargeable batteries of all chemistries and assembly levels. The 2022 statistics is marked as provisional.

The net turnover in the EU battery manufacturing sector is presented in **Figure 38**. It remained stable or slightly increasing (CAGR little below 3%) until 2018, the years 2019-21 brought a dynamic growth with CAGR of 20%, however the fastest growth was observed in 2022, +41%. Overall, between 2015 and 2022 the net turnover has almost tripled, and CAGR reached 15%. This trend is expected to continue. The values for 2020-22 period might be underestimated, as statistics for Poland was extrapolated with a conservative approach, assuming continuation of trends observed in preceding period. As Poland's battery production strongly increased, especially after 2018 (opening of LG Chem plant), a net turnover from that effort might exceed the linear trend applied in extrapolation and thus be underestimated in evaluation based on data until 2019.

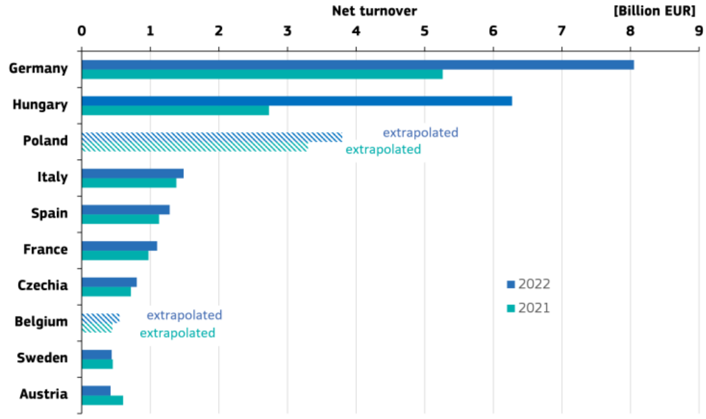
Figure 38. Turnover trends in the EU battery manufacturing sector.



Source: JRC based on Eurostat data

The EU MS with highest turnover in the battery manufacturing sector in 2022 (**Figure 39**) are DE, HU and PL. An especially high increase of turnover is observed in HU, where SK Innovation and Samsung are already operating their recently opened production plants.

Figure 39. Top 10 EU MS with highest turnover in the battery manufacturing sector (PL and BE data are extrapolated since 2020 and 2021 respectively).



Source: JRC based on Eurostat data

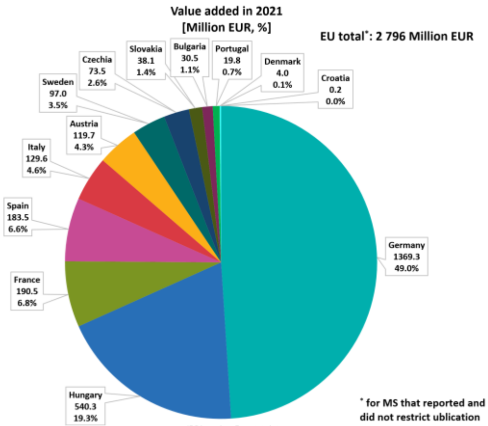
Additionally, BYD (packs assembly), CATL, EVE Power, Samsung, SK Innovation and Sunwoda are at different stages of their new production facilities' development. The net turnover is also increasing very fast in DE, which in a few years is expected to host most of European battery production. Poland has not disclose its statistics since 2020. The missing data was extrapolated from data until 2019 and thus might not properly capture recent developments.

3.2 Gross value added

Statistical data for gross value added is available for 2021 only and only 15 MS provided their statistics non-restricted for publishing. Thus, the presented evaluation does not show the full picture of the battery sector in the EU. Additionally, the analysed statistical data were reported under NACE Rev. 2 category "Manufacture of batteries and accumulators" and include combined data from all battery and accumulators related production activities, including non-rechargeable and rechargeable batteries of all chemistries and assembly levels.

The value added in the battery manufacturing sector is presented in **Figure 40**. Almost 50% of the EU added value was reported from Germany, another 20% came from Hungary. Poland, another big player in the EU battery sector did not disclose its statistics.

Figure 40. Value added in manufacturing of batteries and accumulators sector.



Source: JRC based on Eurostat data

3.3 Environmental and socio-economic sustainability

The production and wide introduction of more sustainable batteries in the EU is a part of the EU Green Deal. It will contribute to decarbonisation of the EU and enhance the independence of the EU from third Countries. [120] The Battery Regulation and the Critical Raw Materials Act (CRMA) [128] implement a reduction of environmental and social impacts through a number of measures, e.g. adoption of a carbon footprint declaration; ethical sourcing of raw materials; collection and recycling targets; recycled content for targeted raw materials; design allowing for removability and replaceability of batteries; promotion of circular strategies other than recycling (repurposing, remanufacturing, reuse), etc. JRC is supporting the implementation of several of the measures mentioned above. [121], [122], [123] The Battery Regulation underlines the need of involving economic operators along the whole value-chain "to ensure the transition to a circular economy and the long-term competitiveness of the Union".

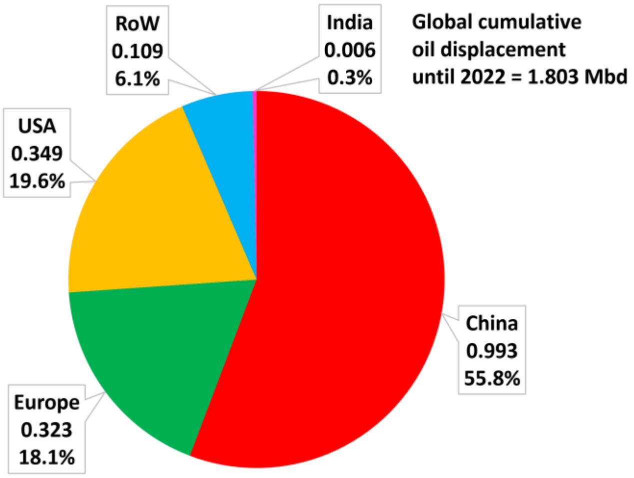
Although there are already several studies addressing sustainability (environmental, economic and social) impacts on batteries, depending on their chemistries and applications (for details see **Annex 2** – the analysis is based on the Sustainability Assessment Framework [124]), further R&D&I efforts are still needed due to the rapid technological development. Several projects are ongoing to reach the above-mentioned objectives, e.g. the IPCEIs. In this context, an added value can be provided through exploitation of already existing/new digital skills and the development of circular business models.

While Annex 2 is focussed on assessment of the batteries' environmental performance except for the use phase, the use phase of batteries is the main source of environmental benefits that can be achieved. Below we present evaluation of the direct emissions that were avoided on roads due to use of batteries in vehicles. This reduction of CO_2 emission on the roads is reached at cost of increased emission due to electricity production for charging the vehicles, however: 1) those emissions are (and will be) decreasing with increased share of renewable energy in the charging grids, 2) evaluation of this part of energy systems exceeds the scope of the current report.

According to IEA data, the use of batteries in vehicles allowed for global cumulative savings of 1.8 Mbd (or 658 million of barrels) of oil equivalent in 2010-22 (before 2010 effect of EVs was negligible, the last data is from 2022). The contribution of regions to this amount is shown in **Figure 41**. 658 million of barrels of oil equivalent of fuels that has not been consumed in vehicles is equivalent to 280 million tonnes of CO_2 that globally was not emitted to the atmosphere. The % share of avoided CO_2 emissions is the same as % of oil displacement in **Figure 41**. For Europe it means 118 million of barrels of oil equivalent than were not imported and 50 Mt of CO_2 that was not emitted. Evolution of the oil displacement trends in the global regions since 2010 is presented in **Figure 42**.

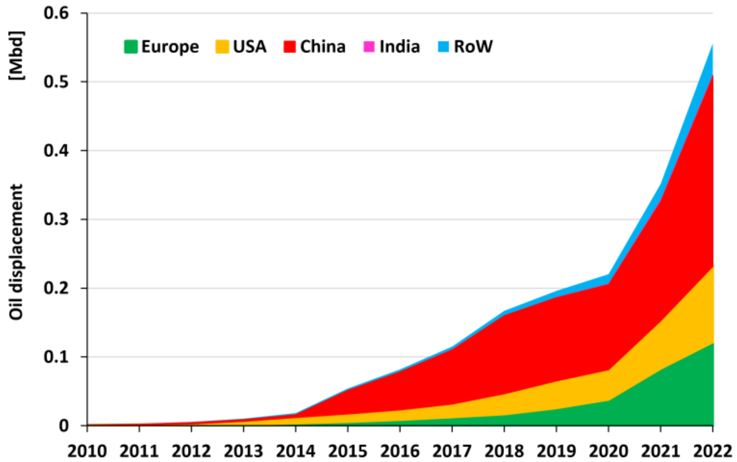
The 2022 data show that in one year only, the global oil displacement reached 207 million of barrels of oil equivalent, equivalent to 88 million tonnes of CO_2 that was not emitted. The distribution of this savings between regions is presented in **Figure 43**.

Figure 41. Share of regions in global cumulative oil displacement in the 2010-22 period.



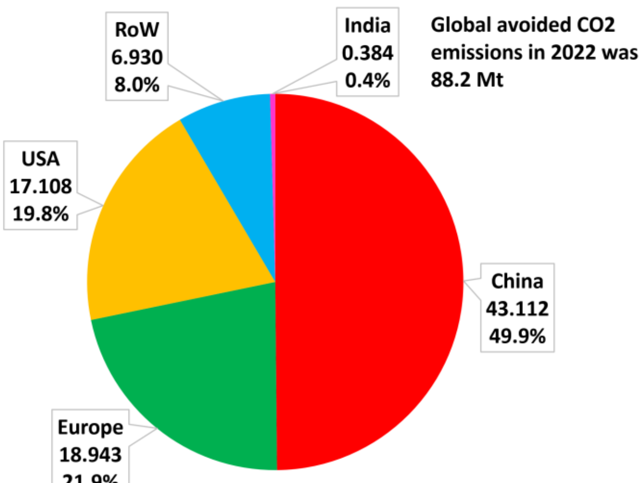
Source: JRC based on IEA data

Figure 42. Oil displacement trends in regions in 2010-22 period.



Source: JRC based on IEA data

Figure 43. Share of regions in global CO_2 emissions reduction in 2022.



Source: JRC based on IEA data

Both, STEPS and APS models, foresee about 1.6 Mbd of displaced oil in 2025 (three-fold increase compared to 2022) and about 4.6-4.9 Mbd of displaced oil in 2030 (nine-to-ten-fold increase compared to 2022).

IRENA provides similar, but slightly lower data: global EV demand for electricity was 106 TWh in 2021 (last available data), and is projected to reach 315 -330 TWh in 2025, 900 - 1 000 TWh in 2030 and 3 200 - 4 600 TWh in 2040. [125] This amount of electricity is equivalent to slightly more than 9 million ton of petrol that was not consumed in 2021 or 28 million ton of CO_2 that was not emitted to the atmosphere.

3.4 Role of EU Companies

The list of global and EU leaders in assessed technologies, SSB and Na-ion batteries, is presented in **Table 10**. The EU headquartered companies are marked with green, US – with yellow, China – with red; RoW – with blue.

The largest company developing and commercializing SSBs is Toyota (Japan), there is however a number of smaller companies, mainly representing the US. The EU is represented through joint ventures only, Blue Solutions (France and Canada) and Factorial (US, Germany and Japan).

The global leader in development and commercialisation of Na-ion batteries is China. The large Chinese companies, China Three Gorges Corporation, CATL and BYD are at front of the run and are followed by about 30 other Chinese players. The EU is represented by Tiamat (planning production together with Neogy from 2025) and Altris (production planned with Northvolt) only, which places it far behind China. It is expected that China will keep its dominating position in the future, and will be followed by RoW (India, UK).

Table 10. Global leaders in solid state and Na-ion battery chemistries.

