ISSN 1831-9424

CLEAN ENERGY
TECHNOLOGY
OBSERVATORY

BATTERY TECHNOLOGY IN THE EUROPEAN UNION

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

2023

EUR 31698 EN

This publication is a Technical report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact information
Name: Marek Bielewski
Address: Westerduinweg 3, NL-1755 LE Petten, The Netherlands
Email: marek.bielewski@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC135406

EUR 31698 EN

PDF ISBN 978-92-68-08427-4 ISSN 1831-9424 doi:10.2760/52259 KJ-NA-31-698-EN-N

Luxembourg: Publications Office of the European Union, 2023

© European Union, 2023

The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union/European Atomic Energy Community, permission must be sought directly from the copyright holders. The European Union does not own the copyright in relation to the following elements:
- Cover page illustration, © Author name / stock.adobe.com
- page 33, Figure 7, source: BloombergNEF

How to cite this report: M. Bielewski, A. Pfrang, D. Quintero-Pulido, S. Bobba, A. Georgakaki, S. Letout, A. Kuokkanen, A. Mountraki, E. Ince, D. Shtjefni, *Clean Energy Technology Observatory: Battery Technology in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/52259, JRC135406.

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. 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. The focus is on sodium-ion, redox-flow, metal-air and zinc batteries. It also contains assessment of market developments, production, trade, patenting, and access to raw materials in the area of batteries in general and especially Li-ion batteries technology.

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 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 inventive 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 pages

Acknowledgements

The authors are grateful to JRC colleagues: Burkhard SCHADE, Andreas SCHMITZ and Andrea DIAZ RINCON , for providing expectations on battery price evolution resulting from the POLES-JRC model.

The authors are grateful to Marcelina GRABOWSKA (JRC) for extraction of TIM data and support related to TIM data evaluation.

The authors are grateful to Marc STEEN (JRC) for discussions and valuable comments during development of the report.

Finally the authors are grateful to everyone else who supported or contributed in any way to development of this report, especially to Thomas SCHLEKER (RTD), Johan BLONDEL (RTD), Jens BARTHOLOMES (ENER), Lelde KIELA-VILUMSONE (ENER), Giulia SERRA (ENER), Alessandro POLITO (ENER), Pablo RIESGO ABELEDO (ENER) and JRC colleagues Nigel TAYLOR (CETO project leader), Andreas SCHMITZ and Burkhard SCHADE for coordination, support, review and comments.

Authors

M. Bielewski, lead author

A. Pfrang, technology expert

D. Quintero-Pulido, technology expert

S. Bobba, technology expert

A. Georgakaki, statistical data provider

S. Letout, statistical data provider

A. Kuokkanen, statistical data provider

A. Mountraki, statistical data provider

E. Ince, statistical data provider

D. Shtjefni, statistical data provider

Executive Summary

Batteries are a key enabler in the context of the Green Deal and the REPowerEU plan to reach climate neutrality and reduce dependency on fuel imports. E-mobility is driving battery markets; lithium-ion batteries will dominate, but other technologies will develop in parallel. 50 million electric vehicles (>1.5 TWh of batteries) and 160 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 (mostly electric with some form of battery energy storage). This report focuses on sodium-ion (Na-ion), redox-flow, zinc based, and metal-air batteries. Also update of the indicators available for battery technologies in general is given. Looking at applications coverage, the most focus is on EV batteries, stationary battery energy storage (BESS), other mobility applications and back-up power.

General Technology Overview and TRL:

The dominating chemistry is lithium-ion (lithium iron phosphate (LFP), nickel cobalt aluminium oxide (NCA) and nickel manganese cobalt oxide 6:2:2 (NMC622)). In the future Li-ion will still dominate, but there will be a shift to low- or zero-cobalt chemistries (LFP, NMC811+). The role of sodium-ion, redox-flow batteries and other technologies will increase significantly.

Sodium-ion batteries have reached the market (TRL 4-9) and commercialisation is led by China, which advance extremely quickly on this. The technology does not rely on any critical raw material, but its specific energy is lower than mainstream lithium-ion chemistries. It targets both electro-mobility and stationary applications.

Redox flow batteries: many chemistries are possible, the most advanced are based on vanadium, but versions based on cheap, non-toxic and non-critical materials are available. Some of these have already reached the market and others are in earlier stages of development (TRL 3-9). They are flexible for power and energy scaling, and potentially suitable for seasonal energy storage. The market is developing quickly, however slower than in case of sodium-ion batteries, and mostly in the US, CA, AU and Asian countries. This technology is expected to be mainly used in stationary applications.

Metal-air batteries: also a diverse group of chemistries, some in commercialisation and others in development (TRL 3-8). The market develop mainly in the US. The technology targets stationary applications.

Zinc batteries – technology commercialized by two companies (based in the US and AU), developed by few others (TRL 7-9). The technology is targeting stationary applications

Technology Deployment

Mobility applications account for about 90% of all the batteries in use, mainly in personal and light duty commercial vehicles. Heavy trucks and other modes of transport are electrified only marginally. The capacity of all Li-ion batteries installed worldwide in vehicles in 2022 reached 550 GWh, an increase of 65% from 2021. Most of the demand came from China followed by Europe. In 2019-20, Europe was gaining market share mainly from China, however, in the last two years this trend has reversed.

Future demand is expected to reach 1.5 TWh in 2025 and 3-3.5 TWh in 2030. About 50-65 additional new giga-factories would be needed to satisfy this demand.

In 2022, global sales of electrified vehicles exceeded 10 million (+55% y/y), reaching 14% share in total vehicles sales (9% in 2021). China accounted for 6 million, the EU for 2.7 million, and the US for 1 million of vehicles. The share of electrified vehicles in internal market in China was 29%, for the first time, higher than in the EU (21%). Sales of electric buses were largest in China reaching 54 000 units, almost 4 000 in EU and 2 000 in US. Global electric heavy duty vehicle registrations reached 60 000 units. China is leading, with about 52 000 new registrations, followed by the US (3 100) and the EU (2 800).

Global installations of battery energy stationary storage (BESS) systems exceeded 76 GWh in 2022, 98% more than in 2021, and the cumulative installations approached 150 GWh. The market expects growth to 240 GWh in 2025 and 411 GWh in 2030. The market leader in 2022 was China, with 43 GWh and 60% share globally. The US took second place with 15 GWh (20%) ahead of the EU with 9 GWh (12%).

Battery prices

In 2022, average global battery price per kWh rose by 7% breaking a long-term trend. Prices in 2023 are expected to stay at the 2022 level and in 2024 return to a decreasing trend. It is expected that in 2026 the average pack price should fall below $100/kWh. This is two years later than previously expected and may negatively influence the development of EV and BESS markets. It is estimated that the cost of Na-ion battery is about 30% lower than a cost of LFP battery.

RD&I Funding and Investments

Annual EU public RD&D investments grew from 60-70 million EUR before 2019 to almost 300 million EUR in 2021. Global growth was less dynamic in this period, bringing the investments from 200-300 million EUR to almost 500 million EUR. The global leaders are the US, EU and UK. The EU leading MS are France (focus on general purpose batteries), Germany (EV batteries) and Austria.

Regarding private RD&I funding and Investments, in 2022, global VC investments in battery developers decreased to 9.5 billion EUR (-21% y/y). This decrease was stronger in the EU (-31%) than in the RoW (-18%), and touched both early stage and later stages investments. Similar trends were observed in the RoW. The biggest innovators were corporations, however start-ups were active in all fields of batteries R&I. The global Top 5 innovation leaders are: Toyota, Bosch, LG Chem, Samsung and BMW.

In the EU the battery IPCEIs from 2020-21 brought about 14 billion EUR of private investments on top of public funding. Beyond R&I, EU industry has invested significantly in integration of batteries with end products. Overall investments in the EU's battery ecosystem are estimated at 180 billion EUR, and directed to more than 160 industrial projects along the battery value chain.

Patenting trends

Japan is a patenting leader since 2009, however its patenting rate strongly decreased in 2020 moving it to the third place. Korea and China show continued growth, taking first and second place respectively. Globally leading companies are LG, CATL and Samsung. The only EU representative is Bosch in 8th position. In general, EU companies increased share of patents filled in the US and ROW at cost of China, Korea and Japan.

Scientific publication trends

Out of analysed non-Li-ion chemistries most scientific interest was on Na-ion technology, followed by zinc batteries (fastest growth), redox-flow and Me-air batteries. In each of these, China is leading, and the EU takes 3rd or 4th place. No strong international collaboration is observed.

Turnover

The turnover in the EU battery manufacturing sector has risen significantly since 2019, showing 55% growth in two years. This is in line with expanding production in the EU battery plants. The trend is expected to continue.

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 through a number of measures, including a carbon footprint declaration, ethical sourcing of raw materials, ambitious collection and recycling targets, inclusion of secondary raw materials in production, promotion of second application of used batteries.

Role of EU Companies

The global leader in Na-ion batteries is China, where big companies, in particular CATL, have been very quick to move to commercialisation. The US is leading in flow batteries, followed by the EU and RoW. There are no major players investing in flow batteries. The EU, despite being strong in R&D, is lagging in the production phase. In the field of Me-air batteries, the global leaders are companies based in the US followed by those from the EU and Canada. The EU prospects for this technology are not clear. European companies have a relatively strong position in R&D, but might migrate with production to locations close to main markets in third countries. The two companies leading the zinc battery market are based in the US and Australia. They already operate commercial plants with production capabilities greater than 1 GWh/y each. One European company is developing the technology (currently TRL 7).

Employment

The number of direct jobs in the EU battery manufacturing is growing at an increasing rate. The leaders are Germany, Poland and Hungary, with the highest growth observed in Hungary and Germany. The sector could create more than one million new jobs in the EU. 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.

EU Production Data

The total value of batteries produced in the EU in 2022 was about 28 billion EUR. The vast majority of produced batteries are EV batteries, and primary (non-rechargeable) batteries accounted for 10-15% of the production. The trend of value of battery production is increasing in the last years at an observed CAGR of 25%.

The evolution of structure of the battery production shows a clear shift from lead-acid batteries dominating in 2011-12, to Li-ion batteries in the last years, however in absolute terms production of lead-acid batteries remains stable. Production of Li-ion batteries in 2022 was at the same level observed in 2021.

Global and EU market leaders

In Na-ion technology, a global leader is China Three Gorges Corporation, operating a world's first Na-ion gigafactory. CATL and BYD plan to start mass production in late 2023 and nearly 30 manufacturing plants at different development stages are being constructed, almost all in China. The EU leader is Tiamat (FR) planning to start production in 2025 and expand the plant to 6 GWh/y production capacity in 2030. Altris (SE) is a supplier of cathode material and Altech (DE) with Fraunhofer (DE) plan a 100 MWh/y sodium solid state battery plant aimed at the BESS market.

In redox-flow batteries, global leaders are: Invinity (UK, CA; 200 MWh/y) and VRB Energy (CN, 1 GWh/y) both in vanadium technology; State Power Investment Corp. (US, 150 MWh/y) and ESS Tech Inc. (US, under construction) in iron flow technology. In the EU a technology leaders are CMBlu (DE), developer of Organic SolidFlow batteries and Elestor (NL), developer of hydrogen-bromine flow battery, both approaching mass production phase.

In Me-air battery technology global leaders are Form Energy (US, first plant under construction), developer of Fe-air battery and E-Zinc (CA, first plant under construction), developer of Zn-air technology. In the EU, AZA Battery (BE) develop Zn-air battery and is still at pre-commercial phase.

In other zinc technologies, global leaders are EOS (US, 800 MWh/y) and Gelion (AU, 2 MWh/y), both developed non-flow zinc-bromine batteries.

The global leaders of mainstream Li-ion battery production are: CATL, LG ES, BYD, Panasonic and SK Innovation, listed in order of annual production in 2022.

Trade and trade balance

The global export of batteries is estimated at 183 billion EUR in 2020-22. The EU export to non-EU countries reached 13 billion EUR in the same time (7.1% of global market). The EU satisfied 50% of its battery demand by imports from non-EU countries. In 2022, the EU export rose by 36%, while in the same time import rose by 120% leading to record high deficit of 15 billion EUR, 190% more than in 2021.

China remained the biggest global exporter, Poland, Germany and Hungary are listed at the second third and fourth place respectively. Germany is the number one global importer. Czechia appeared in both the top 10 exporters and importers lists, while Poland and Netherlands fell off the top 10 global importers list.

Resource efficiency and dependence in relation to EU competitiveness

The EU depends heavily on third countries for raw materials and battery production equipment. The EU share in global cell production is expected to improve, despite strong competition from Asian and US companies. 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, and it should not be expected that it will become one as the third countries rely on less developed energy grid, thus provide more business opportunities for energy storage providers. Due to very high rate of Na-ion batteries commercialisation in China and limited rate in the EU, it should be expected that the EU will develop a dependence on China for this technology.

A possible way to reduce EU's dependence on the supply of raw materials is recycling. As of July 2023, the overall batteries recycling capacity in Europe is 116 kt/y, and is expected to increase to 400 kt/y by 2030. Currently, most of the commercial recyclers in Europe offer only mechanical or pyrometallurgical treatment and thus cannot produce battery-grade secondary raw materials. Usually the black mass containing most valuable metals is sent to recyclers in the Asia-Pacific region for a hydrometallurgical process. This, however, is changing and more recyclers in Europe are expanding their capacities to cover hydrometallurgical processes.

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

Strengths	**Weaknesses**
– Strong automotive industry sector generates demand. – Policies promote technologies that support demand. – Strong EU support for R&D and deployment. – Generally strong 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 materials supply and purification, and for production machinery. – High energy prices and labour costs. – Complex EU legislation and bureaucracy makes investment approval process lengthy. – Conflicts of interest between MS. – Shortage of workers specialised in battery manufacturing. – Regulations and standards are not developed enough.
Opportunities	**Threats**
– Synergies with other value chains, e.g. hydrogen or other forms of energy storage. – Enabler for a wide deployment of RES – Local value chains with reduced geopolitical risks for more sustainable and cheaper (RFB, Na-ion, Zn-based) or more performant (silicon or metal Li anode, solid state, Li-S, etc.) battery solutions. – Shape / contribute to the development of missing international regulations and standards on batteries.	– 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, less performant battery technologies (flow batteries, Na-ion technology). – Risks from toxic materials in batteries production, use and recycling properly managed. – 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 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 Green Deal,[1] the REPowerEU Plan[2] and the European Climate Law[3] aim for EU climate neutrality by 2050. Achieving this objective is only possible with significant technological advancement in energy storage technologies. Storing electricity in batteries is key for decarbonisation of transport and for wide adoption of intermittent renewable energy sources in the EU energy mix. This is because of batteries high energy roundtrip efficiency, achievable specific energy, scalability and increasing price affordability.

Currently the technological advancement in battery technologies is mainly led by automotive sector which is focusing on high performance Li-ion batteries. This is also the biggest market for batteries. Other applications, like e.g. stationary energy storage despite of growing importance, did not reached stage at which significant R&D is focused on satisfying their specific needs. Thus, most of current stationary storage systems still are built using cells initially developed for automotive applications. This split of R&D activities and development of batteries fine-tuned for each application area is expected in future.

The battery technologies develop towards improved Li-ion chemistry, but also towards alternative chemical formulations, looking for better performance, durability, safety and price, but also increasing sustainability and value chain security – aspects that became critical in recent years.

This year the CETO report focuses on sodium-ion (Na-ion), redox-flow, zinc based, and metal-air batteries. Also update of the indicators available for battery technologies in general is given. Looking at applications coverage, the most focus is on EV batteries, stationary battery energy storage (BESS), other mobility applications and back-up power.

The current work is an update of the 2022 edition of CETO report[4].

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 positioning

The report focuses on the factual description of the actual state and refers to the previous period to highlight the changes. Na-ion, redox-flow, Me-air and zinc batteries are in the focus, especially in technology development section. In chapters related to battery production and markets focus is given to Li-ion batteries, actually technology that dominates on the markets. However, where possible information on the other chemistries is given to provide a full picture of the battery sector.

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

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

Annex 2 contain detailed sustainability assessment following the LCA analysis methodology.

The available statistical data, technical reports and scientific publications provide rather complete picture of technology development, technology cost, patenting and scientific publications. In other areas however, there is no statistical data available. This especially apply to gross value added, energy intensity and labour productivity (those parameters are reported to Eurostat at higher level of agglomeration and not available for single product areas), partially also to production data (where several member states restrict access to statistical data). Some indicators are not available for technologies that did not reached market yet, or which are still at their infancy stage.

---

[1] COM(2019) 640 final *The European Green Deal*

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

[3] EU Regulation 2021/1119

[4] M. Bielewski, A. Pfrang, S. Bobba, A. Kronberga, A. Georgakaki, S. Letout, A. Kuokkanen, A. Mountraki, E. Ince, D. Shtjefni, G. Joanny, O. Eulaerts, M. Grabowska, *Clean Energy Technology Observatory: Batteries for energy storage in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/808352, JRC130724

2 Technology status and development trends

2.1 Technology readiness level

2.1.1 Sodium-ion batteries (Na-ion)

After the first commercialisation announcements in 2021, Na-ion batteries are beginning to scale-up. BNEF speculates that at least one major battery manufacturer will present a significant Na-ion battery product roadmap, that two major energy storage systems will be launched and that at least one large-scale two- or three-wheeled-vehicle company will announce a vehicle model powered by sodium-ion batteries.[5]

Recent development of Na-ion batteries was pushed by the EV sector and all current applications using Na-ion chemistry will profit of it. However, in future it is expected that main application areas will decouple, and will push forward development of batteries optimised for a specific application. The Na-ion technology is expected to find use in stationary battery energy storage systems (BESS) including for providing grid services, renewables integration, domestic energy storage, UPS etc. Another area would be traction batteries for some cheaper EVs, low speed EVs, e-bikes, e-scooters, e-buses and e-trucks, where lower cost, high power and durability are an asset.[6] The Eurostat data from 14 countries shows that the average daily distance travelled in an urban environment is in a range 5 - 20 19 km.[7] This is fully compatible with an urban EV powered by Na-ion battery with range of 250 km; which means that a single charge could allow 10 - 40 days of use in an urban traffic.[8] Potential applications include also starting, lighting, and ignition (SLI) batteries and some portable applications.

Na-ion technology has reached parity with Li-ion LFP technology regarding specific energy reaching 160 $Wh{\cdot}kg^{-1}$, while keeping advantage in several other areas (e.g. better performance at low temperature – 90% capacity retention when discharging at -20 °C, cycle life, C-rate, fast-charging 0-80% in 15 min., safety, sustainability, potentially lower price). LFP cells have already found their path to EV battery packs and the same should be expected for Na-ion. With shorter range and increased cycle life and C-rate, Na-ion batteries might be compatible with short range cars and heavy duty applications, but also allowing EV drive over long distance with more numerous but short stops to recharge batteries without compromising durability.