Company	Technology	Notes		2030 expected prod. capacity [GWh/y]
SolidPower	sulfide SSE	cooperate with Ford, BMW and Hyundai		
QuantumScape	Li-SSB (ceramic)	cooperate with VW, Porsche and Mercedes		
BlueSolutions	Li-SSB (polymer)	cooperate with Mercedes, Bolloré		
Ionic Materials	SSB (polymer)	cooperate with Hyundai, Renault, Nissan and Mitsubishi		
Factorial	Li-quasi-SSB (FEST)	cooperate with Hyundai, Stellantis and Mercedes		
Toyota	Li-SSB	commercial production expected from 2027-28		
Welion	semi-SSB Li-LFP	plan by 2030, first semi-SSBs in the market		
SES AI	Li-SSB	cooperate with Hyundai, Kia, Geely and SAIC		
CATL	Na-ion (LO, PBA)	GWh-scale production planned for 2023		10
Faradion (Reliance)	Na-ion (LO)	2-3 GWh/y Gigafactory planned in India by 2024		10
Tiamat	Na-ion (PA)	production at 1.2 GWh/y started in 2023		6
HiNa	Na-ion (LO)	production at 1 GWh/y started in 2022		5
Zoolnasm	Na-ion (Na-S)	Production facility under construction		5
Natron Energy	Na-ion (PBA)	production at 0.6 GWh/y started in 2024		0.6
AMTE	Na-ion	Building a plant in Scotland (UK)		0.5
BYD	Na-ion	Might launch Na-ion EV in 2023		
Altris	Na-ion (PBA)	Northvolt will produce cells		
graphical legend:	EU	US	China	RoW

Source: JRC based on Wood Mackenzie [126], IDTechEx [107] and other open data in the Internet.

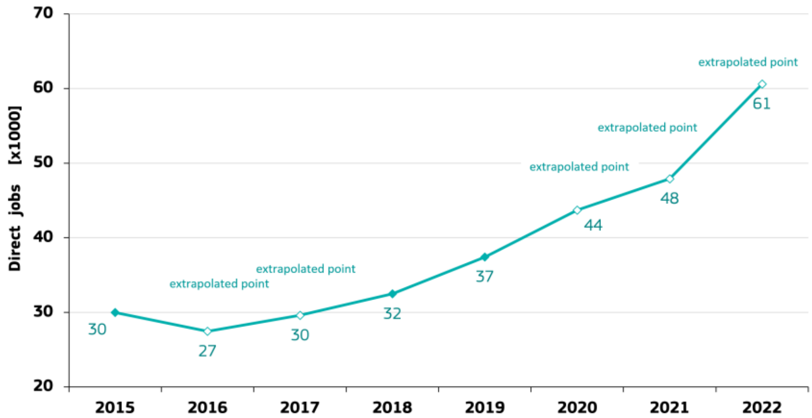
The role of the EU based companies in the value chain of mainstream Li-ion batteries was described in the previous editions of CETO report and did not change strongly since that time.

3.5 Employment

Statistical data on employment in the battery sector is not readily available nor complete. Numerous countries do not disclose their statistics. Where possible, unavailable data were approximated using available data points and trends observed over longer periods. This approach may lead to substantial underestimations, especially for countries that dynamically increased their batteries production in the last years, but did not disclose their statistical data, e.g. Poland (last available data from 2019). The analysed statistical data were reported under NACE Rev. 2 category "Manufacture of batteries and accumulators" and include combined data from all battery and accumulators related activities, including non-rechargeable and re-chargeable batteries of all chemistries and assembly levels. The 2022 statistics is marked as provisional.

The number of direct jobs in the EU battery manufacturing sector is growing at increasing pace (see **Figure 44**) since 2016 and is coherent with an increase of batteries production in the EU. Between 2015 and 2022, employment has doubled and a CAGR reached 11%. This trend is expected to continue. The values for 2020-22 period might be underestimated, as statistics for Poland was extrapolated with a conservative approach, assuming linear continuation of trends observed in the preceding period. As Poland strongly increased battery production, especially after 2018 (opening of LG Chem plant), job creation resulting from that effort might be underestimated through linear extrapolation of data until 2019.

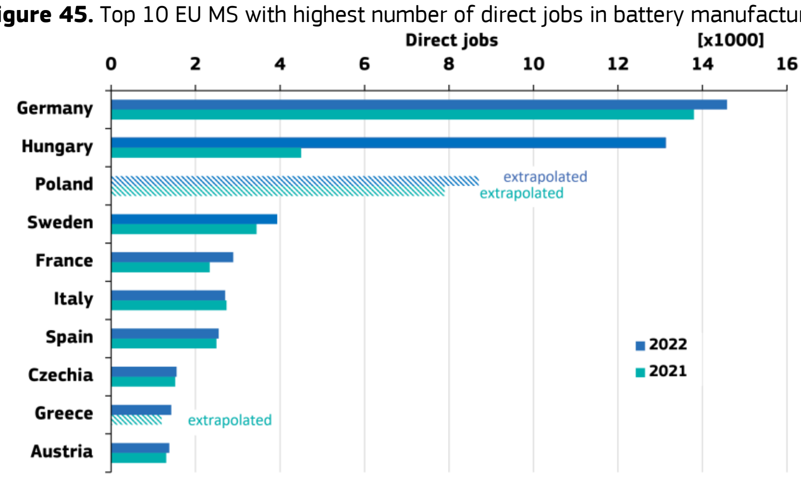
Figure 44. Number of direct jobs in EU battery manufacturing.



Source: JRC based on Eurostat data

The EU MS with the highest number of direct jobs in battery manufacturing in 2022 (see **Figure 45**) are DE, HU and PL. An especially high dynamics of jobs creation is observed in HU, where SK Innovation and Samsung are already operating their recently opened production plants, while BYD (packs assembly), CATL, EVE Power, Samsung, SK Innovation and Sunwoda are at different stages of their new production facilities' development. The number of jobs is also increasing fast in DE, which in a few years is expected to host most of European battery production. Poland has not reported job statistics since 2020. The missing data was extrapolated from the data trends until 2019 and thus might not properly capture recent developments.

Figure 45. Top 10 EU MS with highest number of direct jobs in battery manufacturing.



Source: JRC based on Eurostat data

. The JRC estimates that the EU battery manufacturing sector hosted 90 000 direct jobs, and about 300 000 – 400 000 indirect jobs in 2023. If the development plans of battery manufacturing value chain in the EU are met, in 2030 this might be about 300 000 of direct and about 1.5 million of indirect jobs.

3.6 Energy intensity and labour productivity

No statistical data is available for the assessment of the energy intensity of battery production. The statistical data for labour productivity is available for 2021 only and only 13 MS provided their statistics non-restricted for publishing. Thus, the presented evaluation does not show full picture of the battery sector in the EU. Additionally, the analysed statistical data were reported under NACE Rev. 2 category "Manufacture of batteries and accumulators" and include combined data from all battery and accumulators related production activities, including non-rechargeable and rechargeable batteries of all chemistries and assembly levels. The apparent labour productivity in the battery manufacturing sector is presented in **Figure 46**. This parameter is highest in Slovakia, which do not host large battery production facilities. The second highest productivity was reported for Hungary and the third highest for Germany. Poland, a large EU battery producer did not disclose its statistics.

Figure 46. Apparent labour productivity in the EU battery manufacturing sector in 2021.

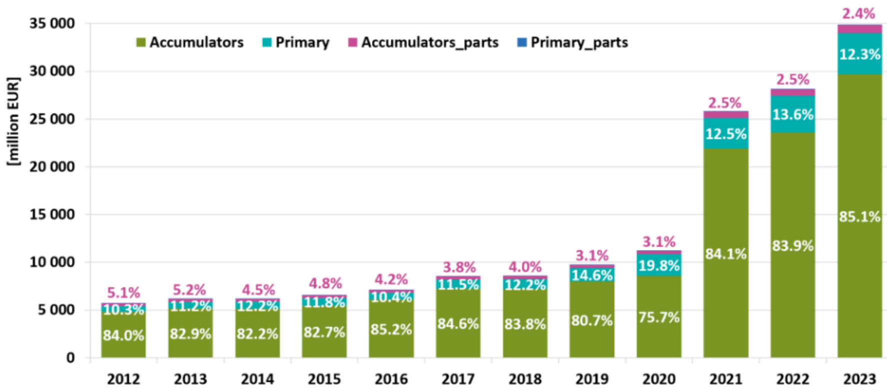
Source: JRC based on Eurostat data

3.7 EU Production Data

JRC analysis is based on PRODCOM [127] data.[14] Some countries keep their production data confidential. Such production, however, is still included in the "EU total" numbers. That's why the sum of countries' production is lower than the EU total. It should be also pointed out 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 2023, the total value of batteries produced in the EU approached 35 billion EUR. The majority of produced batteries (85%) are secondary batteries (accumulators), while primary batteries accounted for 12% of the total production value. The battery production is increasing (see **Figure 47.** *Total value of batteries produced in the EU.*) in the long term, with a CAGR 9% in 2012-2020 period and about 45% in last 3 years. The share of accumulators' parts in long term is slightly decreasing, while it has been stable over the last three years.

Figure 47. Total value of batteries produced in the EU.



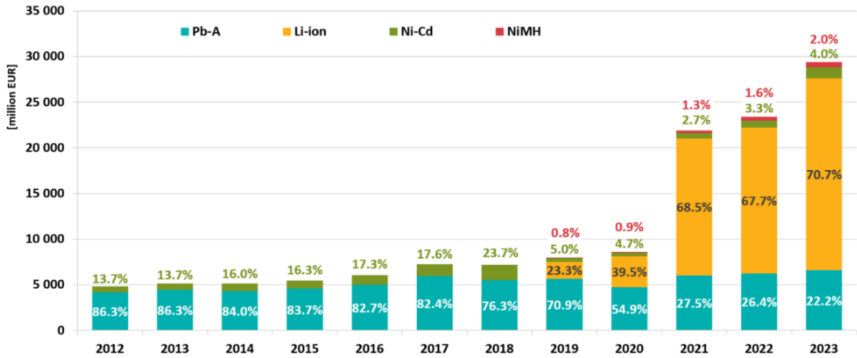
Source: JRC based on PRODCOM data

[14] Codes: 27201100, 27202100, 27202200, 27202300 and 27202400 were discontinued as of 2019 and split into: 27201110, 27201115, 27201120, 27201125, 27201130, 27201140, 27201150, 27201155, 27201160, 27201170, 27201175, 27201190, 27202110, 27202120, 27202230, 27202240, 27202310, 27202320, 27202340, 27202350, 27202396, 27202410 and 27202420.

Production data on Li-ion batteries is available since 2019 (earlier Li-ion batteries were reported together with Ni-Cd and other non-Pb-A batteries under the same code, see **Figure 48**) and since that time is subjected to dynamic growth with CAGR of 83%. This growth however slowed down to a CAGR of 19% in the last two years.

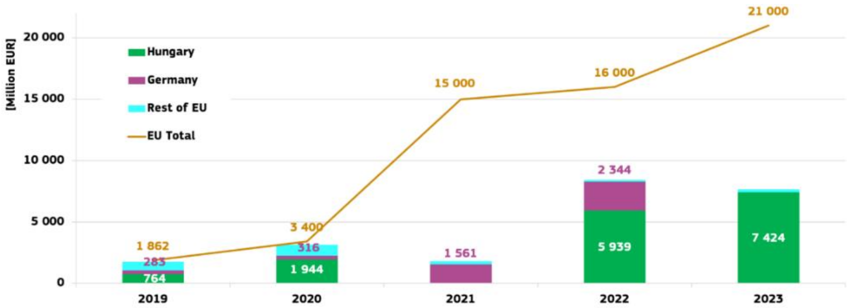
The analysis of Li-ion batteries production trends is very difficult, also due to non-complete data. Production of Li-ion batteries is not disclosed to public domain by some MS. The available data is presented in **Figure 49**. The "Total EU" is the overall production of all MS, including production by MS that didn't disclose MS specific data. The difference between the bars and "Total EU" is the production of MS that restricted their statistics, mainly PL (included in rest of EU in 2019-20), HU (not disclosing data for 2021) and DE (not disclosing data for 2023).

Figure 48. Trends in the EU production of accumulators.



Source: JRC based on PRODCOM data

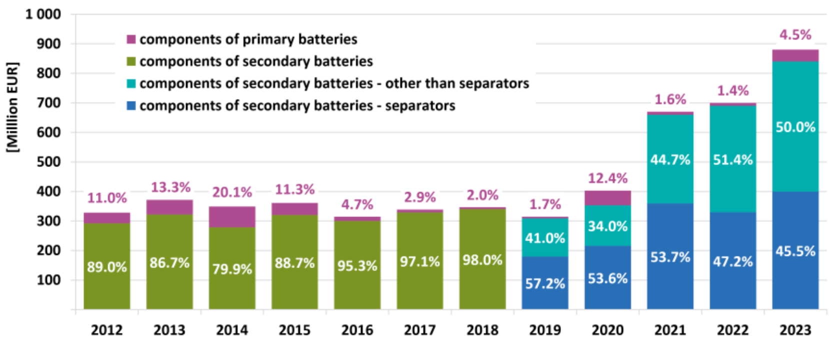
Figure 49. The EU production of Li-ion batteries[15].



Source: JRC based on PRODCOM data

The production of battery parts and components is dominated by production of accumulator parts (95-99% in last three years). It remained stable at about 300-350 million EUR in the period 2012-2019. In 2020, it started dynamic growth to reach almost 900 million EUR in 2023. Since 2019, separate information on production of separator and of all other components is available. Since 2021, the production of separators increased from about 200 to 350 million EUR and remained stable at this level until 2023. Production of all other components is growing since 2020, from about 150 million EUR to 450 million EUR in 2023. For details, see **Figure 50**.

Figure 50. The EU production of battery parts.



Source: JRC based on PRODCOM data

15 27202350 code only (Li-ion)

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

Policy considerations

It has been globally recognized that batteries are a key enabling technology and therefore policies for developing batteries and battery value chains have been set in all key legislations.

In 2017, the European Commission launched the European Battery Alliance to set a sustainable and competitive battery value chain in Europe. It was supported by the Strategic Action Plan on Batteries and approval of 6.1 billion EUR of public support under two IPCEIs.

In 2023, the Battery Regulation entered into force, aiming to minimise the environmental impact of batteries. By leveraging the EU's internal market, this goal will extend beyond the EU and will promote the production of sustainable high-quality batteries world-wide. The access to the EU market will e.g. require achieving minimum performance and durability targets, safety requirements for stationary batteries, minimum recycled content in new batteries, appropriate collection and recycling of end-of-life batteries and sharing of selected information through a new battery passport. The Battery Regulation also aims at better functioning markets for secondary raw materials and related industrial processes in order to reduce the EU's dependence on imports of materials of strategic importance.

Despite these achievements in legislation, the global playing field is unbalanced, which has a negative impact on competitiveness of the EU companies.

In 2022, the US adopted several policy measures to support domestic cell and EV production under the Inflation Reduction Act (IRA). [128] It has profound impact heavily subsidizing production in the US, providing at least 369 billion USD to the US clean energy sector. It should result in at least 80 billion USD of new investments in production facilities across the whole battery supply chain. The effect of IRA has been a clear shift of investments in cell production facilities to the US. [129]

China has strongly supported 'New Energy Vehicles' (NEV, in practice EVs), with subsidies, while at the same time introducing non-financial motivation, such as purchase restrictions for internal combustion engine powered cars in big cities, priority access, discounted or free parking for NEVs, etc.

In response, the EU started new initiatives in 2023 to rebalance competitiveness. The Temporary Crisis and Transition Framework (TCTF) [130] facilitated state aid for batteries manufacturing, matching state aid offered to non-EU locations. The Critical Raw Materials Act (CRMA) [131] aims at increasing collection and recycling of waste products, increasing domestic supply of strategic raw materials. The Net Zero Industry Act (NZIA) [132] aims at scaling up the net zero technologies including batteries by a simplification of the regulatory framework and fast-track permitting.

Cost considerations

Considering these policy measures, values chains and electricity cost being significantly higher in Europe, an average BEV produced in the EU might become 4 000 USD more expensive than a BEV produced in China or US (it should be kept in mind the technology difference, in China LFP batteries are widely accepted in vehicles while Europe focuses on better performing, but more costly NMC chemistry). Price of an average BEV produced in the US would be comparable to that made in China.

Similar trends are observed for battery packs: currently the average EV battery pack in the EU costs 20% more than in China and 8% more than in the US. This difference, however, has been decreasing over last years. It is expected that IRA could bring down the cost of battery packs in the US to the level of Chinese packs, while in the EU price could even slightly rise due to an increase of energy costs.

The actual cost of setting up a plant producing battery cells is about 106 million EUR per 1 GWh/y of production capacity in the EU. In the US the same production capacity costs about 100 million EUR, while in China it is slightly more than 55 million EUR. [133]

Market development: SSB

In some niche applications SSBs have already found their commercial markets, e.g. small cells of about 1-100 mAh are used in earbuds and other small electronics, although simple re-scaling of those cells to create an EV size battery would result in an unacceptable price. For these reasons applications that require large batteries still wait for appearance of the solid state technology. However, Nio, a Chinese car manufacturer started in June 2024 a program of commercial renting of 150 kWh packs based on WeLion semi-solid-state technology in their swap stations. [74]

Solid Power (US) is the developing a sulfide SSE for SSBs. In 2024 the company aim to increase production of electrolyte. They cooperate with Ford, BMW and Hyundai as customers for their batteries, and formed a partnership with SK Innovation for manufacturing of automotive-scale cells [63].

Quantum Scape (US) is developing a Li-metal SSB with a patented solid ceramic electrolyte. They work on the cell research, prototyping, demo and further they plan commercialisation. [62].

Blue Solutions (FR, CA) is focused on a lithium polymer based solid state battery. They already operate a production facility 1.5 GWh with more than 400 employees. With support from Bolloré they expect to increase production to 2 GWh in 2024. [64]

Ionic materials (US) specialises on polymers, and their electrolyte is already in testing phase by automotive companies (Hyundai, Renault and Mitsubishi). An EV prototype with this technology is expected in 2024 [65]. The latest news from June 2024 is that the company has closed its activity. [66]

Factorial (US, DE, JP) develop a proprietary FEST battery technology. They currently test their batteries (B samples) in demo projects for Mercedes Benz, Hyundai, Stellantis and KIA. In Oct 2023 the company opened their production line of 200 MWh/y in the Boston area. The company plan commercial production of their batteries with a partner, LG Chem. [72], [134]

Toyota (JP) TRL still do R&D of their battery technology and confirmed in Jan 2024 launching of an EV capable of 1 200 km range and a 10 min fast charge by 2027-2028. [67], [68] [69]

WeLion (CN) TRL a producer of Li-ion batteries plan to shift to a semi-solid state battery with metallic Li anode and LFP cathode by 2030. [73]

SES (US, CN, KR) develop Li-metal SSBs of different sizes. They claim starting production by the end of 2024. Prototypes are already tested by Hyundai and SAAIC in China, the US and South Korea. [75]

Gotion (CN) is also developing a SSB. The company plan to begin small scale production of their battery in 2027 and a mass production in 2030. [70]

Sunwoda (CN) another developed of SSB plans to start production of their batteries in 2026 at expected production capacity of 1 GWh/y. [70]

Market development: Na-ion

The technology of Na-ion batteries is being commercialized now and the process advances fast. It however should be stated that reduction of cost of Li-ion battery materials followed by decrease of market price of Li-ion batteries reduced pressure on development of alternative chemistries, including Na-ion. Globally, there are about 30 Na-ion battery manufacturing plants at different development stage, and the first one with production capacity of 1 GWh/y is in operation since Dec 2022. This plant is located in China, owned by China Three Gorges Corporation. [16] It produce Na-ion batteries in HiNa technology.

The global production capacity of Na-ion batteries was reported at 42 GWh/y in 2023, out of which 99.4% was focused in China. It is expected that in the following years this domination of China will only slightly decrease reaching 96.3% out of 186 GWh in 2030. Similar situation is observed for Na-ion anode and cathode active materials. [106], [135] Benchmark Minerals Intelligence has tracked in Mar 2024 a 335.4 GWh of Na-ion cell production capacity out to 2030 comparing to 150 GWh tracked in May 2023. [136]

The global demand for Na-ion batteries was estimated at 4 GWh in 2024, and is expected to reach above 120 GWh in 2034 (CAGR 40%). [107]

In China, the first serially produced EVs powered by Na-ion batteries were delivered to the customers bringing the technology readiness level to 9: in Jan 2024 Yiwei (new EV brand from JAC Group) equipped with 23.2 kWh battery using HiNa 32140 cells of 12 Ah capacity and 140 Wh/kg energy density which allow for 230 km range (CLTC) and at a price below 9 000 USD [137]; in Dec 2023 (roll out of the production line) a JMEV EV3 (Youth Edition) with range of 251 km and using 140-160 Wh/kg cells from Farasis [138].

The largest until now, Na-ion BESS entered into commercial operation phase as of begin of July 2024. This is a 50 MW / 100 MWh project in Qianjiang, Hubei province in China. [139]

[16] The China Three Gorges Corporation company is listed at the United States Department of Defence list of companies with links to the People's Liberation Army operating directly or indirectly in the United States, and thus subjected to the US sanctions. *DOD Releases List of Additional Companies, in Accordance with Section 1237 of FY19 NDAA*, U.S. Department of Defence. August 28, 2020. Archived from the original on 30 August 2020. Retrieved 30 August 2020.

CATL declared in late 2023 that it has started mass production of Na-ion cells and developed a basic industry chain supporting it. Production scale will depend on customer's demand. Chery would be the first user of CATL Na-ion batteries. [136]

In Jan 2024 BYD has announced begin of construction of a 30 GWh/y Na-ion battery factory for "micromobility" devices. [136]

In Nov 2023, Northvolt presented a 160 Wh/kg Na-ion battery developed with Altris. Now the company is finalizing battery prototypes for next-generation energy storage device and after that, they will develop a production line. In Apr 2024, the company opened its first factory for producing Na-ion batteries at its plant in Skellefteå and has plans to expand internationally. [140]

Tiamat plans a 5 GWh/y plant in Hauts-de-France region. It will initially produce Na-ion cells for power tools and stationary storage applications. The "first orders have already been received." Its second-generation batteries will target battery electric vehicle applications. [136]

Reliance Industries, owner of Faradion, is now transferring its next-generation ~190 Wh/kg cell design to production. Reliance will build "a double-digit-gigawatt factory in India", shortly after their Na-ion battery technology will enter into production phase at a megawatt level by 2025. [136]

In Jan 2024, Acculon Energy (US) announced begin of production of its Na-ion batteries for mobility and stationary applications followed by scaling its production up to 2 GWh/y by mid-2024. Natron Energy installed a factory to produce 600 MWh/y of Na-ion batteries at Clarios Meadowbrook facility. It started commercial operation at April 2024. [141]

Market development: Li-ion

The global top 10 Li-ion batteries producers ranked according to their actual production in 2023 [142] are presented in **Table 11**.