Na is the sixth most abundant element in the Earth crust and can be extracted from seawater, which takes out risks related to limited resources or geopolitical issues. The general consensus is that Na-ion batteries will always remain cheaper than Li-ion (provided that cathode and anode are not based on expensive materials e.g. vanadium). Deployment of Na-ion batteries is expected to reduce pressure on Li prices and introduce more competition to the battery sector, helping to further reduce prices of batteries in general.

Na-ion batteries are assumed “environmentally friendly” as they use much less toxic materials and do not contain Co, Ni, Mn, Cu, Li, metals that are either toxic or the production of which negatively impacts the environment (consumption of water, energy, emitting pollutions, etc.).

Na-ion batteries are assumed safer than Li-ion batteries. Using Al for anode current collector do not suffer from too low battery voltage. It was demonstrated that keeping a Na-ion cell shorted (at 0 V) over long periods does not hamper its cycle life.[9] Additionally, Na-ion batteries may use electrolyte with more thermally stable solvents. Both features improve safety of Na-ion technology and favour Na-ion over Li-ion for transportation, storage and use. Transporting Na-ion batteries shorted (at 0 V) cause they are assumed being chemicals only, not batteries. This removes several restrictions and some bureaucratic burden.

The cell design and working principle of Na-ion batteries are analogous to that of Li-ion, with the difference that charge transfer and electrochemical reactions involve sodium ions (Na^+) instead of lithium (Li^+). A cathode active material containing sodium ions and an anode able to accept sodium atoms are deposited on metallic current collectors and immersed in a liquid electrolyte providing mobility of ions. To avoid internal short-circuit an electrically non-conductive but permeable for Na^+ ions separator is placed between the electrodes.

During charging, Na^+ ions are released from the cathode active material, transported to the anode side and intercalated into the anode active material. During battery discharge the reactions spontaneously occur in the

---

[5] https://about.bnef.com/blog/top-10-energy-storage-trends-in-2023/

[6] Sodium-ion update: *A make-or-break year for the battery market disruptor*, Jan 2023, Wood Mackenzie

[7] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Average_distance_per_person_per_day_(kilometres)_v3.png

[8] https://energypost.eu/sodium-ion-batteries-ready-for-commercialisation-for-grids-homes-even-compact-evs/

[9] J. Barker, C.W. Wright, *Storage and/or transportation of sodium-ion cells*, United States Patent Application No. 2017/0237270 Filed by Faradion Limited on 22 Aug 2014

opposite direction when electrons flow via external circuit is allowed. As Na^+ ions are much bigger than Li^+ ions (ionic radius of 1.02 Å for Na^+ vs. 0.76 Å for Li^+), different active materials are needed for Na-ion batteries.

Cathode materials can be grouped into 3 classes of compounds: layered transition metal oxides (LTM), polyanion compounds (PA) and Prussian blue analogues (PBA), see **Table 2**; each class having its own advantages and drawbacks.[10]

Table 2. Cathode materials for Na-ion batteries (scale: green = good, red = bad).

	capacity [mAh·g^{-1}]	voltage [V]	specific energy at material level [Wh·kg^{-1}]	C-rate	stability /cycle life	remarks
layered oxides	130-140	2.5 - 4.3	400 - 600	4C - 10C	-	prone to phase changes
polyanion compounds	110-160	2.0 - 4.8	400 - 600	6C - 12C	++	Fast Na^+ diffusion, poor electronic conductivity
Prussian blue analogues	120	2.8 - 3.4	500	16C - 50C	+++	easy production

Source: JRC, 2023

	technology developer	cell specific energy current (future) design [Wh·kg^{-1}]	cell cycle life
layered oxides	Faradion	160 (190)	4 000
	HiNa	145 (180)	8 000-10 000
	Svolt	135	2 000
	Li-Fun	140 (160)	10 000
polyanion compounds	Tiamat	122	5 000
	Godi	120	10 000
	EVE	135	n.a.
	Zoolnasm	140	n.a.
Prussian blue analogues	CATL	160 (200)	3 000 – 6 000
	Natron	140	50 000

Source: JRC, 2023

Faradion has developed and patented an oxide-based cathode material.[11]

CATL for their hybrid Na-ion/Li-ion EV battery pack will probably use a layered oxide, but Prussian blue analogues (e.g. $Na_2MnFe(CN)_6$) and phosphates are also described in their patents.[12]

Shenzhen Institute of Advanced Technology of the Chinese Academy of Sciences, in collaboration with the National Institute of Synchrotron Radiation Sources of Thailand has developed a mixed polyanionic compound.[13]

---

[10] D. Saritha, R. Sujithra, *A concise review on cathode materials for Na-ion batteries*, Materials Today: Proceedings, in press, doi:10.1016/j.matpr.2023.03.401

[11] E. Kendrick, R. Gruar, M. Nishijima, H. Mizuhata, T. Otani, I. Asako, Y. Kamimura, *Tin-Containing Compounds*, United States Patent No. US 10,263,254, Issued 16 Apr 2019, Filed by Faradion Limited and Sharp Kabushiki Kaisha on 22 May 2014.

[12] Advanced Li-ion, and Beyond Lithium Batteries 2022-2032: Technologies, Players, Trends, Markets. IDTechEx, 2022

[13] T. Song, W. Yao P. Kiadkhunthod, Y. Zheng, N. Wu, X. Zhou, S. Tunmee, S. Sattayaporn, Y. Tang, *A Low-Cost and Environmentally Friendly Mixed Polyanionic Cathode for Sodium-Ion Storage*, Angew. Chem. Int. Ed. 59 (2020) 74020535 doi:10.1002/anie.201912272.

Novasis Energies has developed and patented Prussian blue analogues (PBA) for its Na-ion batteries. [14, 15]

Anode materials selection for Na-ion batteries is dominated by so called "hard carbon", a disordered amorphous carbon material. It can store about 300 $mAh·g^{-1}$ with a good cycling stability and working potential around 0.15 V vs. Na/Na^+.[16] There are several companies commercially offering hard carbon for Na-ion batteries.[17]

As potential alternative to hard carbon, some sodium titanate phases offer capacities of 90 - 180 $mAh·g^{-1}$ at working potentials <1.0 V vs. Na/Na^+ and good cycling stability.[18] Also some metal oxides, sulfides or pure metals, e.g. SnO_2, SnS_2, Sn or Sb are able to store sodium via an alloy or conversion reaction mechanism. They suffer, however, from severe stress-strain during work cycles especially for large-format cells, leading to their fast degradation.

Electrolyte: Na-ion cells can use aqueous or organic solvent electrolytes. Due to the limited electrochemical stability window of water, cells with aqueous electrolytes have lower voltages and thus also lower energy densities. To better utilise the voltage range of active materials, organic solvent-based electrolytes known from Li-ion cells are usually used. Mixtures of ethylene carbonate, propylene carbonate and dimethyl carbonate (EC:PC:DMC) or ethylene carbonate, propylene carbonate and dimethoxyethane (EC:PC:DME) allow required ionic mobility resulting in good C-rate capability. Those mixtures are richer in more thermally stable propylene carbonate comparing to Li-ion batteries (which use more of highly flammable diethyl carbonate and/or dimethyl carbonate).

The most often used salt additive, allowing for transport of sodium ions in non-aqueous electrolytes is sodium hexafluorophosphate.

Another concept is to use gel-polymer electrolyte, which is less prone to leakage issues.[19]

Finally there is an idea to use a super-high concentrated salt containing Na^+ ions in aqueous solution, which is called water-in-salt (WiS), e.g. inert-cation-assisted WiS electrolyte containing Na^+ and tetraethylammonium (TEA+) inert cation in super-high concentrations of 31 $mol·kg^{-1}$ exhibits a wide electrochemical window of 3.3 V, prohibits dissolution of transition metal from the cathode, and provides single step intercalation process of sodium into both cathode and anode electrodes during cycling.[20]

Current collectors: in contrast to Li-ion batteries, where copper foil is required for the anode, Na-ion cells may use aluminium as current collector at both electrodes. This is possible for two reasons: 1) due to higher potential of Na/Na^+ comparing to Li/Li^+, the voltage window of Na-ion batteries is smaller than that of Li-ion batteries, preventing Al dissolving when battery fully charged, 2) Al does not alloy with Na (in contrast it forms an alloy with Li that would be created in Li-ion batteries) that is formed at the anode during discharge and would irreversibly damage current collector structure and consume Li leading to capacity degradation. In result Na-ion cells have advantage of using cheaper and lighter Al instead of Cu. Additionally, Na-ion batteries can be fully discharged (to 0 V) without risk of damage.

The technology of manufacturing Na-ion batteries is very similar to that of Li-ion; hence, there is a significant synergy. This implies little additional cost and short time when switching an existing Li-ion battery plant to Na-ion technology.

The technology readiness level (TRL) for Na-ion batteries depicts the state of development of active materials, cell designs and validation of manufacturing processes. The technology is still in the optimisation phase. Large scale demonstration Na-ion based BESS are already in use phase, multiple prototypes of smaller batteries were developed delivering promising results. A number of companies, mainly Chinese, with CATL at front, are already at commercialisation stage. The TRL is 6-9 depending on exact battery chemistry and design taken into account.

---

[14] Y. Lu, L. Wang, J. Cheng, J.B. Goodenough, *Prussian blue: a new framework of electrode materials for sodium batteries*, Chemical Communications. 48 (2012) 6544 doi:10.1039/C2CC31777J.

[15] Y. Lu, H. Kisdarjono, J.J. Lee, D. Evans, *Transition metal hexacyanoferrate battery cathode with single plateau charge/discharge curve*, United States Patent No. 9,099,718 Issued 04 Aug 2015, Filed by Sharp Laboratories of America, Inc. on 03 Oct 2013.

[16] D.A. Stevens, J.R. Dahn, *High Capacity Anode Materials for Rechargeable Sodium-Ion Batteries*, Journal of the Electrochemical Society, 147 (2000) 1271, doi:10.1149/1.1393348.

[17] https://www.takomabattery.com/global-top-10-hard-carbon-anode-manufacturers/

[18] A. Rudola, N. Sharma, P. Balaya, *Introducing a 0.2 V sodium-ion battery anode: The $Na_2Ti_3O_7$ to $Na_{3-x}Ti_3O_7$ pathway*, Electrochemistry Communications 61 (2015) 10, doi:10.1016/j.elecom.2015.09.016.

[19] O.V. Lonchakova, O.A. Semenikhin, M.V. Zakharkin, E.A. Karpushkin, V.G. Sergeyev, E.V. Antipov, *Efficient gel-polymer electrolyte for sodium-ion batteries based on poly(acrylonitrile-co-methyl acrylate)*, Electrochim. Acta, 334 (2020) 135512, doi:10.1016/j.electacta.2019.135512.

[20] L. Jiang, L. Liu, J. Yue, Q. Zhang, A. Zhou, O. Borodin, L. Suo, H. Li, L. Chen, K. Xu, Y.S. Hu, *High-Voltage Aqueous Na-Ion Battery Enabled by Inert-Cation-Assisted Water-in-Salt Electrolyte*, Adv. Mater., 32 (2020) 1904427; doi:10.1002/adma.201904427.

Recycling: current sorting processes do not separate Na-ion cells due to marginal share of this chemistry in EoL battery streams. Na-ion technology involves several chemically different active materials, thus separate recycling of them may be considered if technical or economic circumstances require that approach. Due to structural, and partly chemical similarities to Li-ion batteries some synergy effects might be expected, leading to faster adoption of recycling processes.

As Na-ion batteries do not contain costly metals like Co, Ni, Cu or Li, there is much less economical drive to recycle them. Thus, the economic viability and sustainability of recovering most of Na-ion battery materials needs to be further investigated.

Recycling of cathode materials will strongly depend on chemical formulation, e.g. sodium vanadium phosphate (NVP, $Na_3V_2(PO_4)_3$) can be directly reused in the regenerative process.[21] Recycling of vanadium, due to its price would be a recycling driver for batteries based on such compound. For chemistries based on iron the economy of the process would be not favourable, although technological development is observed in recycling Li-ion batteries, including LFP chemistries. Further technology progress and synergies are expected.

Recycling of sodium salt technically would be easy for its high solubility in water, however due to low price of sodium salts the economy of the process is unsure. Moreover, due to the novelty of the Na-ion technology, environmental performances of recycling sodium salts should be further investigated.

Recycling of metallic sodium technically should not be problematic: due to its reactivity with water, it could easily be converted into soluble alkali and leached out. However further conversion into pure metal form is an energy intensive electrolysis of molten salt or hydroxide. Direct recycling of metallic sodium (in a process analogous to electrochemical copper refining) would also be possible, but it requires non-aqueous solvent similar to battery electrolyte. Moreover, metallic sodium must be handled in moisture-free, inert atmosphere due to its reactivity.

Recycling hard carbon still requires development, similarly like recycling of graphite from Li-ion batteries; however strong synergy between recycling Na-ion and Li-ion batteries might be expected.

Recycling of the electrolyte would be the same as for Li-ion batteries as very similar solvents are used. However, for the moment commercial recycling of Li-ion batteries electrolyte is not yet adopted.

As aluminium is used for both current collectors, the recycling process would be simpler than for Li-ion batteries. However, when a pyro-metallurgical process is used as initial step in Li-ion batteries recycling, the aluminium is not recovered and this is also expected to apply to Na-ion batteries.

Plastic or iron casing materials can be segregated using physical methods and separately recycled. The process would be identical like in case of Li-ion batteries, however, when using a pyro-metallurgical process as initial step in Li-ion batteries recycling, the casing materials (both plastics and iron) are not recovered.

2.1.2 Redox-flow batteries (RFB)

The heart of a redox-flow battery (RFB) is an electrochemical cell, where the reduction and oxidation reactions take place. It is composed of anode and cathode, anode and cathode volumes filled with anolyte and catholyte and separated by an ion exchange membrane. The membrane prevents mixing of electrolytes and allows only selected ions to pass through to complete the redox reaction. Both electrode volumes are connected with tanks external to the electrochemical cell and scalable, storing additional amounts of anolyte and catholyte containing dissolved or dispersed active materials. Those chemicals are continuously changing their concentrations following battery state of charge. During charging, electrochemical reduction occurs in one electrolyte and oxidation in the other. On discharge, the reactions advance in the opposite direction releasing electrical energy.

The amount of energy that can be exchanged directly depends on the amount of chemicals available for redox reactions in electrolytes. Thus adding external containers with additional electrolyte enhances the storage capacity of the battery, but requires continuous pumping of electrolyte between the electrochemical cell and the reservoirs. Because of this design redox-flow batteries are also called batteries with external energy storage (External = in tanks, outside the electrochemical cell). [22]

---

[21] T. Liu, Y. Zhang, C. Chen, Z. Lin, S. Zhang, J. Lu, *Sustainability-inspired cell design for a fully recyclable sodium ion battery*, Nat Commun. 10 (2019) 1965; doi:10.1038/s41467-019-09933-0

[22] In Li-ion technology active materials are deposited on metallic current collectors inside the battery, thus Li-ion batteries are called batteries with internal energy storage.

The storage capacity and power of the system can thus be independently adjusted to best fit the needs in a given location and use case. This is easily done by enlarging the tank volume for electrolytes (for storage capacity) and the reaction cells (for power). As the electrolytes are stored in separate tanks and possibility of cross-contamination is very limited (to electrochemical cell only), the self-discharge is very low. RFBs are free of degradation mechanisms caused by phase changes of active materials. For this reason, redox-flow batteries are more durable than Li-ion batteries and can be operated for 20 years or more in grid support applications such as, peak shaving, frequency regulation or load balancing. Also, the electrolytes can be easily renewed or replaced without need to replace the entire energy conversion device. (The mentioned 20 years of operational life is rather related to type of contracts signed than technical limitations of the energy storage systems).

RFBs utilize non-flammable aqueous electrolytes and therefore are free of fire risks.

RFBs target stationary energy storage and some first systems are already in use. However, significantly higher technology adoption rate is needed to reach industry- or grid-relevant scale. Modularised RFB installed in standard shipping containers are easily transportable, and can be used as “mobile” energy storage devices serving customers at different locations.

Flow batteries can switch between charging and discharging within a 0.1 s, however, this is considerably larger than 0.001 s achievable to batteries with internal energy storage. This reaction time difference is important especially for grid services like back-up power or frequency regulation. Thus RFB systems might need hybridisation with small Li-ion or Na-ion battery.

Use of RFBs in automotive applications was also investigated. The architecture of RFBs makes it possible to ultra-fast charge the battery by ”refuelling” the reservoirs with charged electrolytes. Several OEMs, such as Volkswagen, Toyota and Stellantis (former Fiat) have been experimenting with this concept, however it has not found industrial application until now.[23] Further major R&D would be needed, including organic systems, improving performance (energy and power density), system architectures, durability, and overall cost reduction.

RFBs exist in many chemical formulations, much more diverse variety than in case of e.g. Li-ion batteries.

Vanadium Redox-Flow Battery (VRFB) - the commercially available and most developed RFB system – is offered by a number of suppliers. In this chemistry, the same element, vanadium (at four different oxidation states) is used in both anolyte and catholyte leading to minimal electrolytes cross-contamination. Typically, the energy density of VFBs is about 25 $Wh \cdot L^{-1}$, round-trip efficiency is 70-80% and life time is 20 years and more than 15 000 cycles. The operating temperature range is 5 – 45 °C. Water based electrolytes minimize fire risk. The system cost in EUR/kWh is comparable or higher than that of Li-ion batteries, with active materials being a major part of the cost. R&D activities are focused on system design, cost reduction, development of fluorine-free membranes, overall performance and durability.

Iron-chromium (ICRFB) technology was pioneered by NASA (US) and Mitsui (JP) in the 1970–1980s. It utilizes low-cost and abundant iron and chromium chlorides in aqueous solution of hydrochloric acid. The Energy density of 39 $Wh \cdot L^{-1}$,[24] and the RTE of 70-85%, higher at elevated temperature of 40-65 °C[25] are reported. The cycle life is reaching 10 000 cycles.[26] ICRFB suffered from continuous capacity decay due to hydrogen generation as by-product and electrolyte intermixing, but recently this drawback was overcome, moving the technology out of the laboratory. Electrochemical purification of electrolyte is capable to remove impurities causing hydrogen evolution.[27] Compared with other flow batteries, ICRFBs have a wider operating temperature range of -20 to 70 °C. The electrolyte is relatively low toxic and low corrosive. The technology is one of the most price competitive among energy storage systems. ICRFBs fully detach power from storage capacity.