Table 11. Global top 10 battery manufacturers (actual cell production).

	company	production in 2023 [GWh]	Share in global production [%]	rank change 2023 (rank change 2022)
1.	CATL (CN)	242.7	34.1 (34.8)	0 (0)
2.	BYD (CN)	115.9	16.3 (11.8)	0 (+1)
3.	LG Energy Solution (KR)	108.5	15.3 (14.4)	0 (0)
4.	Panasonic (JP)	56.6	8.0 (9.6)	0 (-1)
5.	SK (KR)	40.7	5.7 (6.5)	0 (+1)
6.	Samsung SDI (KR)	35.7	5.0 (4.9)	0 (-1)
7.	CALB (CN)	23.5	3.3 (4.1)	0 (0)
8.	Farasis	16.5	2.3 (-)	new (-)
9.	Envision AESC	8.3	1.2 (-)	new (-)
10.	Sunwoda (CN)	7.0	1.0 (1.5)	-1 (0)
	Others	56.0	7.9 (-)	
	total	711.4	100.0 (-)	

Source: JRC based on Visual Capitalist data

4.2 Trade and trade balance

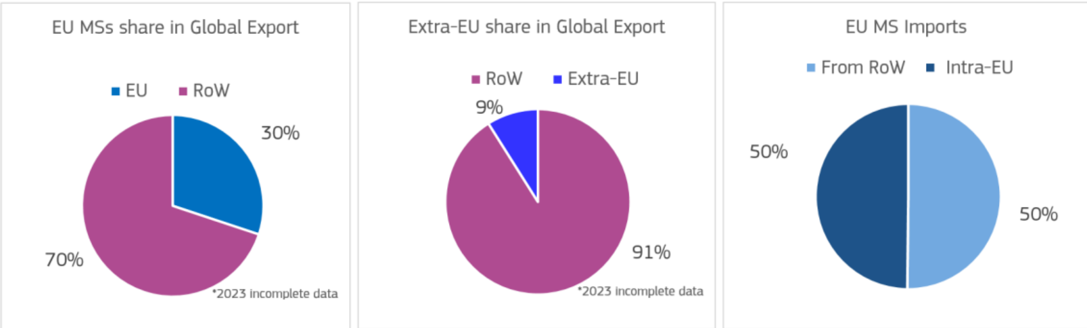
JRC analysis is based on COMEXT and COMTRADE code: 850760[17]; export figures include also re-export. The trade statistics is usually presented for period of 2 or 3 years, to reduce short term variability and enhance trends. The last available data is from 2023, and is marked in databases as "incomplete", thus possibly subjected to further changes.

The global export of batteries is estimated at 260 billion EUR in the 2021-23 period. The EU export to non-EU countries reached almost 17.9 billion EUR, while the intra-EU exports of EU MSs summed up to 60.3 billion EUR in that period. The summary share of EU MSs in global exports reached 30%. On the other hand, the share of

[17] Lithium-ion accumulators (excl. spent)

EU (as a whole entity) in global exports (in this case the intra-EU exports are not included to the global exports) was 9.0% in 2021-23 (-0.2 pp compared to 2020-22). The total EU MSs exports including the EU internal exports, were at level of 78 billion EUR, which corresponds to 30.1% of the global export. The EU member states sourced half of their battery imports from non-EU countries, while another half was imported EU internally. The EU export and import shares in global export and import of batteries are presented in **Figure 51**.

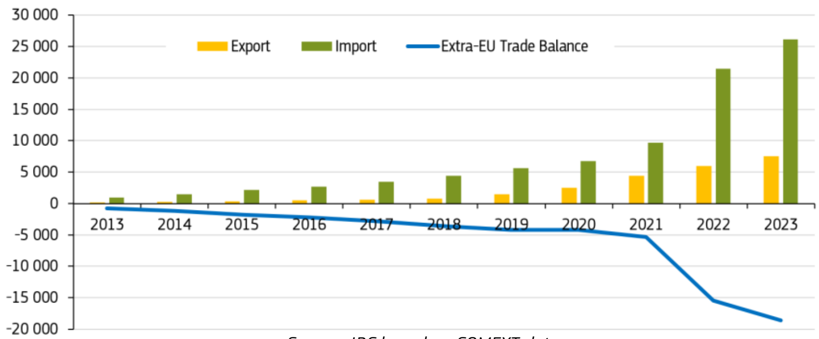
Figure 51. Share of total EU MSs and EU-external export in the global battery exports, source of the EU imports.



Source: JRC based on COMTRADE and COMEXT data

The evolution of the EU-external exports, imports and trade balance in the period 2013-23 is presented in **Figure 52**. In 2023, the EU export and import rose at similar rate, by 25% and 22% respectively. The negative trade balance reached a new record of -18.6 billion EUR, 26% more than in 2022.

Figure 52. The EU battery exports, imports and trade balance [million EUR] in 2023



Source: JRC based on COMEXT data

During 2020-22[18] the fastest growing markets[19] - with increasing growth rates - were the US, South Korea, Mexico, India and Hong Kong. Growing markets that exhibit decreased growth rates relative to 2019-21 were: Vietnam, UK, Japan and Brazil. Hong Kong and South Africa appeared new on the list of growing markets, while China and Russia lost positions on the list due to the negative growth in the last reporting period. The EU is most important provider of batteries for Mexico (53% of Mexico imports come from the EU, +13 pp in respect to previous period), Switzerland (40%, -4 pp), UK (35%, -2 pp), Turkey (25, +22 pp) and China (16%, +4 pp); for details see **Table 12**.

Table 12. Growing markets based on a 2-year (2020-22) average of net import change, in parentheses values from previous (2019-21) period.

Country	2-year average of net import change [Million EUR]	Total import (2020-21) [Million EUR]	% import from the EU [%]
United States	4 493 (208)	24 401 (14 494)	10 (9)
South Korea	1 989 (1 738)	9 676 (5 384)	2 (3)
Mexico	917 (638)	4 788 (2 690)	53 (40)
Vietnam	869 (1 472)	8 793 (6 603)	4 (4)
India	756 (166)	4 768 (3 489)	1 (1)
United Kingdom	643 (1 203)	3 886 (2 457)	35 (37)

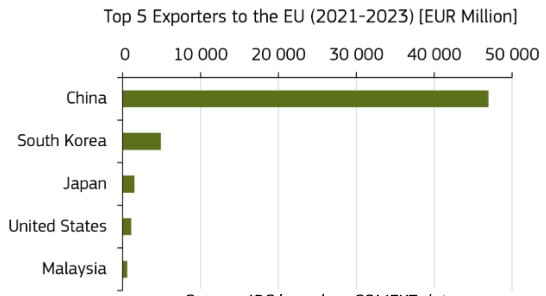
[18] Last complete data available for 2022; for 2023 comtrade does not provide estimates for the missing values as comext does.
[19] Calculated as $net\ import\ change = [(import_{2021} - import_{2020}) + (import_{2022} - import_{2021})]/2$

Japan	502 (1 707)	4 775 (3 872)	1 (1)
Hong Kong	377 (new)	10 155 (new)	2 (new)
Australia	362 (168)	1 959 (1 285)	4 (4)
Other Asian	321 (390)	2 011 (1 373)	3 (3)
South Africa	285 (new)	1 044 (new)	2 (new)
Canada	208 (281)	1 594 (1 083)	9 (7)
Turkey	179 (125)	1 161 (478)	25 (3)
Switzerland	106 (86)	833 (590)	40 (44)
Brazil	103 (258)	1 288 (1 065)	1 (1)
Singapore	97 (135)	829 (597)	10 (17)
Indonesia	83 (77)	958 (789)	0
Thailand	81 (40)	941 (640)	6 (8)
Philippines	11 (80)	688 (504)	1 (1)
China	out of list (3 458)	9 182 (9 677)	16 (12)
Russia	out of list (43)	n/a (438)	n/a (6)

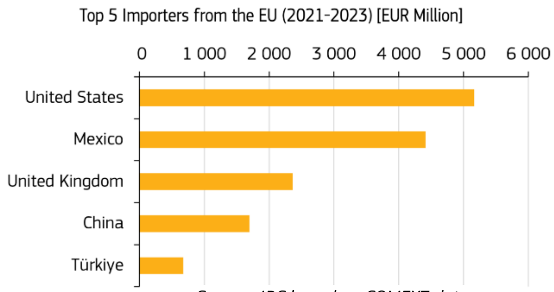
Source: JRC based on COMTRADE data

The top 5 EU partners in battery import and export are shown in **Figure 53**. China remains the main source of batteries import to the EU and strengthened its position covering 81.9% of the EU import needs in 2021-23 (up from 72% in 2020-22). If only one year is taken into account, the share of China in extra-EU imports grew from 82% in 2022 to 86% in 2023. Imports from China thus clearly exceed the 65% limit set by NZIA. [132], [143] South Korea was ranked second in import, being responsible for 8.5%, while the third Japan covered 2.6%. Together, the top three countries covered 93.1% of the EU import needs. The main destinations of batteries exported from the EU were US (35.8%), Mexico (30.6%) and UK (16.4%). On the 5th position Turkey replaced Switzerland.

Figure 53. Top 5 battery exporters to the EU (left), and importers from the EU (right) in 2021-23.



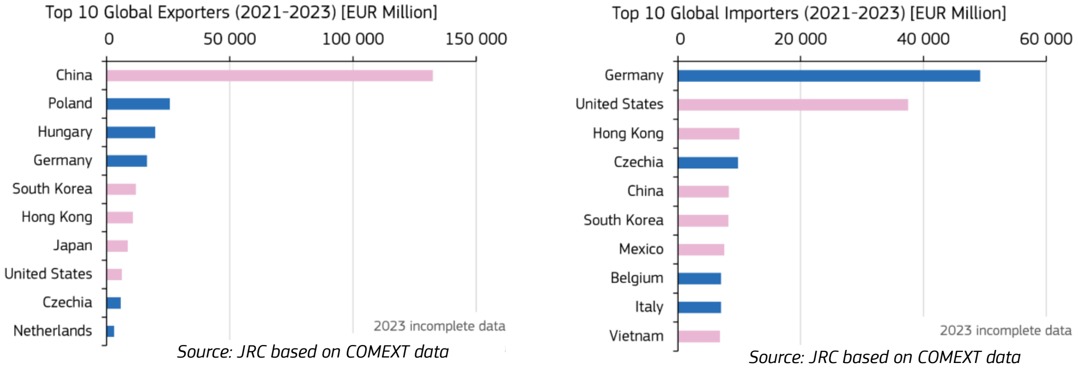
Source: JRC based on COMEXT data



Source: JRC based on COMEXT data

The global top 10 countries in battery exports and imports are presented in **Figure 54**. In global top 10 of battery exporters, China occupies first position, far in front of Poland, Hungary (+1 position), Germany (-1) and South Korea (+1). Germany is the largest importer, followed by the US, Hong Kong, Czech Republic (+1) and China (-1). Vietnam lowered its position to 10 (-4) South Korea (position 6), Belgium (8) and Italy (9) appeared on the top 10 importers list, while Japan (8 in previous period), India (9) and Spain (10) went off.

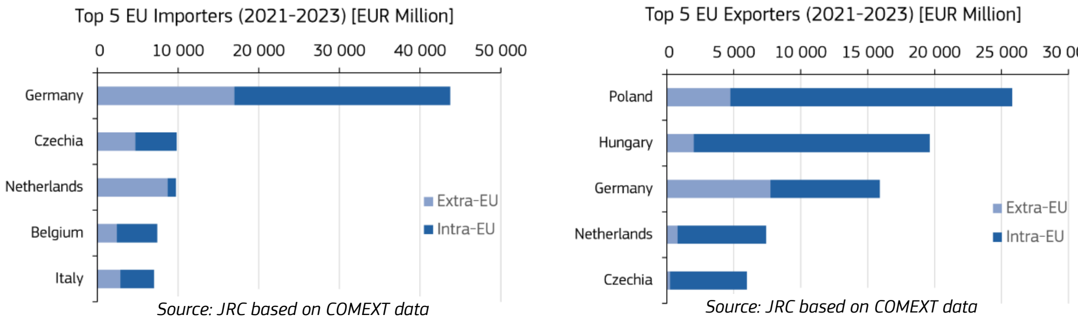
Figure 54. Global top 10 battery exporters (left) and importers (right) in 2021-23



Source: JRC based on COMEXT data *Source: JRC based on COMEXT data*

The top 5 EU importers and exporters – including intra-EU trade – are shown in **Figure 55**. Germany is by far largest importer satisfying about 60% of their needs from intra-EU sources and is followed by Czech Republic (which replaced Netherlands on second position) and Netherlands that source their batteries almost entirely from the EU sources. Germany, Czech Republic and Netherlands brought 86%, 58% and 87% of their extra-EU imports, respectively, from China. Poland, Hungary (which replaced Germany) and Germany were the top EU exporters, and only Poland and Hungary reached a positive trade balance among EU MS.

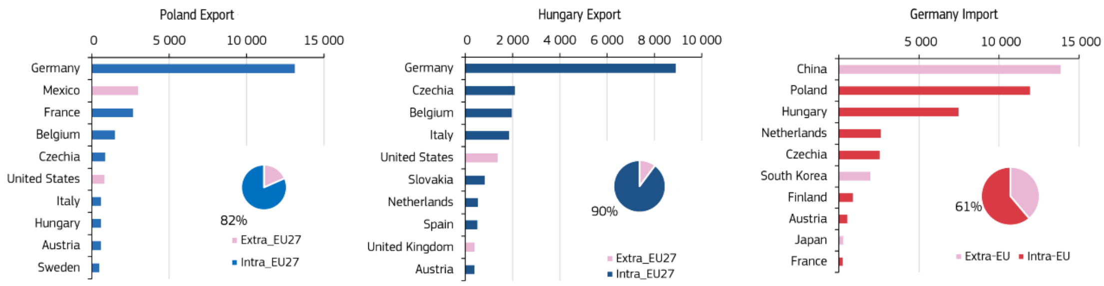
Figure 55. Top 5 EU MS in battery imports (left) and exports (right) in 2021-23 in million EUR



Source: JRC based on COMEXT data *Source: JRC based on COMEXT data*

Main directions of export from Poland and Hungary, as well as main sources of import to Germany are presented in **Figure 56**. 82% (-1 pp) of Polish battery export was directed to the EU member states, the main directions were: Germany, Mexico, France, Belgium, Czech Republic (new in top 10), US (+3), Italy (+1), Hungary (-1), Austria (-4) and Sweden (-4). Turkey lost its position in the Top 10. Hungary placed 90% of it's exports in the internal EU market, the main destinations were: Germany, Czech Republic, Belgium, Italy, US, Slovakia, Netherlands, Spain (+1) UK (+1) and Austria (-2). Germany covers 61% of their needs from the EU internal market (+2 pp) and imports mainly from China (+1), Poland (-1), Hungary (no position change, but fast growth), Netherlands (+1), Czech Republic (+1), South Korea (-2), Finland (-1), Austria (-1), Japan and France.

Figure 56. Top 10 destinations of PL (left) and HU (middle) exports as well as top 10 sources of DE imports (right) in 2021-23 in million EUR



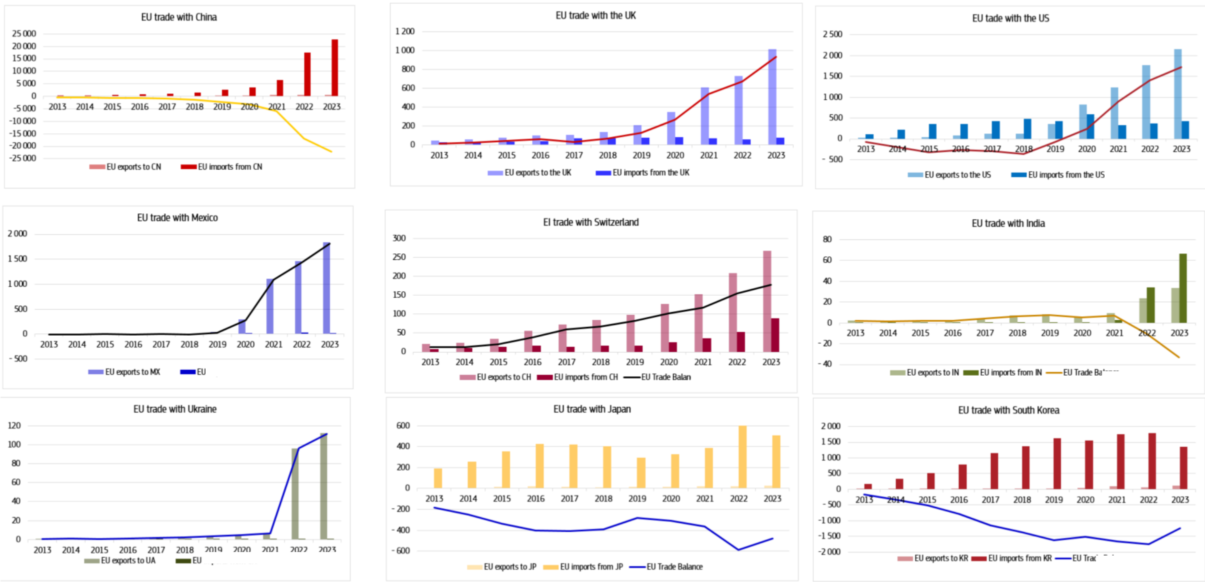
Source: JRC based on COMEXT data

Analysing the trends of the EU trade with its selected partners (see **Figure 57**), it should be noted that:

- EU imports from China increased very fast in last three years and were not compensated by exports, which caused a large and incresing negative trade balance.
- Since 2019, the EU strongly increased its exports to Mexico and UK, after earlier periods characterized by no-trade (MX) or slightly positive balance (UK).

- Since 2019, the EU strongly increased exports to the US reversing an earlier negative trade balance.
- EU is steadily increasing export to Switzerland, although at still rather limited level.
- Imports from South Korea and Japan at long term increase at limited pace with almost no export to those countries, generating a significant (KR) or limited (JP) trade deficit. In 2023, however, imports from both countries has decreased.
- In 2022, export to Ukraine jumped, remaining however at low level. In 2023 the increase was limited.
- In 2022, export to India rose fast, more than doubling within one year. However, import in the same period multiplied, reversing the earlier observed positive trade balance. In 2023, the dynamics of those trends has decreased, the trends however remain still valid. The trade with India remains low.

Figure 57. Time trends in EU trade with selected non-EU partners in 2012-22



Source: JRC based on COMEXT data

EU imports also a vast majority of raw materials and components required for battery production. Development of local supply chains around existing production centres in the EU is already observed, however this advances at limited pace. The EU imports also most of cell manufacturing equipment.

4.3 Resource efficiency and dependence in relation to EU competitiveness

The NZIA requires that by 2030 the EU internal annual production capacity of batteries is able to cover at least 40% of the EU's demand, including all main components like e.g. cathode and anode active materials or separators. The CRMA sets further requirements, such as 10% of local extraction, 40% of local processing and 45% of local recycling of materials from the critical raw materials list by 2030. In 2023, an updated list of CRMs was published by the Commission, including the following battery related raw materials: lithium, cobalt, manganese, nickel, copper, natural graphite, phosphorus, silicon, titanium and vanadium. [131]

EU remains strong in the application field, holding about 25% of global EV production. However, the competition from Chinese companies is very strong and the fastest growing EV producers are Chinese.

The NZIA limit set on EU internal battery cell production capacity (560 GWh/y in 2030) should be easily met if all announced production projects are successfully executed. The progress of development of those projects should, however, be carefully monitored, as not all announced projects have entered the realisation phase yet, and some seem suspended. [144] The production capacity for battery cells in Europe at the end of 2023 was estimated to 175 GWh/y. [145]

Industrial projects for production of cathode active materials sum up to 690 kt of production capacity in 2030, not much below 820 kt required by NZIA, however all projects focus on nickel-based chemistries, while LFP cathode is not covered by production at all. [144] The production capacity of cathode materials in Europe at the end of 2023 was estimated equivalent to 40 GWh/y of cells production. [145]

The projects for anode active materials production (mainly natural and artificial graphite) foresee 360 kt production capacity in 2030, more than 340 kt required by NZIA. [144]

The current separator production capacity is 340 million m^2 and will expand[20] to 1.54 billion m^2 by 2030 only in the SK IE factories in Poland. [146] This is equivalent to about 150 GWh of Li-ion batteries. Together with other already announced projects [147], [148], the chance to reach the 560 GWh/y limit set in NZIA for 2030 is high. The production capacity of separators in Europe at the end of 2023 was estimated equivalent to 120 GWh/y of cells production. [145]

There are several electrolyte producers in the EU and the NZIA limit of production capacity set to equivalent of 560 GWh/y of cells production in 2030 should be easily reached. The production capacity of electrolytes in Europe at the end of 2023 was estimated equivalent to 230 GWh/y of cells production. [145]

The EU depends heavily on third countries for battery raw materials, processed materials and also battery production equipment. This topic was broadly presented in the 2022 edition of CETO. [7]

Recycling EoL batteries available in the EU is one of the possible ways to reduce EU's dependence on the supply of battery raw materials. Details on recycling processes is available in the CETO 2023 report. [1]

The battery recycling capacity in the EU was about 200 kt (500 kt in China, 200 kt in the US) at the end of 2023, and is expected to grow to about 400 kt in 2030. On the other hand, there were about 80 kt (400 kt globally) of battery material available for recycling in 2023, and the expected amount for 2030 is about 300[21] kt (1 400 kt globally). [149], [133] The battery recycling capacity of the EU already is, and will remain in timeframe of 2030 above the 45% limit set by CRMA. However, most of commercial recyclers in the EU offer only mechanical or pyrometallurgical recycling, which do not produce battery-grade secondary raw materials. The black mass recovered in the EU recycling plants (which is containing most valuable metals) usually is sold to recyclers in the Asia-Pacific region for a hydrometallurgical process to obtain battery-grade secondary materials. Only few recyclers in Europe expand their capacities to cover hydrometallurgical processes (e.g. Fortum, Harjavalta, FI).

There is some potential to cover part of EU demand for lithium from highly mineralized water extracted in geothermal systems. Potential of this source is estimated to cover even 25% of EU demand for lithium in 2030. [150] The challenge, however, is that each system has its unique chemical characteristics rendering standardisation of the extraction methods difficult and increasing investors' risks.

Development and deployment of batteries free of CRMs would significantly reduce dependence of the EU from third country suppliers. The examples here would be a Na-ion (PBA chemistry) or redox-flow (non-vanadium) batteries that are very well suited for stationary energy storage. Similarly, a low-CRM Li-ion (LFP chemistry) would help to reach the same goal.

Development of smart functions of energy grids and consumer systems allowing to flexibly manage grid loads may reduce needs for energy storage systems, reducing required investments and relieve pressure on batteries production. [125]

[20] 340 million m^2 plant in operation, 340 million m^2 plant at test run, 2 x 430 million m^2 plants under construction
[21] JRC internal estimation

5 Conclusions

Na-ion batteries are being commercialised and their production is scaling up quickly. The technology is at the critical point, where first generations of the commercially produced Na-ion batteries are being tested in their first large scale application areas. A positive feedback from those applications will cause very fast scale up and wide deployment, while less positive results could limit its application to specific niche markets. Chinese companies are most active in Na-ion batteries production and testing in field conditions. The position of the EU is rather weak, with only two companies aiming to start production of Na-ion batteries.

With specific energy comparable to LFP, similar or better electrical performance, increased safety and lower price, Na-ion batteries are very likely to enter the lower end of the EV market, especially for urban mobility EVs, micro-mobility and light means of transport, just like LFP chemistry has already done. Furthermore, in the stationary energy storage market Na-ion batteries will most likely play a significant role as well, due to potentially lower investment cost and durability.

Na-ion batteries are exposed to geopolitical risks to a very limited extent, and could significantly contribute to decreasing dependency of the EU from third countries, both, in the area of battery raw materials, and energy carriers (indirectly, by enhancing in-house generation and consumption of renewable energy and stabilising the energy grids). Na-ion technology does not require CRMs and generally uses less costly materials.