---

[23] A. Khor, P. Leung, M.R. Mohamed, C. Flox, Q. Xu, L. An, R.G.A. Wills, J.R. Morante, A.A. Shah, *Review of zinc-based hybrid flow batteries: From fundamentals to applications*, Materials Today Energy 8 (2018) 80, doi: 10.1016/j.mtener.2017.12.012

[24] J.E. Jang, R. Kim, S. Jayasubramaniyan, C. Lee, J. Choi, Y. Lee, S. Kang, J. Ryu, S.W. Lee, J. Cho, D.W. Lee, H.K. Song, W. Choe, D.H. Seo, H.W. Lee, *Full-Hexacyanometallate Aqueous Redox Flow Batteries Exceeding 1.5 V in an Aqueous Solution*, Adv. Energy Mater. 13 (2023) 2300707, doi: 10.1002/aenm.202300707

[25] C. Sun H. Zhang, *Review of the Development of First-Generation Redox Flow Batteries: Iron-Chromium System*, ChemSusChem 15 (2022) 1, doi: 10.1002/cssc.202101798

[26] https://www.tycorun.com/blogs/news/iron-chromium-flow-battery-one-of-energy-storage-batteries#Application-of-iron-chromium-flow-battery

[27] C. Tai-Chieh Wan, K.E. Rodby, M.L. Perry, Y.M. Chiang, F.R. Brushett, *Hydrogen evolution mitigation in iron-chromium redox flow batteries via electrochemical purification of the electrolyte*, Journal of Power Sources 554 (2023) 232248, doi: 10.1016/j.jpowsour.2022.232248

All-Iron Flow Battery (IRFB) – chemistry first developed by ESS and supported under ARPA-E scheme, in the EU by Voltstorage (DE). All iron flow battery employ only iron at different oxidation states which leads to minimal electrolytes cross-contamination. The reported energy density is 20-30 Wh·L^{-1}, round-trip efficiency is 70% (better at elevated) temperature and the operating temperature range is 5 – 60 °C.[28] There are available solutions for 4-12 h energy storage, that are 20-25 years durable and expected to perform at least 10 000 cycles during life time. The capital cost of 10 kW / 100 kWh system is estimated at about 76 USD/kWh.[29] Water based electrolytes minimize fire risk. This chemistry does not fully decouple energy from power as one of the reactants is metallic iron that is deposited on the negative electrode. Thus the amount of space available there (size of stack) also defines the available energy storage capacity (and not only available power).

Zinc-bromine "flow" version. This type of flow battery is developed by Redflow (AU) and Primus Power (US). The negative electrode is made of carbon felt or more expensive titanium mesh, the electrolyte is aqueous based. Available are products with 60–85 Wh·kg^{-1} specific energy and 15–65 Wh·L^{-1} energy density, 70-80% of round-trip efficiency and cycle life of >5 000 charge cycles. This technology requires full discharge every 1-4 cycles to fully remove zinc from the anode – this is to eliminate dendrite growth which would result in membrane puncture. Water based electrolyte minimize fire risk. R&D is focused on membrane materials, reducing corrosion (bromine is very reactive), cost reduction and upscaling production capabilities. This chemistry does not fully decouple energy from power, as one of the reactants is metallic zinc that deposits on the negative electrode. Thus the amount of space available there (size of stack) defines also the available energy storage capacity.

Sulfur-bromide (SBB), also known as polysulfide-bromine (PSB) battery – two prototype systems at Little Barford Power Station (UK) and Tennessee Valley Authority (US) were never completed due to engineering issues related with upscaling the 10 kW stack to 100 kW. The difficulties were regarding leakages, fractures of endplates, electrodes and PVDF-liner in tanks as well as irreversible oxidation of sulfur to sulfate. The research was later continued by Dalian Institute of Chemical Physics (CN). They developed a 1 kW system operating at 40 mA·cm^{-2} with a roundtrip energy efficiency of 82% using new electrode materials.[30] Nevertheless, the interest in SBB has decreased after 2006, likely due to the problem with sulfur deposition in the porous anode during cycling, and competition from other, readily available chemistries. Currently the interest in SBB is mainly limited to academic research. In 2018-19, SBBs with Li^+ and Na^+ conducting ceramic separators[31,32] have been demonstrated. They showed over 100 cycles durability without noticeable degradation, however they were operated at low current density of ca. 1 mA·cm^{-2} due to the high ohmic resistance of the separator.

Organic redox flow battery is a new concept developed after 2009. A huge variety of organic redox systems is known with a broad range of properties, which still can be extended by chemical modifications of active molecules. This should allow to find an "ideal" redox system. Organic RFB are still under development.

CMblu (DE) is developing an Organic SolidFlow Battery Technology, based on naturally occurring active molecules (the chemistry is not disclosed) stored in solid form in tanks and in contact with aqueous electrolyte that bring them to the reaction cells. The company claim 90% RTE, theoretically unlimited cycle life, high safety and not use critical and rare materials. The technology is intended for stationary energy storage and fully decouples power from storage capacity.[33]

Kemiwatt (FR) is another developer of an organic flow battery technology, also not disclosing details. The company claims capacity retention of 99.99932% per cycle, which, assuming 1 cycle per day would mean that after 20 years of operation (Kemiwatt's targeted lifetime) only 5% of capacity loss is observed. A 10 kW prototype was developed in 2016 and a 20 kW industrial demonstrator one year later. The technology is water

---

[28] https://pv-magazine-usa.com/2021/10/08/iron-flow-battery-tech-shows-early-promise-for-mid-duration-energy-storage/

[29] X. Liu, T. Li, Z. Yuan, X. Li, Low-cost all-iron flow battery with high performance towards long-duration energy storage, Journal of Energy Chemistry 73 (2022) 445, doi: 10.1016/j.jechem.2022.06.041

[30] H. Zhou, H. Zhang, P. Zhao, B. Yi, *Novel cobalt coated carbon felt as high performance negative electrode in sodium polysulfide/bromine redox flow battery,* Electrochimica Acta, 51 (2006) 6304, doi:10.1016/j.electacta.2006.03.106

[31] L. Wang, X. Wang, J. Liu, H. Yang, C. Fu, Y. Xia, T. Liu, *A rechargeable metal-free full-liquid sulfur–bromine battery for sustainable energy storage,* Journal of Materials Chemistry A 6 (2018) 20737 doi:10.1039/c8ta07951j

[32] M. M. Gross, A. Manthiram, *Long-life polysulfide-polyhalide batteries with a mediator-ion solid electrolyte,* Acs Applied Energy Materials 2 (2019) 3445 doi:10.1021/acsaem.9b00253

[33] https://www.cmblu.com/en/technology/

based, safe and use low cost materials.[34] The company declares several containerized systems are currently under test for different applications after which full commercialisation is planned.

Hydrogen-bromine flow battery is developed by Elestor (NL). This technology uses a water solution of hydrogen bromide (HBr) as electrolyte. During charge, H_2 and HBr_3 are generated and stored in a separate tank, or accumulated in the electrolyte. During discharge, the reactions are reversed and the system returns to its initial stage without side reactions. The theoretical energy density of HBr flow battery is 196 $Wh{\cdot}L^{-1}$. Some works report achieving energy density very close to theoretical,[35] but Elestor do not disclose parameters of their system. The RTE of the battery is about 65-75%. The containerized system can deliver 200 kW for 10 h.[36] The company claims high system durability and the cheapest LCoES among all batteries. The active materials are abundant and free of geopolitical risks. Elestor is on the way to commercialise their product.[37]

A number of other chemistries, such as e.g. quinone-bromide are at R&D stage.

The key technical barrier that limits wide market penetration of RFB technologies is the generally low energy density, <50 $Wh{\cdot}L^{-1}$ for most RFB systems. Only a few chemistries such as zinc-based systems exceed this value. Other research items requiring attention are: avoiding dendrite growth on metal anodes, irreversible materials crossover, gas evolution, slow kinetics or corrosion.

The other barrier limiting spread of RFB technologies is cost. For wider deployment, RFB technology has to outperform competing technologies, at least in some aspects. Technical performance is not in favour of RFBs, whereas safety is, hence cost is a key parameter. Due to low market development RFB cost is high, comparable or even higher than that of Li-ion batteries. With market development the cost should decrease, due to effect of scale, automation of production, etc.

To improve the energy density of RFBs, new designs and electrolytes aim to increase cell voltage and “effective concentration” of redox-active materials, including also identification, modification and synthesis of novel redox active molecules. The traditional designs using transition metal species in non-aqueous electrolytes usually take the form of ligand modified inorganic species or metal coordination complexes. They can produce cell voltages >2.0 V, however usually are based on more expensive metals (e.g. nickel, ruthenium and cobalt) and suffer from limited solubility of their complexes leading to low energy density.

Recent investigations target organic active materials soluble in water, and sodium chloride salt as charge shuttle. One of the major challenges is the search for promising redox organic materials with favourable combination of redox potential, solubility, and stability among huge variety of organic molecules. Also, research efforts have been made to tailor organic molecules to enhance their properties, and to novel membranes.[38]

To realise the expected cost benefit over metal-based chemistries, the cost of production of organic redox-active materials needs to be as low as possible, starting from low-cost materials, using simple chemical reactions with high conversion rate, and avoiding purification steps.

Recycling: RFB is a new technology without dominating chemistry, but a variety of possible chemistries. Thus, recycling processes for many chemistries are not well developed yet.

Recycling of electrolytes should be feasible, as electrolytes consist of solutions ready for further chemical processing. Initially recycling processes used in general chemistry sectors would become available, later, with increased maturity, dedicated recycling processes are expected to emerge. Due to its high cost, recycling vanadium is already economically attractive. For other chemistries, the economy of the process needs to be assessed further.

Plastics might constitute a high fraction of the RFB weight. It was demonstrated that reduction or substitution of polytetrafluoroethylene in VRFB should be on the research agenda to decrease the impact of these

---

[34] https://www.youtube.com/watch?v=mRYwPKMUyO0

[35] M. Kuttinger, J.K. Wlodarczyk, D. Daubner, P. Fischer, J. Tubke, High energy density electrolytes for H_2/Br_2 redox flow batteries, their polybromide composition and influence on battery cycling limits, RSC Adv. 11 (2021) 5218, doi: 10.1039/d0ra10721b

[36] https://www.pv-magazine.com/2022/08/31/hydrogen-bromide-flow-battery-for-large-scale-renewables-storage/

[37] https://innovationorigins.com/en/with-a-30-million-investment-elestor-aims-to-take-its-hydrogen-bromine-flow-battery-to-gigawatt-scale-production/

[38] Z. Li, T. Jiang, M. Ali, C. Wu, W. Chen, Recent Progress in Organic Species for Redox Flow Batteries, Energy Storage Materials 50 (2022) 105, doi: 10.1016/j.ensm.2022.04.038

batteries.[39] Recycling of plastics should be technically possible, but the economy of the process requires further assessment.

2.1.3 Metal air batteries (Me-air)

This type of batteries employs redox reactions of metal at the anode and oxygen at the cathode. Oxygen is exchanged directly with the surrounding air, so the electrochemical cell in this design is open. During discharge the metal at the anode is oxidized and oxygen (absorbed from the air) is reduced at the cathode. During charging, metal is electroplated back onto the anode and oxygen is released at the cathode. Those processes are closely related to that of fuel cells and for this reason Me-air batteries are sometimes considered as fuel cells, where metal "Me" is a "fuel". As one of the reactants (oxygen) does not need to be stored in the battery a significantly higher energy density can be achieved, theoretically up to 35 times larger than achievable in commercial Li-ion batteries. **Table 3** shows theoretical parameters of selected metal-air systems.[40,41] In this design the reactions generating electricity depend on oxygen concentration (air supply) and thus the power of the battery can be limited by this factor. When no forced ventilation is available, the battery usually can provide stable current at low power. A pulse work at higher power is also possible as the battery will consume the oxygen already present in the channels/openings. Me-air batteries generally suffer from their low-rate capability, mostly due to slow kinetics of oxygen reactions at the cathode; durability issues, usually due to dendrites formation and corrosion during electrochemical reactions; less developed materials for electrodes, electrolyte additives and separators. Those areas are also the main R&D directions in Me-air technology. Metal-air batteries development profits from general industry technologies development, especially in the area of 3D printing and laser processing. The R&D in the field is mainly driven by potential EV application. Currently the biggest market segments, are supply of low power electronic equipment, aerospace, and military.

Table 3. Theoretical electrochemical parameters of selected Me-air systems. In lines below TRL: parameters obtained from real systems.

system	Li-air	Mg-air	Al-air	Zn-air		Fe-air
capacity (anode, mat. level) (Ah·g^{-1})	3.86	2.21	2.98	0.82		0.96
Voltage (V)	2.96	2.09	2.71	1.66		1.26
Specific energy (Wh·kg^{-1})	5 928	5 238	5 779	1 218		1 080
Energy density (Wh·L^{-1})	7 989	9 619	10 347	6 136		3 244
TRL	4	3	5	6 and 7		6 and 7
Specific energy "Cell level" Wh·kg^{-1*}	800	NA	600-1 000	100-300	300	15
developer	Polyplus (US)	Honda (JP), Seitec (DE)	Phinenergy (IS)	Phinenergy (IS)	Zinc8 (US)	Form Energy (US)
battery type	primary	secondary	secondary	secondary	secondary	secondary
target application	Military, Ship	EV	EV, home	home, grid	home, grid	home, grid

- Battery specific energy as reported by the company; *Source: JRC, 2023*

Li-air battery developed by Polyplus (US) is based on their Li-seawater (Li-water system) battery and is pairing their patented Protected Lithium Electrode with water-based cathode engineered to admit atmospheric air. This construction is claimed to reach >800 Wh·kg^{-1} cell-level specific energy (for a 10 Ah cell) and at pack level, the battery can deliver >500 Wh·kg^{-1}.[42] The same anode technology is used by the company in their Li-S batteries

---

[39] L. Unterreiner, V. Jülch, S. Reith, *Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA)*, Energy Procedia 99 (2016) 229, doi: 10.1016/j.egypro.2016.10.113

[40] S. J. Visco, P. B. Company, L. Berkeley, *Lithium – Air*, 376–383, 2009

[41] L. Yaqoob, T. Noor, N. Iqbal, *An overview of metal-air batteries, current progress, and future perspectives*, J. Energy Storage B 56 (2022) 106075 doi: 10.1016/j.est.2022.106075

[42] https://polyplus.com/product-pipeline/

and has some potential to replace regular graphite/silicon based anodes with a thin lithium metal electrode covered with a solid-state monolithic glass separator conductive for Li^+ ions.

Al-air battery developed by the Phinenergy (IS) is a stackable, easily scalable system. It offers 8 kWh of energy per 1 kg of Al and works with water-based electrolyte. After discharge, when the metallic aluminium is consumed, the system must be “charged” with new metallic aluminium plates, and a fresh electrolyte. The aluminium hydroxide created needs to be removed and recycled (converting into metal Al in the aluminium plant). The technology was tested in India in two cellular antenna sites of local telecom and in Italy together with Ericsson.[43] The tests were considered successful, the system was able to provide power for periods exceeding 10 hours. The company started commercialisation of the system.[44]

An Al-air system was also developed by the same company for electric vehicles. It needs to be hybridised with a small Li-ion battery to cover peak power needs. In 2021 the company started cooperation with Indian Oil Corporation (IN) on commercialisation of this technology. A JV company was set up and prototypes of EVs, trucks and buses were developed.[45] In 2022 the company started collaborating with Hindalco, to produce aluminium plates and recycle aluminium hydroxide.[46]

Zinc-air chemistry has noted increased research interest in recent years, despite being developed since the early 19th century. Since a few decades Zn-air batteries are used as button cells replacing mercury-based cells in small electronic devices. Recent advancements allowed to develop bigger and more powerful batteries targeting mobility and stationary applications. Also this technology is developed by Phinenergy (IS). A Zn-air energy storage system is composed of separate charging, storage, and discharging units, decoupling charging power, storage capacity and discharge power, and allowing to tailor the energy storage system to specific needs. The charge unit is scaled to the power source the battery works with, the storage size is scaled by adjusting the amount of zinc stored and is directly proportional to the energy storage needs, while the discharge unit is scaled to the consumer need for power.[47] This battery type has synergies with alkaline fuel cells, especially regarding the oxygen reduction reaction (ORR) electrode.

A Zinc-air system developed and patented by Zinc8 is called by the company a regenerative fuel cell system, but technically is a Zn-air battery. It consists of an air flow electrode with zinc compartment immersed in a solution of potassium hydroxide. During charging, power is used to generate zinc particles in a zinc regenerator, while oxygen is released to the atmosphere as a by-product. The zinc particles flow to the storage tank and are stored in KOH electrolyte. During discharge, the zinc particles are delivered to the power stack where they react with oxygen to generate electricity and zinc oxide which is stored for subsequent regeneration during charging.

The technology is fully scalable, non-flammable and based on non-toxic materials with low supply risks. It however suffers from limited cycle life, currently lower than that of Li-ion batteries. This is due to the formation of by-products during the discharge process. Another challenge is the relatively slow charging rate of zinc air batteries. Both issues are subject of intensive R&D with some promise of success.

The company claims the investment cost for an 8-h storage system in their technology is about 250 USD/kWh, less than half of VRFB cost and about 20% less than cost of Li-ion system. For longer storage time this cost advantage increases further, e.g. to about 120 USD/kWh for 50 h system.[48] The company expects to produce this system for residential and grid storage applications.

Another developer of a Zn-air battery is AZA Battery (BE) that developed a three-electrode battery controlled by a proprietary battery management system (BMS). AZA battery is composed of a zinc electrode (energy store, consisting of specially treated zinc-oxide) immersed in water-based KOH electrolyte; a dedicated gas diffusion electrode; and third, an auxiliary electrode (metallic mesh coated with proprietary composite) used to charge the battery. This design allows for deep cycles of 100% DoD. The cost of materials at cell level is less than 15 USD/kWh and the total cost of the battery is below 30 USD/kWh at commercial production scale. The battery

---

[43] https://www.bizportal.co.il/capitalmarket/news/article/796653

[44] https://www.bizportal.co.il/capitalmarket/news/article/797464

[45] https://timesofindia.indiatimes.com/auto/news/an-ev-battery-that-doesnt-need-electricity-for-charging/articleshow/81902959.cms

[46] https://economictimes.indiatimes.com/industry/renewables/hindalco-israels-phinergy-partner-to-develop-aluminium-air-batteries-for-evs-in-india/articleshow/92949961.cms

[47] https://phinergy.com/solutions/energy-storage

[48] https://www.zinc8energy.com/technology

does not require cooling, and performance is enhanced in elevated temperatures. The AZA Battery is suitable for stationary energy storage, backup, and mobility applications.[49]

E-Zinc (CA) is another developer of a Zn-air battery. The electrochemical cell consists of a top, charging section and a bottom, discharging section, both immersed in aqueous KOH electrolyte. During charging, metallic zinc is deposited on the electrodes in the charging section. This metal is periodically wiped off the charging electrodes and sinks in the electrolyte into the spaces between the discharging electrodes. During discharging, metallic zinc is dissolved back into the electrolyte and is available for the next charging.