Analysis of the Na-ion technology indicators leads to the conclusion that the EU is not putting enough effort to remain in the race for Na-ion batteries and there is a very high risk that China will dominate this technology.

Solid state batteries are being prepared for commercialisation in EV applications and technology of their production is developed for scaling up and meeting requirements of the automotive sector. The technology is already commercialized in the field of small electronic equipment, where high costs of production per kWh are less critical due to small size of the batteries. The cost of SSBs is expected to significantly decrease in timeframe of 10 years, approaching todays average cost of Li-ion batteries. The technology is also safer than traditional Li-ion chemistries due to lack of volatile organic solvents, and allows for fast charging.

The technology is considered as highly relevant for automotive industry, and especially the segment of high-end / performance cars, thus the EU players are actively participating in it's the development. The global competition for this technology is in full run.

Solid state batteries are exposed to similar geopolitical risks as traditional Li-ion chemistries.

The **Li-ion batteries** market and especially the EV market advances in the EU at a decreased pace, while China significantly strengthened its position.

The most demand comes from the mobility segment. The stock of EVs in the total EU fleet is increasing, but it was still slightly below 3% in 2023, thus the major effect on conventional fuels consumption is still to be observed in next years. The Chinese EV producers experience fastest growth in the global scale, and expand internationally due to the internal market limits. Buses are the most electrified sector of transport with the share of EVs in the fleet exceeding 3%. Electric trucks are still in the infancy period. The stationary energy storage market is developing quickly, and the leading regions are the US, China and the EU.

The average cost of batteries decreased by 14% from 2022 to 2023, resuming the decreasing trend, which is expected to continue. In the long term the costs of stationary systems and truck batteries will converge and remain about doubled, compared to EV batteries.

The EU is quickly developing its battery production capacities, however the international environment remains challenging, highly competitive and focused on price reduction. The EU experienced a very high and increasing deficit in battery trade, despite increasing internal production. The EU still depends heavily on third countries for raw battery materials and battery production equipment.

Li-ion batteries are exposed to different levels of geopolitical risks, depending on exact chemical formulation; ranging from medium for LFP to high for NCA or NMC. The raw materials are costly and prone to price volatility.

Analysis of the Na-ion technology indicators shows that only the high performance Li-ion batteries, closely related to the automotive sector are in focus of the EU industry. The new production capacity extension is on track to cover the EU needs in 2030. However, the LFP chemistry, an enabling technology for higher utilisation of renewable energy, which also is less CRM-intensive is not in focus of the EU industry, and China keeps a dominating position in production of LFP batteries.

Development of energy markets and grids supporting flexibility of demand, dynamic pricing and sectors coupling could significantly release pressure on physical installation of electricity storage and associates costs. All initiatives resulting in electricity price decrease will improve competitiveness of EU battery producers.

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List of abbreviations and definitions

18650	one of standard formats of cylindrical batteries; 18 mm diameter, 65 mm length
21700	one of standard formats of cylindrical batteries; 21 mm diameter, 70 mm length
4680	one of standard formats of cylindrical batteries; 46 mm diameter, 80 mm length
AABC	Advanced Automotive Battery Conference
ACEA	European Automobile Manufacturers' Association
Ah	amphour, unit of battery capacity, battery has 1 Ah capacity if fully charged can provide current of 1 A over time of 1 h, before is fully discharged
APS	Announced Pledges Scenario of IEA
ASSB	all solid state battery, synonym to solid state battery
AU	Australia
BE	Belgium
BESS	battery energy stationary storage
BEV	battery electric vehicle
BMW	Bayerische Motoren Werke AG
BNEF	Bloomberg New Energy Finance
BTM	behind the meter, batteries installed at end user, on the "behind energy meter" side
BYD	Build Your Dreams, BYD Company Limited
C	C-rate; reciprocal of time (in hours) over which the battery was (dis)charged; charge at 1C means full charge over 1 h, discharge at 0.1C means full discharge over 10 h.
CA	Canada
CATL	Contemporary Amperex Technology Co. Limited
CAGR	compound annual growth rate
CETO	Clean Energy Technology Observatory
CHJ	company name
CN	China
COMEXT	statistical database on trade of goods managed by Eurostat
COMTRADE	United Nations Commodity Trade Statistics Database
CRM	Critical Raw Material
CRMA	Critical Raw Materials Act
CZ	Czech Republic
DE	Germany
DK	Denmark
EAFO	European Alternative Fuel Observatory
EASE	The European Association for Storage of Energy
EC	European Commission
EFTA	European Free Trade Association
EMMES	European Market Monitor on Energy Storage
ENER	The Directorate General for Energy, a Directorate General of the European Commission
EoL	end of life
ES	Spain
EVE	company name
EU	European Union
FI	Finland
FR	France
FWCI	Field Weighted Citation Impact
GR	Greece

GROW	The Directorate General for Internal Market, Industry, Entrepreneurship and SMEs, a Directorate General of the European Commission
GWh	gigawatthour; energy unit = $3.6 \cdot 10^{12}$ J
ha	hectare, land area unit
HEV	hybrid electric vehicle
HU	Hungary
HK	Hong Kong
ICE	internal combustion engine
IEA	International Energy Agency
IN	India
IPCEI	Important Project of Common European Interest
IRA	Inflation Reduction Act
IS	Israel
IT	Italy
JP	Japan
JRC	Joint Research Centre
kWh	kilowatt hour, energy unit = $3.6 \cdot 10^{6}$ J
KR	South Korea
L	litre, volume unit = 1 dm^3
LCA	Life Cycle Assessment analysis
LCO	lithium cobalt oxide, battery chemistry
LFP	lithium iron phosphate, battery chemistry
Li-ion	lithium ion, family of battery chemistries
Li-SSB	solid state battery with metallic lithium anode
LMFP	lithium manganese iron phosphate, battery chemistry
LMP	lithium manganese phosphate, battery chemistry
LO	layered oxide
LTM	layered transition metal oxides, a family of compounds described with general formula Na_xTMO_2, TM = transition metal(s), e.g. $Na_{0.75}Ni_{0.82}Co_{0.12}Mn_{0.06}O_2$
M&A	Merger & Acquisitions
mAh	milliamphour, 1 mAh = $1 \cdot 10^{-3}$ Ah
MS	Member State, country belonging to the European Union
MW	megawatt, unit of power = 10^6 W
MWh	megawatt hour, energy unit = $3.6 \cdot 10^{9}$ J
NA	not available
Na-ion	sodium-ion, family of battery chemistries
Na-S	sodium-sulfur, chemistry of batteries
NCA	nickel cobalt aluminium oxide
NEV	New Energy Vehicles
Ni-Cd	nickel-cadmium, chemistry of batteries
NL	Netherlands
NMC	nickel manganese cobalt oxide, family of Li-ion battery chemistries
NZIA	Net Zero Industry Act
OCV	open circuit voltage
OECD	Organisation for Economic Cooperation and Development
PA	polyanion compounds, family of compounds based on transition metals surrounded by $(XO_4)_n$ X = Si, S, P, W, As, Mo) tetrahedrons, e.g. $NaFePO_4$

PATSTAT	Worldwide Patent Statistical Database
Pb-A	lead acid, battery chemistry
PBA	Prussian blue analogues, group of compounds based on iron hexacyanide, e.g. $Na_2Mn[Fe(CN)_6]$
PEO	polyethylene oxide
PHEV	plug-in hybrid electric vehicle
PL	Poland
POLES-JRC	a global energy model covering the entire energy balance, from energy demand to primary supply
pp.	percentage point
PRODCOM	PRODuction COMmunautaire, provides statistics on the production of manufactured goods
PV	photovoltaic
PVDF	Polyvinylidene fluoride, non-reactive thermoplastic fluoropolymer
RD&I	Research, Development and Innovation
RES	renewable energy storage
RFB	redox flow battery
RoW	rest of the world
RTD	The Directorate General for Research and Innovation, a Directorate General of the European Commission
RTE	round trip efficiency – ratio of energy drought from battery during full discharge to energy needed to fully charge it prior discharge
SE	Sweden
semi-SSB	batteries utilizing either gel electrolyte or both, solid state and liquid electrolyte in one cell
SET	The European Strategic Energy Technology Plan
SETIS	SET Plan information system
SEI	solid electrolyte interphase, a layer on the surface of electrode material created upon its reaction with electrolyte
SI	specialisation index
SK	Slovakia
SLI	starter-light-ignition, standard 12 V (24 V) battery in a car
SoA	state-of-art, best available product/technology in a class
SSB	solid state batteries, batteries utilizing solid state electrolyte
SSE	solid state electrolyte
STEPS	Stated Policy Scenario of IEA
SWOT	strength-weakness-opportunity-threat analysis
TCTF	Temporary Crisis and Transition Framework
TIM	Tools for Innovation Monitoring
TM	transition metal
TRL	technology readiness level
TWh	terawatthour, energy unit = $3.6 \cdot 10^{15}$ J
UK	United Kingdom
US	United States of America
USD	US dollars, in case followed by the year, it express the value in real dollars of concerned year
UPS	uninterrupted power supply
VC	Venture Capital
VW	Volkswagen
Wh	watthour, energy unit = $3.6 \cdot 10^{3}$ J
y	year

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Annexes

Annex 1. Data Sources for the CETO Indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	IDTechEx, other reports, Internet
	Installed capacity & energy production	IEA, IDTechEx, other reports, Internet
	Technology costs	BNEF, POLES-JRC
	Public and private RD&I funding	IEA, PATSTAT (indirect)
	Patenting trends	PATSTAT
	Scientific publication trends	TIM
Value chain analysis	Turnover	EUROSTAT
	Gross Value Added	EUROSTAT
	Environmental and socio-economic sustainability	IEA, internal LCA analysis, scientific literature
	EU companies and roles	Available reports, Internet
	Employment	EUROSTAT
	Energy intensity and labour productivity	not available / EUROSTAT
	EU industrial production	PRODCOM
Global markets and the EU positioning	Global market growth and relevant short-to-medium term projections	IEA, other reports, Internet
	EU market share vs third countries share, including EU market leaders and global market leaders	IEA, other reports, Internet
	EU trade (imports, exports) and trade balance	COMEXT, COMTRADE
	Resource efficiency and dependencies (in relation EU competiveness)	Available reports, Internet

Annex 2. Sustainability Assessment Framework

The detailed explanation of Table 1 is available in the report "Proposal for a Sustainability Assessment Framework for energy technologies" [124], developed to support the Clean Energy Technology Observatory (CETO) in the sustainability assessment of energy technologies. In the sustainability assessment framework (SAF) sustainability aspects based on the Driver-Pressure-State-Impact-Response framework are captured and, in the following table, some relevant information was reported for batteries.

Note that this is not an exhaustive analysis concerning all chemistries available on the EU market, mainly due to data gaps. Also, note that any comparison between numerical values should be made carefully within the same assumptions (including but not limited to functional unit, system boundaries, methods and lifetime. Finally, the update of the Product Environmental Footprint Category Rules (PEFCR) is under consultation[22].

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
Market trend	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.	- Evolution of demand for a certain technology over time, - EU market share	- At global level, the demand of Li-ion automotive batteries has increased and most of the demand comes from China, Europe being second, followed by the US. Future demand is expected to reach 1.5 TWh in 2025 and 3.7-6 TWh in 2030 - In 2023, Europe accounts for almost 25% of the EV sales, following China (about 60%). *Source: CETO Report on batteries 2024*	Additional information can be retrieved from the report "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study". [120]
Trade and trade balance	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.	- EU share in global export - Extra EU trade balance	- The total EU exports of batteries were at level of almost 17.9 billion EUR. - The EU trade deficit reached 18.6 billion EUR, 26% more than in 2022. *Source: CETO Report on batteries 2024*	
Cost of energy	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts	For power generation technologies: Levelized Cost Of Electricity (LCOE) For storage technologies: Levelized Cost of Storage (LCOS)	An LCC analysis was developed for the Ecodesign Preparatory study. [151] The study provides the Capital Expenditure (CAPEX), the Operational Expenditure (OPEX) and the Levelized Cost Of Electricity (LCOE) for batteries used in BEV, PHEV, truck and ESS applications (residential and commercial). According to the BloombergNEF's annual	Table 40 of the Ecodesign Preparatory study [151] provides information on the methodology and the assumptions behind.