This technology decouples power from energy, allowing low-cost scaling of storage capacity and can be operated in the temperature range from -30 °C to 60 °C. The company claims that the system retains 100% of its usable capacity throughout its lifetime.[50]

An iron-air (Fe-air) battery is being developed by Form Energy (US). In this technology, iron electrochemical oxidation is employed to provide energy and the reverse reaction of iron electroplating during battery charging. The battery “breathes” oxygen from air, consuming it when discharging and releasing it during charge process. The Fe-air technology uses a water-based electrolyte. There is no risk of thermal runaway, no toxic, scarce or costly materials are used, and the battery is easy to recycle. The technology however is characterised by a low-rate capability of approx. 0.01C and RTE significantly lower than half of that observed for Li-ion batteries. Thus, it would require hybridisation with another technology, e.g. Li-ion, to deal with short duration pulses of high power. The Fe-air energy storage system requires significant land use of about 0.15-0.2 ha/MW. Assuming a system storage time of 100 h, this is equivalent to 1.5-2 ha/GWh. The technology is cheap, below 10% cost of the equivalent storage size in Li-ion technology and targeting use for grid applications.[51] In 2018 Form Energy bought all patents of bankrupted NantEnergy (former Fluidic Energy, developer of Zn-air battery). Form Energy developed iron anode and paired it with air cathode acquired from NantEnergy to build its Fe-air battery.[52]

2.1.4 Zn-based batteries (ZBB)

This is a group of battery technologies using zinc as (one of) the main active materials. This grouping is however a bit artificial, as batteries belonging to it employ very different designs, like e.g. Zn-Br redox flow and Zn-O metal-air system. Thus in this chapter we present the zinc based, non-RFB and non Me-air systems, while zinc based flow- and air- technologies are included in the relevant chapters on redox-flow and metal-air batteries. Zinc-carbon and zinc-manganese, both well-known as non-rechargeable batteries of general use (e.g. AA or AAA 1.5 V batteries) will be omitted, and are included in previous reports by JRC. [53, 54]

Zinc as an active material for batteries has several advantages: it is non-toxic, abundant, cheap, and its supply is not exposed to major geopolitical risks. Electrochemically, zinc has a low standard potential of -0.76 V, theoretical capacities of ~800 $mAh{\cdot}g^{-1}$ and ~6 000 $mAh{\cdot}cm^{-3}$,[55] and is stable in aqueous solutions at a wide range of pH. Zinc electrodeposition has a Coulomb efficiency between 90% and 95% on different substrates.[56] Because of its low standard potential, Zn is used as negative electrode in batteries and can be paired with many redox systems on the cathode side leading do to whole range of chemistries and designs. Overall, ZBB are important technologies with the potential to compete with other batteries.

Nickel-Zinc (NiZn) is a long known technology patented by Thomas Edison in 1901.[57] With variable scientific and commercial interest over the history, it is still a potentially useful technology. NiZn batteries have similar

---

[49] https://www.azabattery.com/technology

[50] https://e-zinc.ca/technology/

[51] https://formenergy.com/technology/battery-technology/

[52] https://www.canarymedia.com/articles/long-duration-energy-storage/stealthy-storage-contender-form-energy-reveals-secret-formula

[53] Gonella, S., Bruchhausen, M. and Ruiz Ruiz, V., Available Data and Initial Analysis on Performance and Durability for Portable Batteries of General Use - Preliminary Scenarios for Minimum Requirements, EUR 31231 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-57199-5, doi:10.2760/58194, JRC130387.

[54] Ruiz Ruiz, V. and Bruchhausen, M., Portable batteries of general use: First stakeholder consultation meeting and analysis of survey results, EUR 31464 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-68-01352-6, doi:10.2760/410136, JRC132710.

[55] L. Wang, J. Zheng, *Recent advances in cathode materials of rechargeable aqueous zinc- ion batteries*, Mater. Today Adv. 7 (2020) 100078, doi: 10.1016/j.mtadv.2020.100078

[56] J.-Y. Lee, J.-W. Kim, M.-K. Lee, H.-J. Shin, H.-T. Kim, S.-M. Park, *Effects of Organic Additives on Initial Stages of Zinc Electroplating on Iron*, J. Electrochem. Soc. 151 (2004) C25, doi: 10.1149/1.1627344

[57] T. A. Edison, *Reversible galvanic battery*, United States Patent No. 684,204 Filed by Thomas Edison on 31 Oct 1900

chemistry to nickel-metal hydride batteries, using alkaline electrolyte (potassium hydroxide, KOH) and Zn as the negative electrode while NiOH is the positive electrode. The NiZn battery has a nominal voltage of 1.6 V. Recent improvements allowed to reach a cycle life of 500 cycles at 100% depth of discharge (DoD). With an operating temperature range (discharge) from -20 °C to 50 °C, a power density of 31% higher than for Li-ion batteries, fast charge capability and long shelf life, the technology may be used in stationary, motive and industrial applications, like UPS, specialty and hybrid electric vehicles, start-stop systems, EV charger power buffering, military applications.[58] The batteries do not suffer from thermal runaway and are non-flammable. NiZn cells do not tend to leak, do not spill their content, their production is not CO_2 intensive and they are easy to recycle. The zinc electrode contains no lead, cadmium, or mercury. They also offer a total cost of ownership lower than for Li-ion and lead-acid (Pb-A) batteries (in UPS application). NiZn batteries are commercially available on the market at TRL 9, e.g. from ZincFive[59], that offers modules and systems for backup power, industrial engine starting and micro-grid applications.

Zinc-bromine – "none-flow" designs involve the same chemical reactions and active materials as zinc-bromine RFB batteries, however the design and passive materials are different. The "none-flow" versions were developed by Gelion (AU) and EOS Energy Enterprise (US).

Gelion proposes 1.2 kWh monoblock battery with specific energy of 120 $Wh \cdot kg^{-1}$, round-trip efficiency of >87% and charging quicker than the flow version. The battery has several advantages: the liquid electrolyte is replaced with a gel that is fire retardant, they can work at temperatures 0 - 50 °C, complete discharge to 0 V do not decrease performance and is expected to perform >5 000 cycles of 100% DoD over its life time. Production of batteries can be scaled to gigawatt capacity by adapting existing lead–acid battery factories. The battery is also >95% recyclable.[60] Expected use is in industrial and grid applications. Gelion batteries will be tested for a period of between six months and one year at the 1.2 MW Acciona Energy experimental photovoltaic plant in Tudela.[61] The company R&D focuses on the battery BMS, software development and overall design improvements. The decision on production upscaling is expected in Q2 2024,[62] however, their business model does not foresee batteries manufacturing in-house, but rather licence to partners with existing production capabilities, both Australia internal and overseas. Currently the technology is at TRL 7.

EOS Z3 battery is a Zn aqueous base battery that stores electrical energy through zinc deposition. The system is designed for 3-12 h energy storage, it has a round trip efficiency of about 80-85% (higher with reduced DoD) and a lifetime of 6 000 cycles or 20 years. The battery supports 100% DoD use pattern. The producer claims 91% capacity retention over the first 3 years followed by no-degradation behaviour thereafter. The battery is also tolerant to high temperatures (however, as water-based it cannot be overheated to >100 °C) and after exposure to the temperature of >90 °C it fully recovers after a rest period.[63] The cost was estimated about $250/kWh in Q1 2021. The company is currently developing a containerized solution for grid applications.

The sea-salt battery was developed by Dr Ten (NL/IS).[64] The technology is based on a mix of Na, Zn and Mg salts, additives, and carbon graphite electrodes. This technology is cheap, safe, and easy to maintain and to recycle.[65] The battery has a specific energy of 10-60 $Wh \cdot kg^{-1}$ and a specific energy of 20-70 $Wh \cdot L^{-1}$, and it is in constant improvement. It has proven more than 10 000 operational cycles and more than 60 000 short cycles.[66] The company has already installed multiple demo systems up to 10 kWh. This technology is targeting stationary applications including home storage and off-grid low-cost systems, especially in less developed regions.[67]

The zinc-ion battery (ZIB) technology is developed by Salient Energy (CA). The technology is based on aqueous electrolyte, provide power similar to Li-ion batteries and lifetime 15-20 years. The company claims that

---

[58] https://zincfive.com/wp-content/uploads/2021/10/MKT-0006-ZincFive-Monobloc-Data-Sheet-Rev-6.0.pdf

[59] https://zincfive.com/company/

[60] https://www.pv-magazine.com/2021/11/03/zinc-bromide-battery-for-stationary-energy-storage-from-australia/

[61] https://gelion.com/pv-magazine-gelion-to-store-solar-power-at-accionas-testing-field/

[62] https://uk.advfn.com/stock-market/london/gelion-GELN/share-news/Gelion-PLC-Lithium-Sulfur-IP-Acq-Innovation-Chal/90481244

[63] https://www.eose.com/technology/

[64] https://www.drten.nl/zeezout-batterij

[65] B. Homan, D. F. Quintero Pulido, M. V. ten Kortenaar, J. L. Hurink, G. J. M. Smit, *Influence of co-depositor materials and modification of substrate on the formation of dendrites on the anode of a zinc-based secondary battery*, Sustain. Energy Technol. Assessments, 42 (2020) 100820, doi: 10.1016/J.SETA.2020.100820.

[66] D. F. Quintero Pulido, M. V. Ten Kortenaar, J. L. Hurink, G. J .M. Smit, *The Role of Off-Grid Houses in the Energy Transition with a Case Study in the Netherlands*, *Energies*, 12 (2019) 2033, doi: 10.3390/en12102033

[67] D. F. Quintero Pulido, *Energy Storage Technologies for Off-grid Houses,* 1st ed. Enschede, The Netherlands: University of Twente, 2019, doi: 10.3990/1.9789036548267

production of their batteries causes CO_2 emission of 66% lower than production of Li-ion batteries and the expected price is 30-50% lower.[68] The company works on demonstration of their technology.

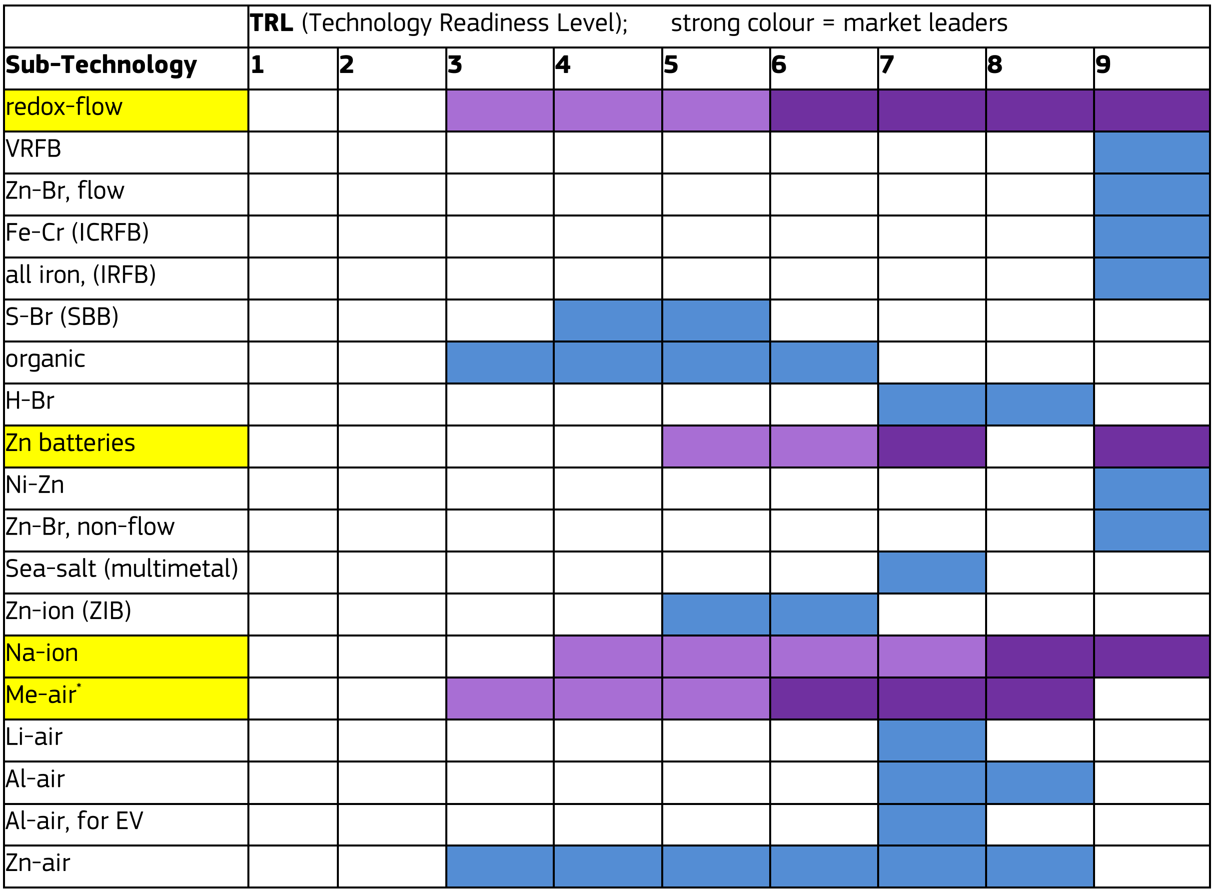
Zinc battery outlook: there are many start-ups (e.g. Dr Ten, ZincFive among others) working on zinc battery technologies, where significant R&D work on the cathode active material is needed. They are however at early stage of development, focusing on the main R&D before prototyping and thus not yet ready for pilot-scale or demonstration (TRL<4).

On the long term, companies need to demonstrate that there is a need in the market for Zn based batteries beyond the demonstration phase. For Zn batteries, scale up of the manufacturing process, including modularisation and automatized production, still needs to be demonstrated.

2.1.5 TRL levels

In **Table 4** a summary of TRL levels of analysed technologies is presented. With dark violet – TRL achieved by technology leaders is marked, with light violet – TRL level achieved by other technology developers, blue – represent TRL achieved for sub-technology.

Table 4. TRL levels of battery technologies



	TRL (Technology Readiness Level); strong colour = market leaders								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
redox-flow			▨	▨	▨	🟪	🟪	🟪	🟪
VRFB									🟦
Zn-Br, flow									🟦
Fe-Cr (ICRFB)									🟦
all iron, (IRFB)									🟦
S-Br (SBB)				🟦	🟦				
organic			🟦	🟦	🟦	🟦			
H-Br							🟦	🟦	
Zn batteries					▨	▨	🟪		🟪
Ni-Zn									🟦
Zn-Br, non-flow									🟦
Sea-salt (multimetal)							🟦		
Zn-ion (ZIB)					🟦	🟦			
Na-ion				▨	▨	▨	▨	🟪	🟪
Me-air*			▨	▨	▨	🟪	🟪	🟪	
Li-air							🟦		
Al-air							🟦	🟦	
Al-air, for EV							🟦		
Zn-air			🟦	🟦	🟦	🟦	🟦	🟦	

* Coin-cells for small electronics not included; *Source: JRC, 2023*

2.1.6 Hybridisation of batteries with other energy storage technologies

Beyond their ability to store electrical energy, batteries also offer very short ramp-up times. This makes them very attractive for use in grid supporting applications, also in combination with other energy storage (or generation) methods. Batteries can start to deliver energy on request and reach full power within one millisecond, which cannot be achieved by many other energy storage technologies (see **Table 5**). Thus, adding a battery component to an existing, or construction of hybrid energy storage system is an attractive option that will likely be used more widely in the future. The battery part can provide energy immediately after the need

---

[68] www.rechargenews.com/transition/zinc-ion-batteries-up-to-50-cheaper-than-lithium-ion-with-no-raw-materials-concerns/2-1-939768

for it was registered, giving time to ramp-up the (usually) bigger and slower component, e.g. a pumped hydro[69] or compressed air system. In such combination, slow systems could be used e.g. in frequency regulation, following the grid demand and balancing actual energy generation but also in back-up power, including black start capabilities.[70] Batteries can be also added to existing power plants, independent of the plant's technology, increasing flexibility of operation and reducing energy losses during grid balancing.

Table 5. Overview of characteristics of main energy storage technologies

	time of storage	time to reach full power	rate of ramp-up	energy storage
Li-ion battery	hours	0.001 s	6 000 000 %·min^{-1}	electrochemical
Na-ion battery	hours	0.001 s	6 000 000 %·min^{-1}	electrochemical
redox-flow battery	hours-months	0.1 s	60 000 %·min^{-1}	electrochemical
pumped hydro	hours-months	10-500 s	10 %·min^{-1}	mechanical
compressed air	hours	500 s	10 %·min^{-1}	mechanical with thermal management
flywheel	seconds-minutes	0.001 s	6 000 000 %·min^{-1}	mechanical, inertia
hydrogen + fuel cell	seconds-minutes	immediate, fast decrease	-	"electrochemical inertia"
	hours-months	100 – 10 000 s	40 %·min^{-1}	electrochemical + fuel storage
coal power plant	seconds	immediate, fast decrease	-	spinning reserve
	months	5 000 – 20 000 s depending on state at start	<4 %·min^{-1}	fuel storage
natural gas power plant	seconds	immediate, fast decrease	-	spinning reserve
	months, NG storage limit	2 000 – 10 000 s depending on state at start	15 %·min^{-1}	fuel storage
nuclear power plant	seconds	immediate, fast decrease	-	spinning reserve
	practically unlimited	4 000 – 40 000 s design depending[71]	2.5-10 %·min^{-1} [72]	fuel storage
wind	seconds	immediate, fast decrease	-	mechanical, inertia

Source: JRC, 2023

In hybrid systems, the battery needs to be dimensioned with a power similar to that of the second component of the hybrid system, and energy storage capacity at least allowing to supply energy until the second component is ready to provide required power – in "UPS mode"; or to be able to cover short term grid variability and power spikes while the second source follow slow grid profile, e.g. covering evening peak – in "hybrid vehicle regime". Using a shared grid connection allows for better utilisation of the existing infrastructure.

It is observed that batteries integrated with solar PV installations have ratio of battery storage capacity to PV installation power of about 2.5 MWh/MW, indicating an average storage time of 2.5 h. In case of batteries integrated with wind generation sources, this ratio is usually much lower.[73] This indicates batteries serve

---

[69] Quaranta, E., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., and Grabowska, M., *Clean Energy Technology Observatory: Hydropower and Pumped Hydropower Storage in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2023

[70] power plants to generate energy require some supply of energy from the grid; if the grid is down, the power plant cannot be started

[71] https://www.eia.gov/todayinenergy/detail.php?id=45956

[72] https://www.powermag.com/flexible-operation-of-nuclear-power-plants-ramps-up/

[73] RhoMotion, *Battery Energy Stationary Storage Outlook, Q1 2023*, 2023

different purposes in both cases. In PV parks, they are used to shift energy from the peak generation hours to peak demand hours, while in wind farms batteries are used to smoothen the short-time variation of the wind source at a time frame much below one hour.

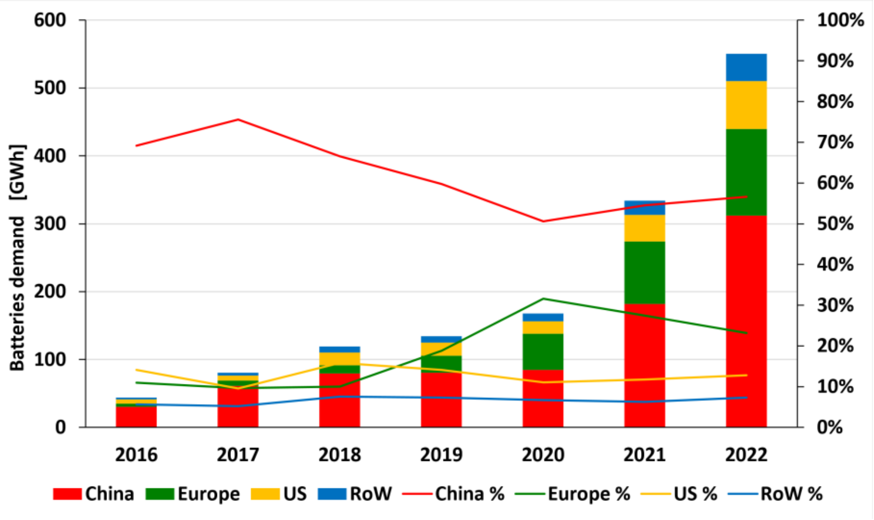
Another technology that emerged recently is hybridisation of energy storage in battery and production of green hydrogen via water electrolysis. The technology is called "battolyser" and emerged from nickel-iron battery technology. The battery when fully charged do not need to be disconnected, but automatically start splitting water into hydrogen and oxygen. This capability allow to follow the source generation profile and no curtailment due to high state of charge of battery. The technology developer, Battolyser Systems (NL) claims 80% efficiency in electrolyser mode at nominal capacity and no electrochemical degradation. The company is setting up their first production line aiming at production capacity of 50 MW / 50 MWh in 2024. In the same time a second factory of 1 GW / 1 GWh production capacity is being developed in Rotterdam. It is expected to commence operations in 2025.

2.2 Installed Capacity and Production

Installed capacity: batteries for EV applications

The capacity of all Li-ion batteries installed in 2022 worldwide in vehicles reached 550 GWh and rose by 65% from 2021 (about 330 GWh). Most of the demand comes from China, Europe being second, followed by the US (see **Figure 1**). Europe was gaining market share in the period 2019-20, mainly from China, but also from the US. In last two years, however, the tendency reversed, partially compensating earlier gains.

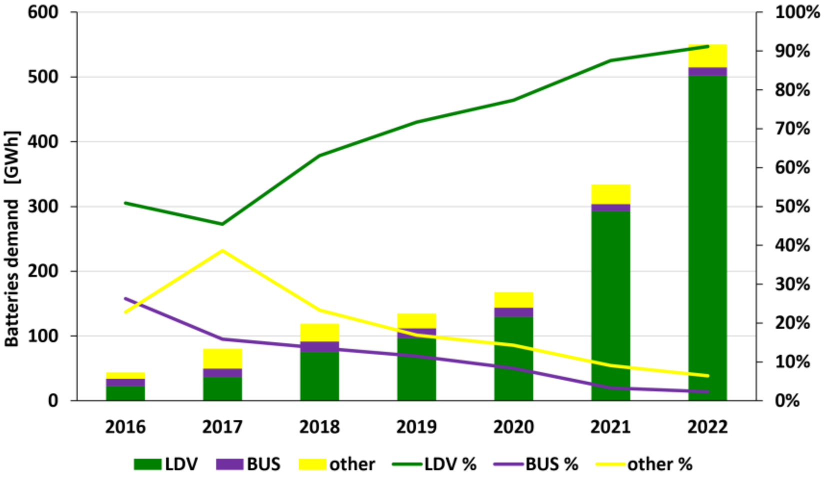
Figure 1. Li-ion automotive batteries demand per region (bars, left axis), and share of global demand (lines, right axis).



Source: JRC based on IEA data.

This growth was mainly driven by the increase of passenger cars production and a growing average size of battery installed in a vehicle (see **Figure 2**).

Figure 2. World-wide batteries demand per application.



Source: JRC based on IEA data.

The global Li-ion battery manufacturing capacity reached about 1.5 TWh/y in 2022 and the average utilisation rate was close to 35%, down from 43% in 2021.

Future demand is expected to reach 1.5 TWh in 2025 and 3-3.5 TWh in 2030.[74] To satisfy this demand about 50-65 new gigafactories of 35 GWh/y production capacity each, would be needed by 2030 in addition to today's battery production capacity. This demand will still be dominated by personal and light duty vehicles, accounting for around 90% of it. The expected in 2030 battery demand from buses is about 120 GWh (3-4%), from two/three-wheelers about 160 GWh (4-5%) and from trucks some 80-170 GWh (2-5%) depending on the analysed IEA scenario.

The regional split shows continued leadership of China with slightly reduced advantage in long term, the EU and US following roughly the same path and reaching about half of the size of Chinese market and RoW growing to roughly half of the EU or US market size by 2050.

Commercialisation of Na-ion batteries progresses fast, there are nearly 30 Na-ion battery manufacturing plants currently operating, under construction or in planning phase, almost all in China. Their combined yearly production capacity is estimated at over 100 GWh, comparable to the global Li-ion production capacity in 2016.[75]

Car sales

The statistical data presented in this chapter are in the vast majority cited from the IEA "Global EV outlook 2023" report,[75] unless indicated otherwise.

In 2022, sales of electrified vehicles (BEV + PHEV) exceeded 10 million globally (+55% relative to 2021) despite a 3% drop in total car sales. This translates into an increase of the share of electrified vehicles in total sales from 9% in 2021 to 14% in 2022. BEVs were accounting for more than 70% of these sales. The stock of electrified vehicles reached 26 million in 2022 rising by 60% from 2021, with BEVs accounting for about 70% of this number.

Sales of electrified vehicles in China in 2022 reached almost 6 million (BEVs 4.4 million, +60%; PHEVs 1.5 million, +200%), leaving far behind other regions. The registrations of electrified vehicles in China was also close to 6 million (60% of global registrations) and the stock of electrified vehicles reached 13.8 million exceeding 50% of the global fleet. The share of electrified vehicles in the Chinese market reached 29% in 2022 comparing to 16% in 2021, reaching the 2025 target of 20% share in the sales (defined as New Energy Vehicles, NEVs) already three years ahead. China also targets a 50% share of NEVs sales by 2030 in highly polluted regions and a 40% share country-wide.

This growth likely results from strong purchase incentives, initially planned until end of 2020 and then extended to the end of 2022 due to Covid-19. It is not fully clear, if the share of NEVs in the car market will remain above

---

[74] V. Irle, EV Volumes, EV sales review for 2022-2023, AABC Europe 2023, Mainz, Germany

[75] IEA *Global EV outlook 2023*, 2023

the 20% target in 2023. The sales from the Q1 2023 are more than 20% higher comparing to Q1 2022 suggesting continued growth. It is expected that the Chinese Market will grow until 2040, and then stabilise at about 40 million vehicles a year with full electrification of the market of passenger vehicles. The market of commercial vehicles is expected to reach full electrification in 2045.[76]

In China several car producers announced EVs powered by Na-ion batteries, e.g. BYD (Seagull, range 300 km, price 11 600 USD), VW-JAC JV (Sehol EX10, range 250 km). BYD plans to progressively equip with Na-ion batteries all its models cheaper than 29 000 USD. First EVs with Na-ion batteries should be placed on the market in 2023-24, bringing the technology readiness level to 9. In 2022, this technology was still at TRL6 (prototype tested in intended environment, expected performance achieved) and in 2021 at TRL 4 (small prototype tested in laboratory conditions).

In Europe[77], sales of electrified vehicles reached 2.7 million in 2022, increasing by 15% relative to 2021, which is significantly less than the increase by 65% in 2021. BEV sales rose by 30%, while PHEV sales shrunk by 3%. The dynamics of the whole European car market was recorded at -3% relative to 2021. Europe accounted for 10% of global increase of the electrified vehicles market and kept its position of global second largest market (25% of global market), behind China (60%) and before the US (10%).

The share of BEVs in total vehicles registrations in the EU in 2022 reached 12.1%, 3 percent points more than in 2021. The share of PHEVs has increased by 0.5 percent point reaching 9.4%. Together, electrified vehicles correspond to 21.5% of the total new car registrations in EU. In 2022, China has significantly left behind the EU in this statistics after a jump from 18% in 2021 to 29% in 2022. The EU has slightly increased the advantage over third US (13% in 2021 to 13.5% in 2022).

In the US, sales of electrified vehicles reached about 1 million, increasing by 55% relative to 2021. This number was pushed by BEVs increase by 70%, (nearly 800 000 pieces) and much less dynamically growing sales of PHEVs that rose by 15% (around 200 000 vehicles). This growth was observed despite in 2022 a 8% drop relative to 2021 in total car sales was recorded, and despite the drop in the US was significantly stronger than the global average of -3%. United States accounted for 10% of the increase of global sales of electrified vehicles in 2022. The total stock of electrified cars reached 3 million, 40% more than in 2021 and accounted for about 10% of the global stock. The share of electrified vehicles in the market reached 8% in 2022 increasing from 5% in 2021.

The acceleration in sales growth observed in 2022 is likely to continue in 2023 and beyond, profiting from the US policy support, namely the Inflation Reduction Act (IRA) that has triggered global producers to expand their US manufacturing capabilities. In the period Aug 2022 - Mar 2023, global EV and battery producers announced investments of 52 billion USD in US, half of this amount for battery manufacturing, and the rest equally split between battery components and EV manufacturing. Altogether, companies announced USD 75-108 billion investments in US, including tentative commitments since adoption of IRA. As an example, Tesla plans to relocate battery manufacturing part of its Giga Berlin plant to Texas.[78] However, the recent news is that that Tesla experience technical issues with their dry process to make electrodes and thus want to focus on Giga Texas, putting battery part of Giga Berlin (that suffered from delays) on hold. This news do not stress IRA and energy cost aspects. Anyways, Tesla moves battery production equipment except that for electrode production to the US.[79]

The 2021 forecasts of 9 million units for global market with >50% share of China in 2022 appeared underestimated, especially for China, confirming faster growth of the Chinese market than estimated earlier.[80]

Summary of EV market growth is presented in **Figure 3**. The green bars depict electrified vehicles market (vehicles sold) in 2022, see bottom axis; blue bars – electrified vehicles market in 2021, bottom axis; violet bars – total vehicle market change in 2022 in the region in respect to 2021, top axis; green numbers next to the graph represent the change of electrified vehicles market in 2022 in respect to 2021.

---

[76] Mark Hsueh-lung Lu, *In depth analysis of the Chinese xEV battery industry*, AABC Europe 2023, Mainz, Germany

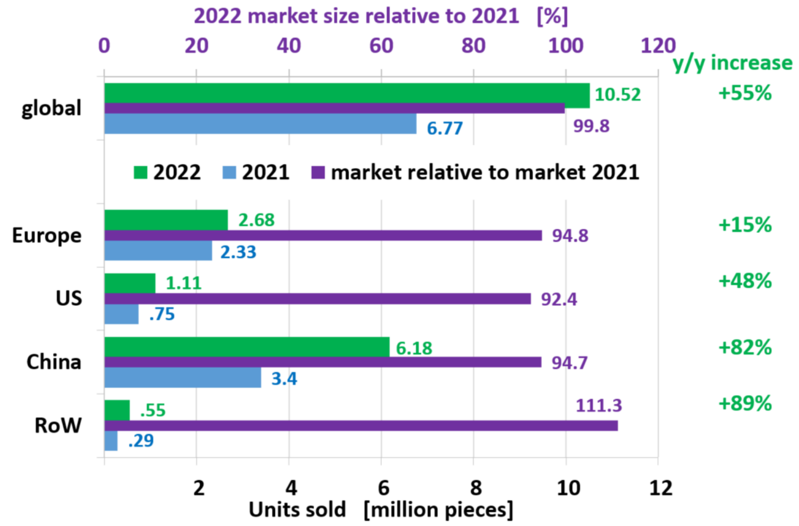
[77] IEA methodology include EU countries, Iceland, Israel, Norway, Switzerland, Turkey and UK

[78] https://insideevs.com/news/612537/tesla-focus-texas-shift-away-berlin/

[79] https://electrek.co/2022/10/14/tesla-into-issues-building-battery-cells-gigafactory-berlin/

[80] M. Bielewski, A. Pfrang, S. Bobba, A. Kronberga, A. Georgakaki, S. Letout, A. Kuokkanen, A. Mountraki, E. Ince, D. Shtjefni, G. Joanny, O. Eulaerts, M. Grabowska, *Clean Energy Technology Observatory: Batteries for energy storage in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/808352, JRC130724.

Figure 3. Electrified vehicles market growth in selected regions.

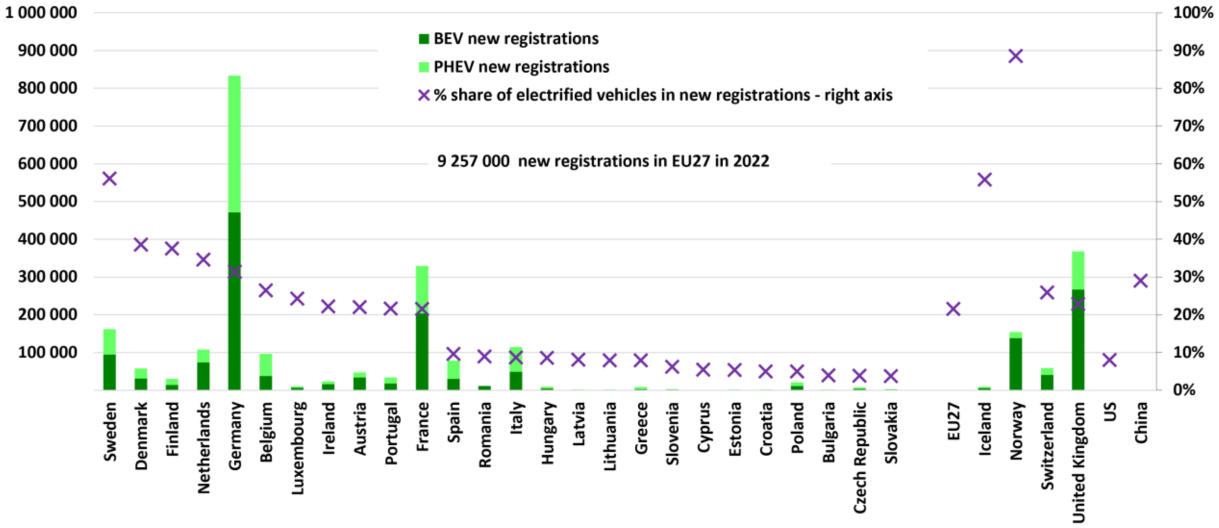


Source: JRC based on EVvolumes data.

The EU registration data of new vehicles (**Figure 4**) indicate that the trend of mobility electrification is continued, especially for BEVs. In terms on absolute numbers DE remain the EU leader, followed by FR, SE and IT, while in market share terms the leader is SE, followed by DK, Fi and NL – both rankings remain unaltered from last year. The division between BEVs and PHEVs has clearly shifted to BEVs, giving them 56% share in the new registrations and faster growth. This tendency is observed in most MSs, especially those with more developed markets. Only in a few markets: FI, BE, ES, IT, HU, GR and SK PHEVs are preferred over BEVs. Together they are 7 MS comparing to 12 in 2021, but usually also in their case the ratio became more favourite for BEVs.

The EU seem to be on track to meet 2021 expectations regarding further growth of electrified passenger cars and light duty vehicles sales. Those are: 3.5 million vehicles in 2025 (31% of all vehicles in this class sold in 2025), 7 million in 2030 (55%) and about 11 million in 2040 (87%).[81]

Figure 4. 2022 sales of electrified vehicles in the EU member states and selected world markets.



Source: JRC based on ACEA data.

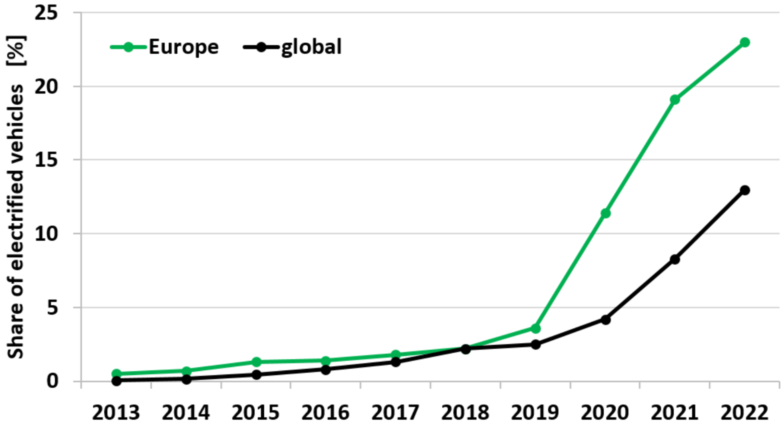
Time evolution of share of electrified vehicles in passenger car sales is presented in **Figure 5**. It shows a dynamic growth since 2020, both globally and in Europe[82]. The rate of the growth trend is higher for Europe, especially in 2020 and 2021, in 2022 the rate of growth has decreased. At global scale the rate of increase keep rising.