[22] https://rechargebatteries.org/media/1st-open-public-consultation-for-the-pefcr-on-batteries-now-open/

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
			battery price survey, battery prices fell from above 1 200 USD/kWh in 2010 by 89% in real terms to 132 USD/kWh in 2021, including an annual drop of 6% from 140 USD/kWh in 2022. 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 USD/kWh on a volume-weighted average basis. 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. *Source: VITO (2019)* [151]; *CETO Report on batteries 2022* [7].	
Critical Raw Materials (CRMs)	The periodical EC list of CRMs should be use as a reference to describe the potential supply chain bottlenecks.	The EC method includes various indicators concerning import reliance, governance, supply concentration, etc.	Several materials belonging to the Critical Raw Materials List for the EU 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). Among the used CRMs, cobalt and lithium are mainly used in cathodes (e.g. NMC cathodes) and natural graphite in anodes. Other CRMs are manganese, nickel, copper, phosphorus, silicon, titanium and vanadium. 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. Enhanced Circular Economy strategies, aiming at maximizing the value of materials extending the lifetime 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. *Source: CETO Report on batteries 2023* [1]	In house JRC knowledge on CRMs in strategic technologies allows for the assessment of CRMs use considering also projected future demand, also compared to the current supply (Carrara et al. 2024). A criticality assessment can also be integrated in LCA using the GeoPol Risk method. A study on Lithium-ion batteries was performed in 2021. [152] Similar assessment could be applied for comparison of different chemistries for batteries.
Technology-specific permitting requirements	No specific guidance is available in the context of sustainability assessment. Assessment can be based on current legislation, expert knowledge and literature review.		Not applicable	

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
Skills and technology development	**Skill development** concerns four categories: 1. Skills gap, the distance between the skill level in society and the skills required for the technology development and deployment; 2. Skill obsolescence, the loss of skills due to the lack of use, or the risk the skills become irrelevant; 3. Skill shortages, when there are jobs, but no qualified staff in the community; 4. Over and under skilling, when people have skills above or below the requirements. **Technology transfer and development** is the process for converting research into economic development, or for using technology, expertise or know-how for a purpose not originally intended by the developing organization. It is fundamental for the improvement of social conditions and to prevent further environmental damage related to old technology use.		"The European Battery Alliance (EBA250) Academy is developing a pan-European education ecosystem for 160 000 workers every year. Alliance for Batteries Technology, Training and Skills (ALBATTS) is working to define industry needs" *Source: CETO Report on batteries 2023* [1]	
Resilience	Resilience is the ability to reduce and withstand the magnitude and duration of disruptive events, which include the capability to anticipate, adsorb adapt to and/or rapidly recover from such an event. This aspect can be qualitatively assessed taking into account the following aspects: diversity in the market, suppliers and technologies; risk reduction; adaptive capacity (Zamagni 2019).	The quantification of resilience is still under discussion. Potential indicators include the supply chain concentration (geographic, market, technologies) and the exposure to risk (trade, natural, technical, geopolitical).	While batteries can substantially contribute to build resilient energy systems, the EU dependence for raw materials and the shortages of manufacturing equipment, construction material, and the skilled labour required are a few reasons why many battery-cell factories experience significant delays. Indeed, the EU is dependent on third countries for the supply of raw materials for the manufacture of LIBs, and the supply is highly concentrated in China. In 2020 it accounted for 60% of refined cobalt, 93% of graphite active materials (from natural and synthetic graphite), 69% of refined lithium, 79% of battery grade manganese (electrolytic and high-purity sulphate) and 63% of nickel sulphate production capacity. The most significant bottlenecks in the EU supply chain are identified for lithium and graphite, as in 2021 there was no capacity to refine lithium or graphite for batteries. *Source: Carrara et al. 2023* [120]	Additional elements for the assessment can take into account the vulnerabilities in the supply chain and consider the following technology-specific criteria (IEA 2022): - Supply chain concentration (at geographical, market and technology level) - Pace and scale of growth - Exposure to trade, natural, technical risk - Response to reduce the impact - Ability to pivot to other materials or technologies - Scale up or conversion lead time (see table 1 in Annex).
Resource efficiency and recycling	Circular economy indicators based on Battery Regulation provisions	e.g. Collection rate Minimum recycling efficiency Recycled content	The Battery Regulation (EU) 2023/1542 foresees progressive minimum collection targets for specific batteries categories, minimum recycling efficiencies for lead-acid, Li-based and other waste batteries. In addition, specific materials recovery	The adoption of more resource-efficient batteries and the increased flows of secondary materials obtained from batteries recycling has potential to maximize the

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
		Durability Removability and replaceability	levels need to be achieved for cobalt, copper, lead, lithium and nickel. *Source: Battery Regulation (EU) 2023/1542, Orefice et al. 2024,* [122] *Bobba et al. 2024.* [121]	value of materials and to keep them within the EU, hence decreasing the EU dependency from imports. In the framework of the Battery Regulation (EU) 2023/1542, new studies on the methodology to calculate the collection rate of portable and LMT batteries, as well as on revising the calculation rules of recycling efficiency and material recovery levels are planned to be published in 2024. [121], [122] 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. 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.
Energy balance	Quantitative indicators	Energy Pay Back Time (EPBT) Energy Return on Energy Invested (EROI) Energy consumption per technology	Energy (electricity mix) is used in manufacturing cells/assembly the battery pack are reported below according to the Product Environmental Footprint Category Rules (PEFCR): • 41.20 MJ/kg of CPT-Li-ion batteries • 12.90 MJ/kg of ICT-Li-ion batteries • 41.20 MJ/kg of ICT-NiMH batteries • 41.20 MJ/kg of 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 and 0.9 MJ from natural gas/kg of CPT-Li-ion batteries • 0.42 $MJ_{electricity}$/kg and 1.24 MJ from natural gas/kg of ICT-Li-ion batteries	Note that new PEFCR are available public consultation recently.

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
			• 0.41 $MJ_{electricity}$/kg and 1.23 MJ from natural gas/kg of ICT-NiMH batteries • 0.69 $MJ_{electricity}$/kg and 2.07 MJ from natural gas/kg of e-mobility Li-ion batteries *Source: CETO Report on batteries 2023* [1]	
Climate change	LCA / Product Environmental Footprint (PEF)	Global warming potential (GWP100)	Based on the PEFCR of batteries, 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) • *Source: CETO Report on batteries 2023* [1]	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
Ozone depletion	LCA / Product Environmental Footprint (PEF)	Ozone Depletion Potential (ODP)	No data are available for all chemistries currently available on the market. As an example, the ozone depletion for NMC batteries is 1.10×10^{-5} kg CFC 11-eq/kWh. [153]	The ozone depletion potential (ODP) has a global effect and leads to increased ultraviolet radiation. The depletion of the stratospheric ozone layer is associated with the emissions of CFCs, HCFCs, CH_3Br, and halons, which are converted to an equivalent value of trichlorofluoromethane (CFC-11). It depends highly on the assessed electricity grid for battery production and the production of aluminium.
Particulate matter/Respiratory inorganics	LCA / Product Environmental Footprint (PEF)	Human health effects associated with exposure to $PM_{2.5}$	As an example, the particulate matter/respiratory inorganics for LFP batteries is 5.26×10^{-5} $kgPM_{2.5eq}$/kWh. [154]	Impacts associated with exposure to $PM_{2.5}$
Ionising radiation, human health	LCA / Product Environmental Footprint (PEF)	Human exposure to ^{235}U	No data are available for all chemistries currently available on the market.	

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
			As an example, the human impacts to ^{235}U for LMO-NMC batteries is 6.89×10^{2} kBq$^{235}U_{eq}$ [155]	
Photochemical ozone formation	LCA / Product Environmental Footprint (PEF)	Tropospheric ozone concentration increase	No data are available for all chemistries currently available on the market. As an example, the photochemical ozone formation for NMC batteries is 6.41×10^{-1} kg_{NMVOC}/kWh. [153]	The photochemical ozone formation potential describes the formation of tropospheric ozone on the ground level, which is stated as the non-methane volatile organic compounds (NMVOC) emissions. In contrast to stratospheric ozone, tropospheric ozone, formed by the oxidation of hydrocarbons (inter alia NMVOC) and NO_x, due to sunlight exposure, is a greenhouse gas and air pollutant and leads to urban smog. Sources are, for example, fossil fuel combustion processes for battery manufacturing, or oil refineries.
Acidification	LCA / Product Environmental Footprint (PEF)	Accumulated Exceedance (AE)	No data are available for all chemistries currently available on the market. As an example, the Acidification for NMC batteries is 1.50 kg H^{+} Mol-eq/kWh. [153]	Acidification has regional and local impacts and is calculated from the emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrochloric acid (HCl), hydrofluoric acid (HF), or ammonium (NH_4). For the overall acidification potential (AP), H^{+} ion molecules are used as an equivalent, as acids extrude those in solutions, and therefore, indicate the number of acids.
Eutrophication, terrestrial	LCA / Product Environmental Footprint (PEF)	Accumulated Exceedance (AE)	No data are available for all chemistries currently available on the market. As an example, the eutrophication, terrestrial for LFP batteries is 1.35×10^{-3} mol N_{eq}/kWh. [154]	Eutrophication describes the accumulation of nutrients like phosphorus and nitrogen in soil or water bodies, which, on a local scale, causes increased growth of algae and leads to oxygen depletion and decreased fish stocks. Eutrophication is split into a distinction of freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), and terrestrial eutrophication potential (TETP). Eutrophication is stated in phosphorus or nitrogen equivalents. Emissions contributing to eutrophication are phosphate (PO_4),
Eutrophication, aquatic freshwater	LCA / Product Environmental Footprint (PEF)	Fraction of nutrients reaching freshwater end compartment (P)	No data are available for all chemistries currently available on the market. As an example, the eutrophication, aquatic freshwater for LMO-NMC batteries is 2.67 kg Peq/kWh. [155]	
Eutrophication, aquatic marine	LCA / Product Environmental Footprint (PEF)	Fraction of nutrients reaching marine end compartment (N)	No data are available for all chemistries currently available on the market. As an example, the eutrophication, aquatic marine for LFP batteries is 5.73×10^{-5} kg N_{eq}/kWh. [154]	

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
				nitrogen monoxide (NO), nitrogen dioxide (NO_2), nitrates (NO_3^-), and ammonia (NH_3) and can be generated, like for acidification, by coal-burning power plants delivering electricity used in the battery manufacturing.
Land use	LCA / Product Environmental Footprint (PEF)	Soil quality index[4] aggregating: biotic production, erosion resistance, mechanical filtration and groundwater replenishment	No significant impacts on land use have been identified by the supporting PEFCR. *Source: CETO Report on batteries 2023* [1]	Main concerns derives from the size of manufacturing plants and the possible increase of such an industrial sector
Water use	LCA / Product Environmental Footprint (PEF)	User deprivation potential (deprivation weighted water consumption)	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 CPT-Li-ion batteries • 11 kg/kg of ICT-Li-ion batteries • 5.5 kg/kg of ICT-NiMH batteries • 11 kg/kg of e-mobility Li-ion batteries *Source: CETO Report on batteries 2023* [1]	
Resource use, minerals and metals	LCA / Product Environmental Footprint (PEF)	Abiotic resource depletion (ADP ultimate reserves)	No data are available for all chemistries currently available on the market. As an example, the resource use, minerals and metals for LMO-NMC batteries is 7.75×10^{-2} $kgSb_{eq}$/kWh. [155]	In Life Cycle Assessment (LCA), the "ADP" method stands for "Abiotic Depletion Potential," which is used to assess the depletion of abiotic resources such as minerals and metals. The unit of measurement for the Resource use, minerals and metals impact category in LCA using the ADP method is typically "kg antimony (Sb) eq" or "kg antimony equivalent." This unit represents the amount of antimony that would have an equivalent impact on abiotic resource depletion as the sum of all the minerals and metals used or depleted throughout the life cycle of the product or process being assessed.