---

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

[82] EVVolumes define Europe geographically, Russia and Turkey are not included to Europe statistics

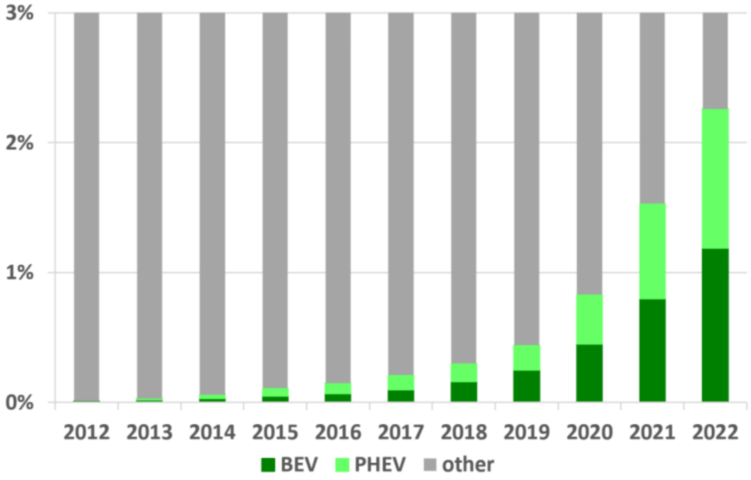
Figure 5. Share of electrified vehicles in passenger cars sales – global and Europe



Source: JRC based on EVvolumes data.

European Alternative Fuels Observatory (EAFO) reports 287 million registered passenger cars (M1 and N1 vehicle categories[83]) in the EU in 2022; out of this, 3.28 million BEVs and 2.74 million PHEVs which correspond to 1.19% and 1.07% respectively of the total number of registered M1 and N1 cars in the EU.[84] Evolution of this number since 2008 is shown in **Figure 6**.

Figure 6. Evolution of BEV and PHEV share in M1+N1 car stock in EU



Source: JRC based on EAFO data.

The latest projection of demand for batteries from the EV industry, that was presented during AABC 2023 conference showed expectations of 1.5 TWh in 2025 and 3.4 TWh in 2030.[74]

In 2022, the storage capacity of batteries of all registered electrified cars in the EU reached almost 220 GWh, assuming an average battery capacity of 55 kWh for BEVs and 14 kWh for PHEVs. By 2030, this number is expected to reach at least 1.5 TWh of batteries capacity in more than 50 million cars according to adopted policy scenarios.[85,86]

It should be noted that on the 2022 list of global top 20 producers of electrified light vehicles (**Table 6**, rank by sales), 10 places are occupied by Chinese producers, including first one (BYD). The Chinese producers note also the highest growth rates, usually above 100% year-to-year.

---

[83] https://alternative-fuels-observatory.ec.europa.eu/general-information/vehicle-types

[84] https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27

[85] Policy scenarios for delivering the European Green Deal, Fit for 55 package, European Commission, 2021

[86] central MIX scenario of the Fit for 55 proposals

Table 6. Global sales of electrified light vehicles in 2022 by OEM / OEM group

	company	global sales [million]	EV [%]	PHEV [%]	change y/y
1.	**BYD**	1.9	50	50	+211%
2.	**Tesla**	1.3	100	0	+40%
3.	**VW**	0.9	70	30	+10%
4.	**GM-Wuling**	0.6	95	5	+13%
5.	**Stellantis**	0.5	60	40	+34%
6.	**Hyundai**	0.5	80	20	+43%
7.	**BMW**	0.4	50	50	+32%
8.	**Geely**	0.4	85	15	+251%
9.	**Mercedes-Benz**	0.4	50	50	+20%
10.	**Renault-Nissan-Mitsubishi**	0.4	85	15	+16%
11.	**GAC**	0.3	100	0	+130%
12.	**SAIC**	0.3	80	20	+8%
13.	**Chery**	0.3	95	5	+136%
14.	**Volvo-Polester**	0.3	45	55	+15%
15.	**Changan**	0.3	90	10	+134%
16.	**Dongfeng**	0.3	95	5	+137%
17.	**Ford**	0.2	55	45	+55%
18.	**Hozon**	0.2	100	0	+113%
19.	**CHJ**	0.1	0	100	+49%
20.	**Great Wall**	0.1	80	20	-4%

Source: EV Volumes data.[87]

Capacity installed: e-buses and heavy-duty vehicles

The statistical data presented in this chapter are in the vast majority cited from the IEA "Global EV outlook 2023" report,[75] unless indicated otherwise.

In 2022, global market of electric buses was almost 66 000 units, 28% less than in 2021 and representing 4.5% of the total global bus market. The global fleet of e-buses exceeded 800 000 units and 3% of the total bus fleet. Thus, the bus sector was the most electrified segment of the road transport. The global electric bus market is expected to reach 300 000 in 2025 and 390 000 in 2030.[88] It is also expected that the fleet of electric buses will reach 1.4 million in 2025 (in STEPS scenario, about 5% of the total bus fleet) and 2.7-3.0 million in 2030 (in STEPS and APS scenarios respectively, about 10% of the total bus fleet).

China continued its domination with 54 000 (82% of global e-bus market, 18% of total bus market in China) units sold, and significant export to Latin America, North America and Europe.

Europe with about 5 000 units sold (40% increase relative to 2021 and 9% of the European bus market) was scored second and the US third (2 000 units, 2% of the US market).

Based on EAFO data,[89] in the EU in 2022 new registrations (M2&M3) reached 3756 units, 914 (32%) more than in 2021 and accounting for 12.7% of the bus market (10.6% in 2021). Finland recorded highest share of electric buses in their market, followed by Netherlands, Denmark and Sweden. France lost its first position it held in 2021. The EU stock of e-buses reached 12 551 units, 40% more than in 2021, which represents 1.4% of the total EU bus fleet. In absolute terms, the leading member states were: DE (2149), FR (1973) and NL (1451).

---

[87] www.ev-volumes.com

[88] IEA Global EV outlook 2022, 2022

[89] https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27/vehicles-and-fleet

In 2022, the global market of electric trucks was about 60 000 units of medium- and heavy-duty trucks, which is about 1.2% of all truck sales. The fleet of e-trucks reached about 320 000 vehicles. It is expected that by 2030 it will reach 3.5-4 million (3-4% of the total fleet).

China continues to dominate production and sales of electric trucks. The Chinese market accounted for sales of about 52 000 of electric medium- and heavy-duty trucks, which is 3.9% of total truck sales in China and about 85% of global sales. Sales in Europe were estimated at 2 800 units (0.5% share in the European trucks market), in the US at 3 100 units (0.4%) and in the RoW 2 300 units (0.1%).

EU electric heavy duty (N2+N3, EAFO data[89]) vehicle registrations reached in 2022 1 658 units (31% more than in 2021, 0.6% market share). The EU stock of heavy duty vehicles is 6.4 million units, out of those 3 854 (0.06%) are electrified. Germany runs the biggest fleet of electrified N2&N3 trucks in the EU with 2 384 units (62% of total EU fleet). Second place is occupied by Netherlands (362 units, 9.4%) followed by Sweden (242 units, 6.3%), France (221 units, 5.7%) and Spain (203 units, 5.3%).

Capacity installed: maritime applications

The total number of battery propelled (pure electric, plug-in and hybrid) ships in the EU (in operation and ordered as of 2022) reached 143, almost 25% of the world fleet of 578 vessels. The global leader is Norway with 251 vessels. Most often, these battery propelled ships are car/passenger ferries (257 worldwide), offshore supply ships (73 worldwide) and "other purpose" ships (152).[90]

No aggregated information on the capacity of installed batteries or chemistry is available.

Capacity installed: stationary battery energy storage

Global situation

Global installations of BESS exceeded 76 GWh in 2022, 98% more than in 2021. The cumulative installations reached almost 150 GWh, also doubling from 2021. The observed trends suggest similarly fast growth of the market in 2023. In the same time, the projections of 2023 market size increased by more than 50 GWh compared to analogous projections made just one quarter ago. This indicates accelerating development of the market. Current market expectations indicate 240 GWh in 2025, 411 GWh in 2030 and 860 GWh in 2040.

In 2022, the Li-ion technology was the dominating chemistry in BESS with a market share of 81%, Pb-A took 16% and flow batteries accounted for about 1%. RhoMotion expect in 2023 further replacement of Pb-A batteries by other technologies. They also expect a peak share of Li-ion technology in the market in 2023, while in longer term, Na-ion and flow batteries will increase their contribution.

China was the market leader in 2022 with almost 60% share of the global market and almost 43 GWh new installations. Over 30 GWh of those were placed on the grid installations market. Comparing this to 3.1 GWh in 2021, almost a 10-fold jump within one year is observed. The US with about 15 GWh of new installations and a 20% share of the global market took second place. The EU share in the global market was about 12%, with slightly more than 9 GWh of installed capacity and 4.5 GW of power.[91] The global market of battery energy storage systems (BESS) is anticipated to double every 3 years until 2040.

Grid BESS market

In 2022, most installations were done on grid systems (front of the meter) that took 60% of the total BESS market. This domination of grid connected systems is expected to even strengthen in the coming years.[73] Li-ion chemistry accounted for 95% (93% in 2021) of grid BESS installations and among Li-ion chemistries, LFP was most used with 85% market share (50% in 2021). The share of Pb-A batteries dropped from 3% in 2021 to 2% in 2023 and the share of flow batteries increased from 1% to 2%. The role of RFBs, Na-ion and other Na-based chemistries (Na-S, ZEBRA) will increase in the future, pushing the Pb-A technology out of the market and reducing the domination of Li-ion, e.g. in begin 2022 the Japanese grid operator approved a Na-S based system (from NGK) to provide balancing services including frequency response. [92]

---

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

[91] https://ease-storage.eu/publication/emmes-7-0-march-2023/

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

The average duration[93] of storage systems installed in 2022 was slightly shorter than in 2021, 2.1 h vs 2.4 h, however in long term this parameter increases and about 3 h average duration is expected in 2040. Currently longest average duration systems are installed in the US (2.7 h), in China (2.0 h) and shortest in the EU (1.6 h).

The projected BESS market for 2030 increased from 150 GWh in 2021 to 283 GWh in 2022, analogously the projected market for 2040 has increased from 426 GWh to 594 GWh.[73,94]

Behind the meter (BTM) BESS market

While in 2021 most of installations (60%) were behind the meter (BTM) systems, in 2022 the ratio has reversed and BTM systems accounted for 40% of all BESS installations. Li-ion chemistry accounted for about 59%, Pb-A for 40% of the installations on BTM market, other technologies contributing only marginally. Pb-A is still the technology of first choice for uninterrupted power supplies (UPS) with a market share of about 60%, however in other areas of the market Pb-A is further displaced by other battery technologies, mainly Li-ion.

The projected BTM market for 2030 increased from 99 GWh in 2021 to 127 GWh in 2022, while the expectation for 2040 has decreased from 277 GWh to 265 GWh. Also the trends in chemistries market shares show some changes: less dominating Li-ion chemistry – 59% now (2022), 83% in 2030 and 81% in 2040 instead of 70% last year (2021), 89% in 2030 and 84% in 2040; more space for Pb-A technology 40% now (2022), 11% in 2030 and 2% in 2040 instead of 30% last year (2021), 1% in 2030 and 0% in 2040; and slower development of Na-ion technology in 2030 time frame – 5% instead of 8% projected in 2021.[73,94]

Among Li-ion chemistries, LFP will be dominating – here the expectations from 2021 were significantly increased and they are: 60% LFP market share now (2022), 70% in 2030 and 76% in 2040 instead of 37%, 57% and 65% respectively expected in 2021. This leaves less space for other chemistries, mainly NMC811+ and NMC622, without significant changes in ratio between them.

Europe

In 2022 the EU market of BESS installations reached 4 500 MW / 7 500 MWh (**Table 7**). Europe contribute to the global market of energy storage with a share of 9% in 2022. In the long term, the EU share is expected to slightly increase and reach about 15% in 2040.

Table 7. 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

Source: EASE/EMMES 7.0

The EU has a well-developed electricity grid and thus 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 changing the situation. Anyway, it is not projected that the EU market would play leading role in global BESS installations.

In EU, Germany has the largest number of home storage systems installed every year. Over 70% of residential solar installations include a battery, thanks to subsidies provided by German federal states, typically ranging EUR 200–300 per kWh. Germany accounts for two-thirds of the EU residential battery storage market.[95] The second biggest market is Italy.

---

[93] 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).

[94] RhoMotion, *Battery Energy Stationary Storage Outlook Q1 2022*, 2022

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

Na-ion projects

There is not a lot information on Na-ion technology deployment, as it is a new technology just entering the markets and most of interest in it comes from China.

Here some examples of demonstration Na-ion based BESS systems:

In Jul 2023 a 5 MW / 10 MWh project was launched at Qingdao, China. The Great Power, a battery technology company is provider of Na-ion batteries, as part of their technology commercialisation process. Qingdao Beian Holdings and Noan Technology Co are partners in the project. The energy storage system will support data centre and help regulate grid infrastructure.[96]

In Nov 2023 LiNa (technology provider) Energy in cooperation with ion Ventures and HORIBA MIRA completed a 1 kW / 1 kWh demonstration project at Nuneaton, UK. It has successfully proven potential of Na-ion batteries use in energy grid frequency regulation via Dynamic Containment, which is based on rapid injection and absorption of power.[97]

RFB projects

Some expectations published in 2018 regarding the market share or RFBs reaching about 50% of the stationary BESS market[98] did not materialise. Li-ion batteries remain the dominant technology for BESS, while RFB are still expected to penetrate more this market in the future.

China is continuing deployment efforts of RFBs and construction of the largest-to-date VRFB energy storage installation, 200 MW / 800 MWh, is advancing in Dalian. The first half of the system was put into operation in 2022, the second half might come in future – now the statements are much less definitive that in the past.[99]

Other countries, especially Australia and US, also deploy large scale VRFB storage facilities, e.g. Port Pirie (AU) 2 MW / 8 MWh,[100] San Juan Island (US) 2.1 MWh.[101]

In June 2023, the LEAG, a major German energy provider, signed an initial agreement with ESS to deploy their long-duration energy storage using iron flow battery technology. The companies agreed to build a 50 MW / 500 MWh system at the Boxberg Power Plant site, expected to be operational in 2027. The resulting 50 MW / 500 MWh module will become a standardized building block in LEAG's plan to deploy 2-3 GWh of storage at their power plant locations.[102]

A demonstration project of 30 MWh iron-chromium RFB (ICRFB) using a container-based design is being developed at Lion Creek Co. Ltd. (HK) (2021 info available). A single 20 foot ISO container can deliver 250 kWh at 35 kW power. Two 40 foot ISO containers hosting an ICRFB, hybridised with a 200 kW, 100 kWh Li-ion battery, can provide 1 100 kWh, at 330 kW. Larger projects might be designed using multiple such 1.1 MWh units. The system cost is lower than 100 $/kWh, and the cost of energy storage using this system is less than $0.02/kWh.[103]

In Feb 2023, China's first megawatt scale ICRFB energy storage demonstration project was successfully tested and approved for commercial use. The project is composed of 34 domestically made "Ronghe 1" battery stacks and four groups of storage tanks, forming a 1 MW / 6 MWh electricity storage system. Currently this is the largest ICRFB in the world.[104]

In Feb 2023, CMBlu (DE) set up a Joint Venture with UNIPER to run a 1 MW / 1 MWh, 2-year long pilot project at the Staudinger power plant in the Rhine Main Area and qualify the Organic SolidFlow battery technology for commercial operation. Should this pilot be considered successful, a 250 MWh commercial system is planned.[105] The company also signed a cooperation agreement with the Governor of Burgenland to set up a 100 MW / 300 MWh system to "make the Burgenland in Austria "energy self-sufficient" by 2030".[106]

---

[96] https://www.energy-storage.news/world-first-grid-scale-sodium-ion-battery-project-in-china-enters-commercial-operation/

[97] https://www.lina.energy/2022/11/16/key-milestone-for-lina-energy-as-it-successfully-demonstrates-its-sodium-ion-technology-for-battery-energy-storage-systems/

[98] Redox Flow Batteries, 2018-2028: *Markets, Trends, Applications; Large, safe, sustainable batteries for residential, C&I, and utility markets*. IDTechEx, 2018

[99] https://www.pv-magazine.com/2022/09/29/china-connects-worlds-largest-redox-flow-battery-system-to-grid/

[100] https://yadlamalkaenergy.com/open-day/

[101] https://invinity.com/2-mwh-sale-orcas-power-light-cooperative/

[102] https://investors.essinc.com/news/news-details/2023/LEAG-and-ESS-to-Develop-Clean-Energy-Hub-for-Germany/default.aspx

[103] https://iopscience.iop.org/article/10.1149/MA2021-013222mtgabs

[104] https://news.cgtn.com/news/2023-03-01/World-s-largest-iron-chromium-flow-battery-successfully-tested-1hOTOSUiAlG/index.html

[105] https://www.cmblu.com/en/press-and-media/uniblu-uniper-cmblu-pilotprojekt-transformation/

[106] https://www.cmblu.com/en/press-and-media/large-scale-storage-systems-make-burgenland-energy-self-sufficient/

Kemiwatt (FR) is another developer of the organic flow battery technology preparing commercialisation of their technology – several demonstrator projects are under testing.

Elestor (NL) is currently building a 3 MWh hydrogen bromine flow battery for Vopak at Vlissingen. The two companies aim to further scale up the storage capacity.[107]

2.3 Technology Costs

According to the *BloombergNEF's annual battery price survey,*[108] the price of Li-ion batteries rose from US 141/kWh in 2021 by 7% in real terms to US 151/kWh in 2022, as presented in **Figure 7**. These prices represent a volume-weighted average across all applications, including different types of EVs, buses and stationary storage and across geographical regions. The observed cost pressure on batteries outpaced the effect of increased use of cheaper chemistries like lithium iron phosphate (LFP). The prices are expected to stay at similar levels in 2023.

For BEV packs, the 2022 price was $138/kWh (+9.3% increase from 2021) on a volume-weighted average basis. At cell level, the average BEV battery price was $115/kWh (+10.8%). This shows that on average in 2022 cells accounted for 83% of the total pack price. This is slightly higher than over the last three years, when the cell-to-pack cost ratio was oscillating around 70:30 split. This is reflecting the changes to pack design, especially the cell-to-pack approach, which helped to reduce pack costs.

The stationary energy storage system costs stay above $300/kWh for a turnkey four-hour duration system, more than in 2022. Costs are expected to remain high in 2023 before dropping in 2024.

BloombergNEF also report the regional price differences: battery packs were cheapest in China, at $127/kWh, while in the U.S. and Europe the cost was respectively 24% and 33% higher. This difference reflects the relative immaturity of the US and EU markets and differences in shares of end-uses. However, comparing the price differences between China and the US and Europe in 2021 and 2022, one can notice the differences has fallen from respectively 40% and 60%, so almost by half, showing converging price trends.

Prices have increased in 2022 despite a continued trend of wider use of low-cost LFP cells. On average, LFP cells were almost 20% cheaper per kWh than NMC cells in 2022 (in 2021 this was almost 30%, the trend reflects a faster price increase for lithium carbonate than for other materials on one hand; and a price reduction of cobalt, the most expensive material in NMC battery on the other). The LFP battery pack prices rose 27% in 2022, compared to 2021.

The increased cost of raw materials and components have been the biggest contributor to the cell price increase observed in 2022. Large battery manufacturers and automakers have turned to more aggressive strategies to compensate materials price volatility, including direct investments in mining and refining projects.

In 2023, battery prices are expected to remain at elevated level, similar to that of 2022 (BNEF project $152/kWh) and to start dropping as of 2024, when new lithium extraction and refining capacities will come online. In 2026, the average pack price should fall below $100/kWh, which is two years later than expected in 2021.[109] This will negatively influence the development of EV and BESS markets.

Additional lithium supply could help to reduce prices in 2024 and later, however the geo-political frictions and trade issues remain the biggest uncertainties in the short-term. Also the market entry of alternative, non Li-ion batteries, especially Na-ion and redox-flow technologies, could alleviate price pressures. This could be observed already in 2026. It is e.g. estimated that the cost of CATL's Na-ion battery is about 30% lower than a cost of LFP battery. IRENA estimates cost on Na-ion batteries at 30-60% of cost of Li-ion batteries (at cell level).[8]

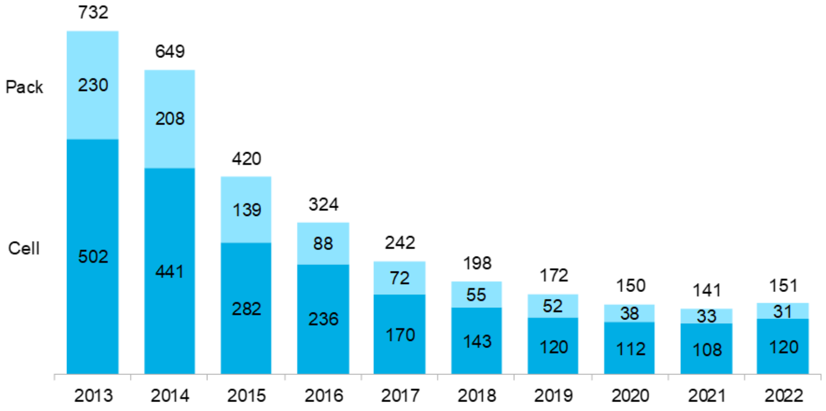
---

[107] https://www.innoenergy.com/news-events/providing-large-scale-long-term-electricity-storage-solutions-for-the-grid/

[108] https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/

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

Figure 7. Volume-weighted average Li-ion battery pack and cell price split (real terms 2022 USD/kWh, based on 178 data points from EVs, buses, commercial vehicles and stationary storage).



Source: BloombergNEF, Dec 2022

According to the POLES-JRC model[110] in the long term, the price for EV batteries is expected to fall to about 60 USD_{2020}/kWh by 2050 and stabilise at that level. The prices of truck batteries and stationary systems will also decrease and converge to about 300-350 USD_{2020}/kWh by 2030. In longer term, the decreasing trend will continue, however, the prices will remain at levels about two times higher than EV batteries and will approach 100-150 USD_{2020}/kWh towards 2050. Please note the unit is USD_{2020} unlike presented in the **Figure 7**.

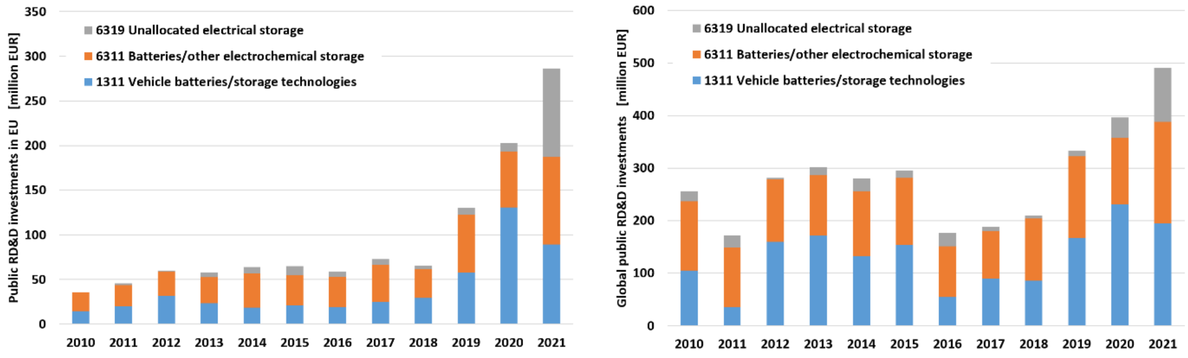
2.4 Public RD&I Funding and Investments

The Analysis is based on IEA data and limited to member state national investments.[111] The code numbering is following the IEA classification. There are many gaps in the available data set, as some MS do not publish data with sufficient level of details, especially for optional 4-digit codes used here. All values are converted from national MS currency to EUR based on the OECD annual national currency average exchange rate. Data for the US is available up to 2015. The IEA is in the process of revising this data in cooperation with the US authorities.

The global and EU public RD&D investments are presented in **Figure 8**. The EU investments have been increasing dynamically since 2019, boosting from stable 60-70 million EUR to almost 300 million EUR in three years. Globally in those three years the growth was much less dynamic, bringing the investments from about 200-300 million EUR to a bit less than 500 million EUR. Global leaders are the US (data missing since 2016, but older data suggest tis with high level of probability), EU and UK. Japan was 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 France, followed by Germany and Austria. France invest slightly more into general purpose batteries while Germany more in EV batteries.

Figure 8. The EU (left) and global (right) public RD&D investments (please note 2022 data is partial)



Source: JRC based on IEA.

---

[110] https://joint-research-centre.ec.europa.eu/poles_en

[111] Energy Technology RD&D Budgets: Overview, IEA, Paris 2023, https://www.iea.org/reports/energy-technology-rdd-budgets-overview

2.5 Private RD&I Funding and Investments

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 is available in the footnote.[112]

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

In 2022, global VC investments (**Figure 9**) in battery developers decreased to 9.5 billion EUR (-21%) after reaching all time-highs, amounting to 12 billion EUR in 2021. This decrease was observed in both the EU (-31%) and RoW (-18%). The early stage investments in the EU has decreased by 15% to 0.14 billion EUR and later stage investments have decreased by 32% to 1.6 billion EUR. Similar trends were observed in the RoW, where the early stage investments has decreased by 20% to 2.9 billion EUR and later stage investments decreased by 22% to 4.9 billion EUR.

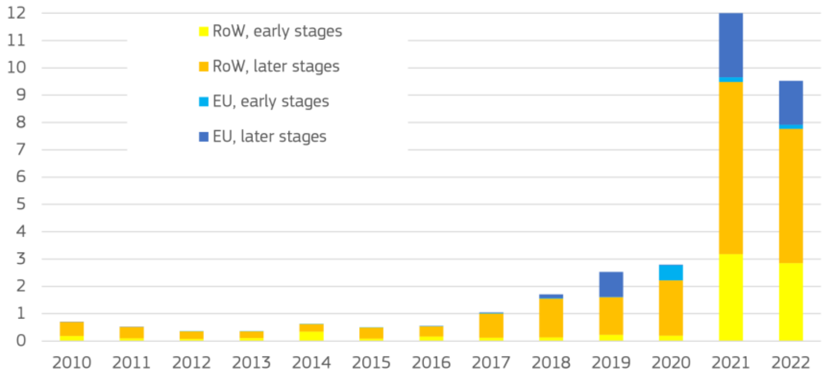
The start-up companies are active on all fields of batteries R&I, from evolutionary improvements of existing technologies to post Li-ion chemistries.

The battery IPCEIs from 2020-21 are bringing 14 billion EUR of private investment on top of public funding.

Beyond R&I funding, the EU industry has invested significantly in integration of batteries with end products.

Overall, the total investments in the EU's battery ecosystem summed up to 180 billion EUR and more than 160 industrial projects along the whole battery value chain until end of 2022[113].

Figure 9. Total VC investments by region [Billion EUR]



JRC based on Pitchbook

---

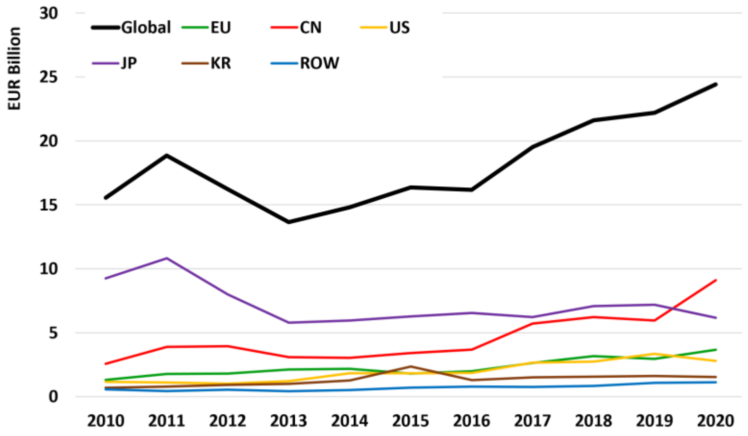
[112] The early and later stages indicators aggregate different types of equity investments in a selection of companies and along the different stages of their growth. The companies are selected based on their activity description (keyword selection, expert review). Only pre-venture (that received Angel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

[113] https://single-market-economy.ec.europa.eu/system/files/2023-03/Main%20takeaways_7th%20High-Level%20Meeting%20of%20EBA.pdf

An alternative methodology was developed by JRC for SETIS, to estimate the private R&I figures using patenting output as a proxy.[114,115] This method however should be interpreted with caution and results should be viewed as provisional and indicative of a trend rather than reflecting absolute values. Using patents as a proxy is resulting in a longer time-lag for data availability; here the 2019 data can be assumed final, while 2020 data are provisional. Figures are revised every year, with new estimates taking into account the most recent information from the EU R&I Scoreboard and patent dataset. The underlying patent information is subjected to periodical revision to maintain coherence with the EU R&I Industrial Scoreboard. This refinement may induce change of results reported in previous years.

According to this methodology, the global private R&I expenditures (**Figure 10**) are steadily increasing since 2013 with a CAGR of about 8%. In 2023 China became a global leader having passed Japan, the EU takes third position and the US the fourth one. China is showing continuous growth at increasing peace, Japan stable expenditures, the EU and US constant growth at low rate.

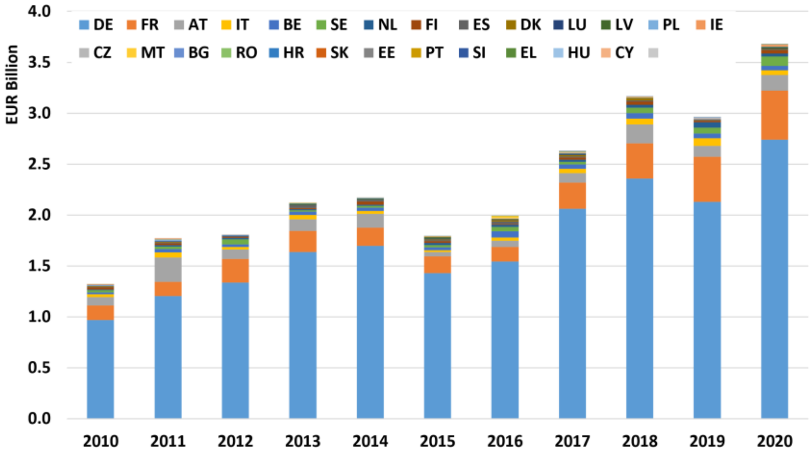
Figure 10. R&I investments estimation from patenting activity by region [Billion EUR]



JRC based on EPO Patstat.

Among the EU MS (see **Figure 11**), the dominating position is taking Germany, followed by France and Austria.

Figure 11. The EU R&I investments estimation from patenting activity by MS [Billion EUR]



JRC based on EPO Patstat.

The list of global Top 10 innovators (see **Table 8**) is dominated by Asian players with only two EU based companies present (Bosch at place 3 and BMW at place 6).

---

[114] A. Fiorini, A. Georgakaki, F. Pasimeni, E. Tzimas, *Monitoring R&I in Low-Carbon Energy Technologies*, Publications Office of the European Union, Luxembourg, 2017, doi:10.2760/434051, JRC105642,

[115] F. Pasimeni, A. Fiorini, A. Georgakaki, *Assessing private R&D spending in Europe for climate change mitigation technologies via patent data,* World Patent Information 59 (2019) 101927 doi:10.1016/j.wpi.2019.101927, JRC106133

Table 8. Global top 10 innovators in period 2015-20

1.	Toyota Motor	JP
2.	Toyota Industries	JP
3.	Robert Bosch	DE
4.	LG Chem	KR
5.	Samsung SDI	KR
6.	Bayerische Motoren Werke (BMW)	DE
7.	Honda Motor	JP
8.	Toyota Jidosha Kabushiki Kaisha	JP
9.	Denso	JP
10.	Panasonic Intellectual Property Management	JP

JRC based on EPO Patstat.

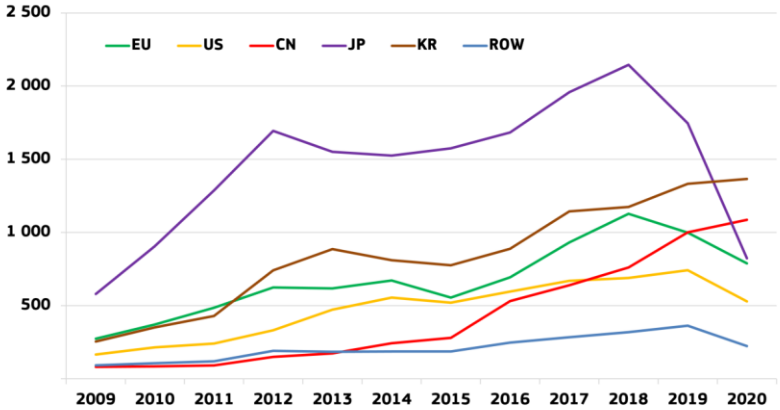
2.6 Patenting trends

The analysis is based on European Patent Office PATSTAT data,[116] 2021 autumn version. The analysis considers only patent applicants. A patent family was used as a proxy of invention. Patent families (inventions) measure the inventive activity. They include all documents relevant to a distinct invention, e.g. applications to multiple authorities, thus preventing multiple counting. A fraction of the family is allocated to each applicant and technology. High-value inventions refer to patent families with applications filed in more than one patent office.

The battery specialisation index (SI) represents patenting intensity in a battery technology for a given country (region) relative to geographical area taken as reference, e.g. global. If the battery SI = 0, the intensity is equal to the global average; if the battery SI < 0 than battery patenting intensity lower than the global average; if the battery SI > 0 than the country patenting effort is higher than the world average.[117] More details are available in the literature.[118,119,120,121,122]

The number of high-value inventions split by region is presented in **Figure 12**. Japan recorded the highest number of the high-value inventions over the period 2009-20. The second is Korea, the EU takes third place. The significant drop of most regions and especially Japan in 2020 is most probably due to incomplete/delayed data, resulting from the Cov-19 crisis. Some changes with respect to the data extracted in 2022 (last year CETO report) are also noted for 2019 and 2018 indicating processing time of patents requests lasting up to 5 years.

Figure 12. Number of high-value inventions by region.



JRC based on EPO Patstat

---

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

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

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

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

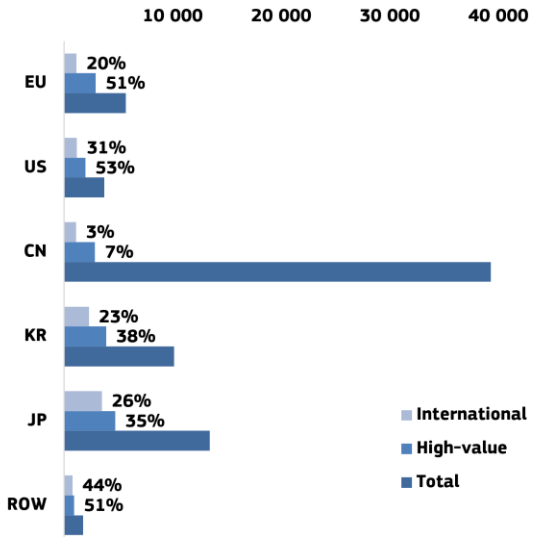
[120] F. Pasimeni, A. Fiorini, A. Georgakaki, *Assessing private R&D spending in Europe for climate change mitigation technologies via patent data* World Patent Information, 59 (2019) 101927 DOI: 10.1016/j.wpi.2019.101927

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

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

As presented in **Figure 13**, in the 2018-2020 period, the total number of inventions, depicted by dark blue bars, was highest for China (39 300, 53% share, +2 pp. increase compared to the 2017-2019 period), followed by Japan (13 400, 18%, -1 pp.) and Korea (10 100, 14%, +1 pp.). The EU (5 700, 8%, no change) is ranked fourth, before the US (3 700, 5%, no change). The share of international inventions among total inventions in the region is marked with lightest blue bars, while the share of high-value inventions is marked with middle intensity blue bars. China reported both indicators lowest of all regions (3% and 7% respectively, both +1 pp.) indicating that China is mostly protecting its own market. Highest interest in international protection was reported for regions with lowest total number of patents.

Figure 13. Number and type of inventions by region in 2018-20 period.



JRC based on EPO Patstat.

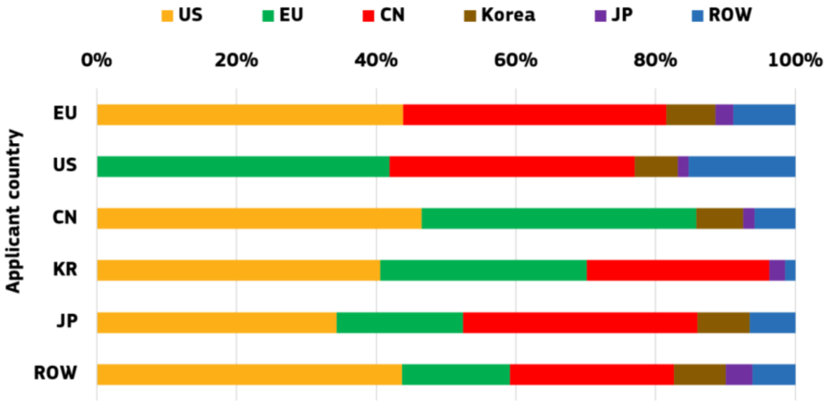
The international protection of high value inventions:

The international protection of the EU inventions goes mostly to US and China, the one of US goes to the EU and China, China protects their inventions mostly in the US and EU. Korea focusses on the US, and China while Japan on the US and China, bit less on EU. The RoW focuses on US, less on China and the EU, see **Figure 14**.