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
Resource use, energy carriers	LCA / Product Environmental Footprint (PEF)	Abiotic resource depletion - fossil fuels (ADP-fossil)	No data are available for all chemistries currently available on the market. As an example, the resource use, energy carriers for LMO-NMC batteries is 7.57×10^4 MJ/kWh. [155]	
Biodiversity	The assessment of biodiversity loss is an environmental aspect still under refinement in the LCA community, with several life cycle impact assessment (LCIA) methods and models being developed with different levels of operationalization. These methods address three direct drivers of biodiversity loss: land use change, climate change and environmental pollution, and water use as other driver (Crenna 2020).		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". *Source: CETO Report on batteries 2023* [1]	
Child labour	Social Life Cycle Impact Assessment (Type I)[23] . The assessment of this aspect should be performed looking at the main suppliers and countries involved in the production of raw materials, intermediate products and components used in batteries.	Percentage of working children under the legal age or 17 years old (total, male and female) – country level	Considering the raw materials used in batteries, Democratic Republic of Congo (DRC) (cobalt) Australia (lithium), South Africa (manganese) and China (nickel and natural graphite) are the main countries at stake. [156] ILO estimates for the SDG indicator "*Proportion of children engaged in economic activity (%)*" are available only for the DRC (13.4% in 2018). This value corresponds to a high risk level according to the reference scale adopted in Maister et al. 2020 (see table 4). The risk of child labour in cobalt mining in the DRC is also largely documented in literature, including for what concerns the "worst forms of child labour"[24] and in the context of Artisanal and Small Scale Mining (ASM) e.g. [157], [158] *Source: authors' assessment*	
Forced labour	Social Life Cycle Impact Assessment (Type I). The assessment of this aspect can be performed looking at the main suppliers and countries involved in the production of raw	Frequency of forced labour (estimated prevalence of population in modern slavery, victims per 1,000 population) - country level	Considering the raw materials used in batteries, DRC (cobalt) Australia (lithium), South Africa (manganese) and China (nickel and natural graphite) are the main countries at stake. [156] The Global Slavery Index provides the following values for the prevalence of forced labour, i.e. the "*estimated proportion of population living in modern slavery per thousand people*".	

[23] The Type I Social Impact Assessment method aims at assessing the social performance or social risk of the system under investigation using a reference scale (UNEP 2020).
[24] According to Worst Forms of Child Labour Convention, 1999

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
	materials, intermediate products and components used in batteries.		These values can be translated in risk levels using the reference scale adopted in Maister et al. 2020 (Table 4) the risk is very low in the case of Australia and South Africa, and is low in the case of DRC and China. - DRC: 4.5 ‰ : low risk - Australia: 1.6 ‰: very low risk - South Africa: 2.7 ‰: very low - China: 4‰ : low risk *Source: authors' assessment*	
Equal opportunities / discrimination	Social Life Cycle Impact Assessment (Type I). The assessment of this aspect can be performed looking at the main suppliers and countries involved in the production of raw materials, intermediate products and components used in batteries.	Gender wage gap (%) - country level Women in the labour force (ratio) – country/sector level	Considering the raw materials used in batteries, DRC (cobalt) Australia (lithium), South Africa (manganese) and China (nickel and natural graphite) are the main countries at stake . [156] For what concerns the indicator "*gender wage gap by occupation (%)*", values can be retrieved from ILOSTAT, but data is available only for one country: South Africa: 9.5 in 2019 (related to "Skill level: total"). The risk level for this value, using the reference scale adopted in Maister et al. 2020, is "low risk". Concerning the indicator "*ratio of women in the labour force*" values can be retrieved by S-LCA databases. The following values and risk levels can be observed for the countries and sector under investigation (year 2015): - DRC, mining sector: 0.81: very low risk - Australia, mining sector: 0.34: high risk - South Africa, mining sector: 0.39: high risk - China: metal processing sector: 0.89: very low risk. The related reference scales are in table 4. *Source: authors' assessment*	
Freedom of association and collective bargaining	Social Life Cycle Impact Assessment (Type I). The assessment of this aspect can be performed looking at the main suppliers and countries	Right to strike / Right to association / Right of collective bargaining (point in scale) Country level	Considering the raw materials used in batteries, DRC (cobalt) Australia (lithium), South Africa (manganese) and China (nickel and natural graphite) are the main countries at stake . [156] For what concerns the indicator "*trade union density (%)*", values can be retrieved both from ILOSTAT and S-LCA	

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
	involved in the production of raw materials, intermediate products and components used in batteries.	Trade union density (%) Country level	databases. The following values and risk levels apply to the countries of interest for batteries (reference scale in table 4): DRC: 13.6% (2012) very high risk Australia: 13.7& (2018) very high risk South Africa: 19.1% (2019) very high risk China: 44.2% (2017) medium risk *Source: authors' assessment*	
Working hours	Social Life Cycle Impact Assessment (Type I). The assessment of this aspect can be performed looking at the main suppliers and countries involved in the production of raw materials, intermediate products and components used in batteries.	Hours of work per employee and week (hours) Country/sector level	Considering the raw materials used in batteries, DRC (cobalt) Australia (lithium), South Africa (manganese) and China (nickel and natural graphite) are the main countries at stake. [156] For what concerns the indicator "*Mean weekly hours actually worked per employed person, by sex and economic activity*", values can be retrieved from ILOSTAT, but data is available only for one country: South Africa, industry: 42.3 hours : low risk (reference scale in table 4). *Source: authors' assessment*	
Fair salary	Social Life Cycle Impact Assessment (Type I). The assessment of this indicator can be performed looking at the main suppliers and countries involved in the production of raw materials, intermediate products and components used in batteries.	Sector average wage, per month Living wage, per month Minimum wage, per month (EUR/month) country/sector level	Considering the raw materials used in batteries, DRC (cobalt) Australia (lithium), South Africa (manganese) and China (nickel and natural graphite) are the main countries at stake. [156] The PSILCA database provides a risk assessment for a set of five indicators related to wage. Among them, the sector average wage is the only sector-specific indicator. The associated risk levels for the countries of interest for batteries are the following: - DRC: 600 USD (2015), medium risk - Australia: 5 819 USD (2014), very low risk - South Africa: 1 268 USD (2017), very low risk - China: 843 (2016), very low risk *Source: authors' assessment*	
Health and safety	Social Life Cycle Impact Assessment (Type I). The assessment of this aspect	Rate of fatal and non-fatal accidents at workplace (# per 100 000 employees)	Considering the raw materials used in batteries, DRC (cobalt) Australia (lithium), South Africa (manganese) and China	

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
	can be performed looking at the main suppliers and countries involved in the production of raw materials, intermediate products and components used in batteries. Can be complemented by a literature review on large accident risk along the life cycle and human health impact on local communities.	- country/sector level	(nickel and natural graphite) are the main countries at stake. [156] For what concerns the indicator "*Rates of fatal accidents at workplace*" and "*Rates of non-fatal accidents at workplace*", values can be retrieved from ILOSTAT (SDG indicator 8.1.1) and risk assessment can be derived based on the reference scale in table 4. However, in the case of countries of interest for batteries, only Australia has values, while for the other countries no data is available: - 1.6 fatal accidents per 100 000 employees (2017) : very low risk - 899 non-fatal accidents per 100 000 employees (2017): low risk Several studies have been published on the working conditions of the mining sector, especially in the case of cobalt extraction in the DRC and in the artisanal mining sector (e.g. [159], [160], (Arvidsson et al. 2022) *Source: authors' assessment*	
Responsible materials sourcing	This category should take into account the supply of raw materials, both in terms of mining practices and country of origin. An assessment at technology level can be based on the identification of the countries of origin of the main raw materials and the verification of the list of conflict-affected and high-risk areas.		For batteries, an extensive literature has described the environmental and health impacts of cobalt extraction in the DRC, documenting health negative effects on local communities, e.g. [159], human right abuses in mining sites and worst forms of child labour [161]. In response to these allegations, many responsible sourcing initiatives have been started by private and public actors. [160], [158] The Battery Regulation requires companies to perform due diligence according to the OECD Guidance. [162] This is based on the identification of risks like severe human right abuses associated with the extraction, transport or trade of minerals, worst forms of child labour, support to non-state armed groups, bribery, money laundering, etc.. *Source: authors' assessment*	
Competition for material	Descriptive, based on narratives and literature		In the case of batteries, the increased materials requirement can create competition for land and water in the mining sites,	

Sustainability aspect	Method/approach	Indicators	Assessment of batteries	Additional insights
resources (incl. water, land, food) and indigenous rights	review. This aspect should focus on the potential competition for material resources (e.g. land, food, water, minerals) created by the technology under investigation.		due, for instance, to the occupation of residential or agricultural land (leading in some cases to forced displacement, eviction and resettlement) or due to the pollution of water resources (Amnesty International 2023). This can affect particularly indigenous populations using these resources as mean of livelihood. This was the case, for instance, in the case of lithium extraction in Bolivia, Chile and Argentina (see public acceptance). *Source: authors' assessment*	
Contribution to economic development (including employment)	Social Life Cycle Impact Assessment (Type I)	E.g.: % of GDP Direct employment (person year/GWh) Total employment (direct+indirect) (person year/GWh)	"The number of direct jobs in the EU battery manufacturing after a single year drop in 2016 is exhibiting growth with increasing rate. This is in line with opening new or extending production in existing battery plants. This trend is expected to continue. The point for 2020 might be underestimated, as Poland and France did not report/disclose their numbers and this missing data was extrapolated with a conservative approach, assuming continuation of trends observed in preceding periods. (...) Concerning education opportunities, the battery sector will require workers skilled in electrochemistry, digitalisation of processes, electronics, programming, etc. The European Battery Alliance EBA250 Academy is developing a panEuropean education ecosystem to cover battery industry's skills needs and provide education to 160 000 workers every year." *Source: CETO Report on batteries 2023* [1]	This aspect can include the following subtopics related to the contribution of the sector to: - Added value - Employment creation (both direct and indirect) - Education and training opportunities
Affordable energy access	Descriptive based on literature review, Should focus on the contribution of the technology for the affordable energy access.		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.	

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			Source: CETO Report on batteries 2023 [1]	
Public acceptance	Descriptive, based on literature review, should also take into account potential impacts on indigenous rights and access to resources.	Insights from the Environmental justice Atlas	The Environmental Justice Atlas [163] documents and systematises information about conflicts and struggles over the exploitation of natural resources and the related production processes. It describes 28 conflicts linked to lithium projects, 5 for manganese, 2 for cobalt, 2 for nickel. For what concerns lithium, the mining activity on Kola peninsula (Russia) have been highly opposed by Indigenous Sami peoples. Conflicts and opposition of the indigenous population in Bolivia and Argentina are documented, due to the competition for water use and coexistence with tourism. In the EU, protests linked to lithium project occurred in Serbia, Portugal and Spain. *Source: authors' assessment*	
Rural development	Descriptive approach based on literature review		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-use 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. ([164], [165] *Source: CETO Report on batteries 2023* [1]	This aspect can into account the following potential repercussions of energy technologies on rural areas: - Employment opportunities - Entrepreneurship and opportunities for local economy (e.g. in terms of diversification, utilization of agricultural by-products, other income-generating activities) - Improved access to energy for rural population and increased energy security.

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