Comparing to the previous edition covering years 2017-19, the following changes ware observed:

- EU increased protection in US (+8%) and ROW (+2%) at cost of China (-8%), Korea (-1%) and Japan (-1%)
- US increased protection in EU (+2%) and ROW (+1%) at cost of China (-2%) and Japan (-1%)
- China increased protection in EU (+3%) and Korea (+2%) at cost of US (-3%), Japan (-1%) and ROW (-1%)
- Korea increased protection in EU (+4%) and ROW (+1%) at cost of US (-2%) and China (-3%)
- Japan increased protection in EU (+3%) at cost of China (-1%), Korea (-1%) and ROW (-1%)
- ROW increased protection in EU (+1%) and ROW (+2%) at cost of China (-2%) and Korea (-1%)

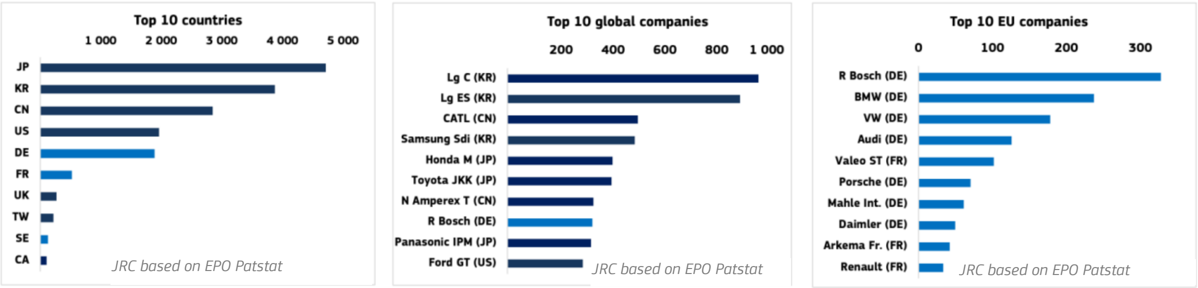
Figure 14. International protection of high-value inventions.



JRC based on EPO Patstat.

The top 10 high value invention counties, global companies and EU companies are present in **Figure 15**. Among the Top 10 high-value invention countries in the period 2018-2020, three EU countries were ranked, Germany (5th place), France (6th) and Sweden (9th, +1 position up). Among the Top 10 companies in 2017-19 in high-value inventions only one EU based company is listed, Bosch (DE, 8th, -3 positions). Analysing the Top 10 EU innovators, it is worth to mention the advance of BMW from position 3 to place 2 linked to increased patenting activity. Bosch kept first place despite reduced patenting effort. It should also be noted that the on the Top 10 EU innovators list only two MS have their representations: DE – 7 companies and FR – 3.

Figure 15. 2018-20 high-value inventions - top 10 countries, global and EU companies.



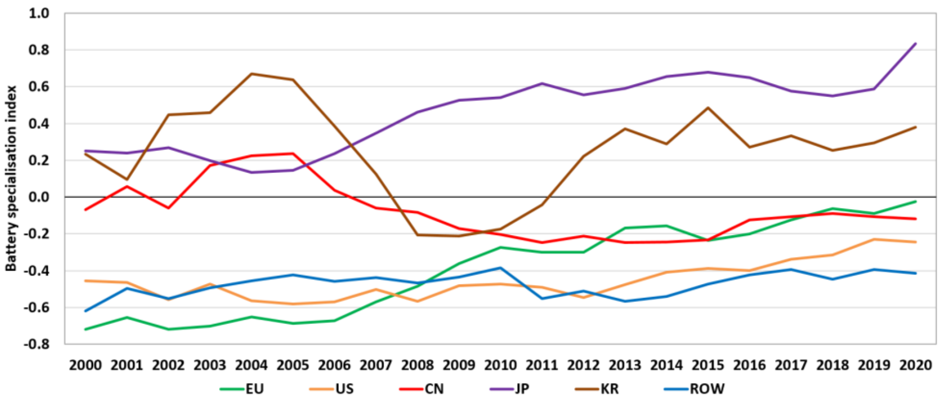
JRC based on EPO Patstat

JRC based on EPO Patstat

JRC based on EPO Patstat

A battery specialisation index (**Figure 16**) shows that Japan is leading in battery technology development continuously since 2007. A strong increase of Japans SI was observed in 2020, however this is not consistent with the decrease of patenting activity of Japan presented in **Figure 12**. Interpretation of this result needs care. Korea (leader before 2007) is on strong second position. The EU is competing for the third position with China. US takes 5th position.

Figure 16. Battery specialisation index.



JRC based on EPO Patstat

2.7 Scientific publication trends

The analysis is based on JRC TIM[123] (Scopus database) and includes global, regional and MS statistics.[124]

The change of publishing activity is expressed as annual change of number of publications per year; [(number of publications/year)/y = publications·y^{-2}].

Zn batteries represents all chemistries based on zinc together, with exception of zinc based flow batteries and Zn-air batteries that are included in the RFB and Me-air groups, respectively.

For geographical analysis of links in Europe a geographical location of the country is taken into account, not membership in the EU. The assessment of collaborations between regions and countries was performed using Tools for Innovation Monitoring (TIM) tool, and is based on analysis of scientific publications. The size of the nodes represent number of documents for a country, lines between two nodes mark co-publications or co-

---

[123] EU, Joint Research Centre, TIM Analytics, http://www.timanalytics.eu/

[124] The following search queries were used in TIM:

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

RFBs - topic:("flow battery" OR (("redox flow" OR redox-flow OR RFB) AND battery)) AND class:article

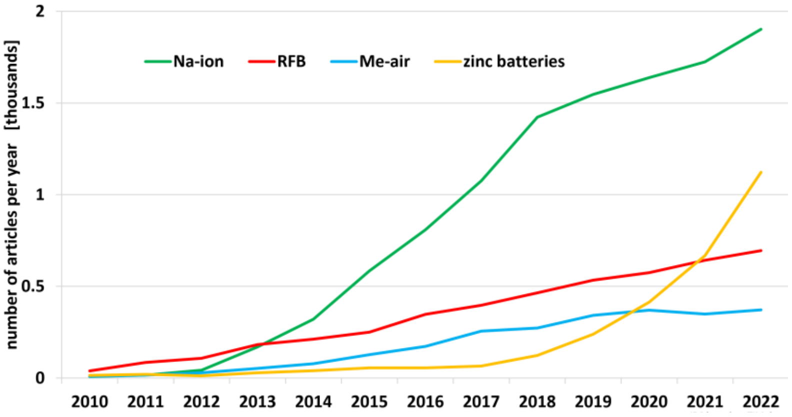
Me-air - topic:(("metal air battery" OR "metal-air battery" OR "Me-air battery")) AND class:article

Zn batteries – (topic: ("zinc battery"~2) AND class: article) NOT topic:("zinc air" OR "zinc-air" OR "redox flow" OR VRFB) 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 the others. Analysis is performed on all publications in the period 2010-22.

For benchmarking regions and Member States regarding citation numbers of publications 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. A 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. The analysis is performed on all publications in the period 2010-22.

Global bibliometric trends for Na-ion, redox flow, Me-air and Zn batteries (**Figure 17**) show increasing interest in those technologies. 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 continue to grow at a rate of about 100 publications·y^{-2}. Publishing activity for RFBs exhibits steady increase of about 50 publications·y^{-2}. Publishing activity for Me-air batteries increases at steady rate of about 30 publications·y^{-2}. Those trends represents well the relative maturity of the assessed technologies. The most interesting trend is however revealed for Zn batteries, which since 2017 grow exponentially. In one year only, from 2021 to 2022, the number of publications rose from about 700 to 1 200, expressing growth of 500 publications·y^{-2}, fastest of all evaluated technologies in the whole analysed period. This indicates rapidly growing interest in Zn batteries.

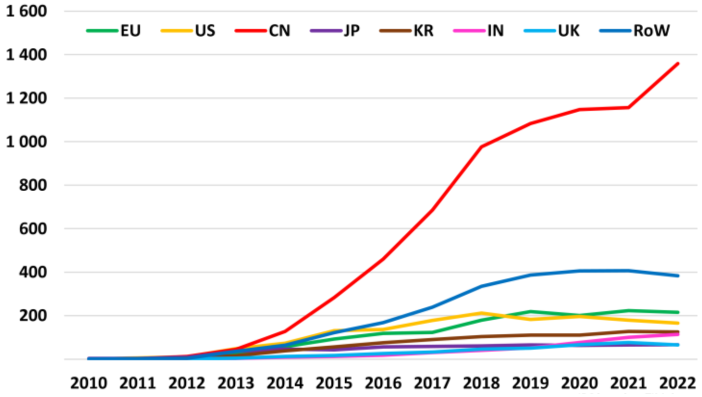
Figure 17. Global publishing activity trends for Na-ion, RFB, Me-air and zinc technologies.



JRC based on TIM data

For **Na-ion batteries,** the analysis of bibliometric trends (**Figure 18**) indicates booming interest of China in period 2013-18 which reduced expansion rate and stabilised in 2020-21. However in 2022 again fast growth of 200 publications·y^{-2} was observed. China is clearly a leader with almost 1 400 publications·y^{-1}, followed by the RoW (400 publications·y^{-1}), EU and US. While in China Na-ion batteries benefit from increasing interest, in RoW there is stagnation in the period 2018-22. Similar stagnation (at lower numbers) is observed in the EU and US, where even a slightly decreasing trend is observed after 2018. Increase of interest is observed in India.

Figure 18. Na-ion technology publishing trends activity per region.

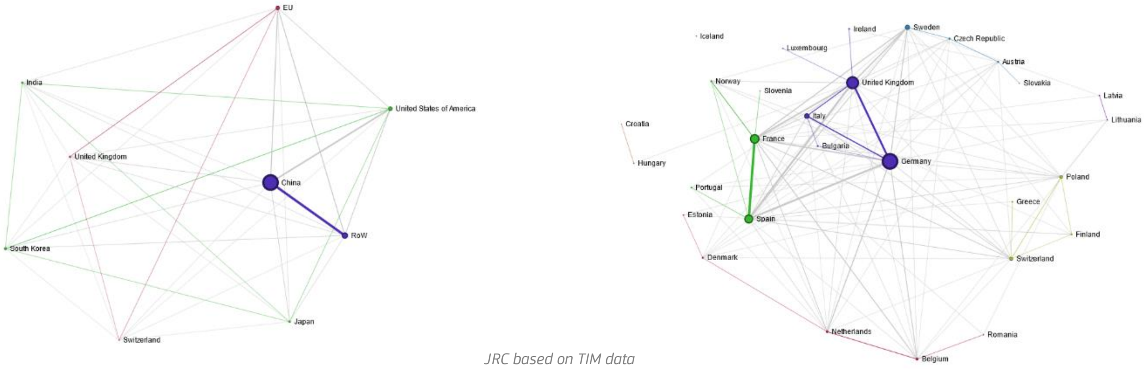


JRC based on TIM data

Globally, the strongest collaboration is observed between China and RoW, for Europe links with UK and RoW are the strongest, but still weak. Among European countries the strongest link is observed between France and

Spain and together with Portugal, Norway and Slovenia it forms a cluster. Another cluster is formed around collaboration of Germany and the UK. Significant links are also observed between Germany and Spain, but also between UK and France and Spain - see **Figure 19**.

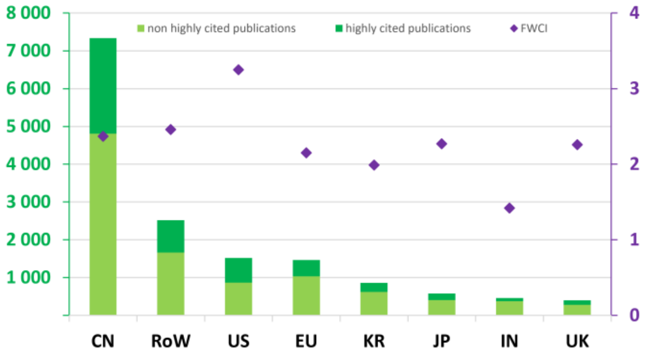
Figure 19. Na-ion batteries inter-regional (left) and intra-Europe (right) links.



JRC based on TIM data

Global leader in Na-ion batteries publications including highly cited publications is China, however the highest share of highly cited publications is observed for US, while China is second (**Figure 20**). The EU is fourth in this category, after RoW. FWCI rank gives similar result.

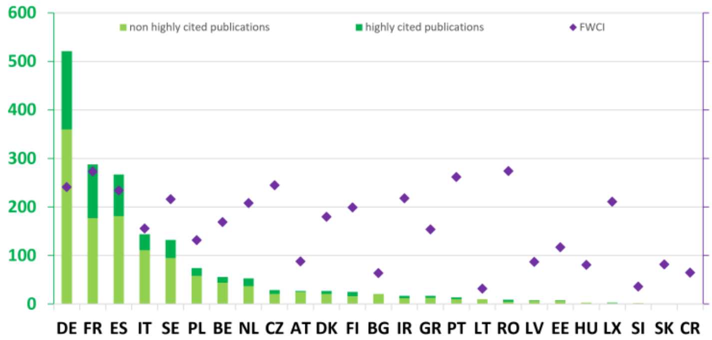
Figure 20. Na-ion batteries publications and FWCI index for regions.



JRC based on TIM data

In the EU Germany is the leader in Na-ion publishing, followed by France and Spain; those countries also have high FWCI (**Figure 21**). For countries lower ranked, the FWCI needs to be interpreted with caution, as due to low number of publications the influence of single highly cited publications might be high and distorting the picture.

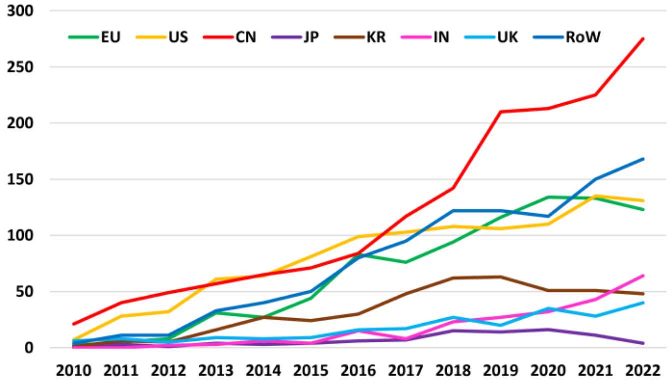
Figure 21. Na-ion batteries publications and FWCI index for the EU MS.



JRC based on TIM data

For **RFB,** analysis of bibliometric trends (see **Figure 22**) indicates growing interest of China – current leader, well overpassing RoW, which in turn passed the US and EU. China seems to continuously accelerate its publishing activity, the RoW keeps steady increase, while the US decrease the rate of increase. China is clearly a leader with 280 publications·y^{-1}, followed by the RoW (160 publications·y^{-1}), the US and EU (both about 130 publications·y^{-1}). The EU is probably entering a stagnation period, or even decrease, after a second year of decreasing number of publications in 2022. India clearly accelerates its publishing rate, as well as UK.

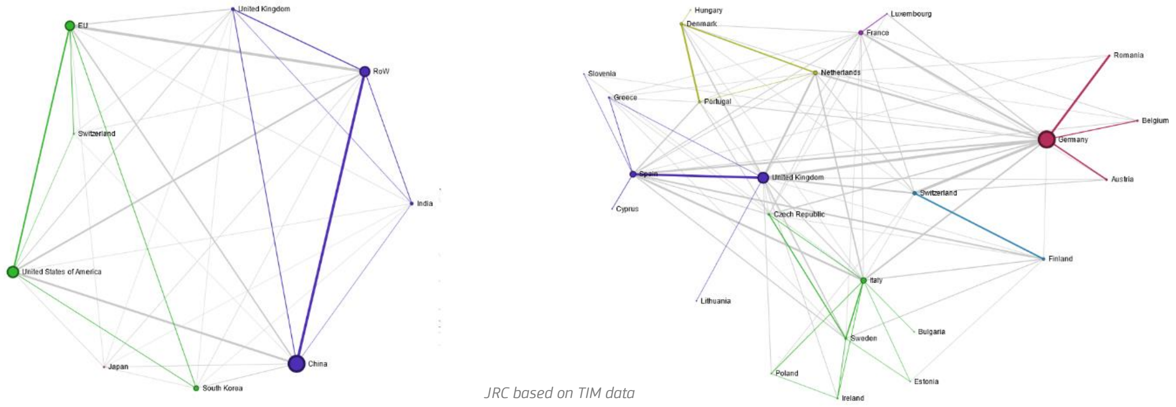
Figure 22. RFB technology publishing activity trends per region.



JRC based on TIM data

Globally, the strongest links are observed between RoW and China and between RoW and the EU (**Figure 23**). There are two clusters found, one around China and RoW, another one around the EU and US. Among European countries the strongest links are observed between Germany, Netherlands, France, Spain and Italy, without presence of clearly developed clusters. Beginnings of three clusters focused around Italy, UK and Germany can be observed.

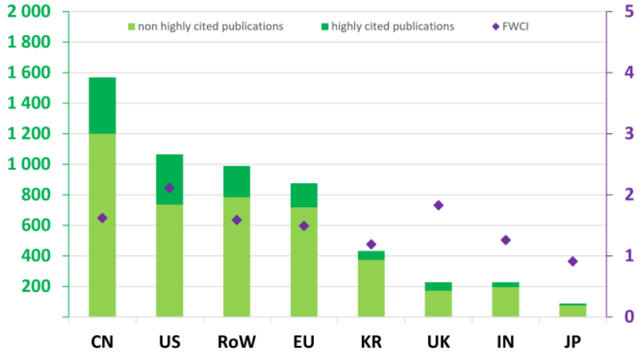
Figure 23. Redox-flow batteries Inter-regional (left) and intra-Europe (right) links.



JRC based on TIM data

China is a global leader in RFB publications and highly cited publications, however the ratio of highly cited to all publications is most favourable for the US (**Figure 24**). China is second, the EU is fourth after RoW.

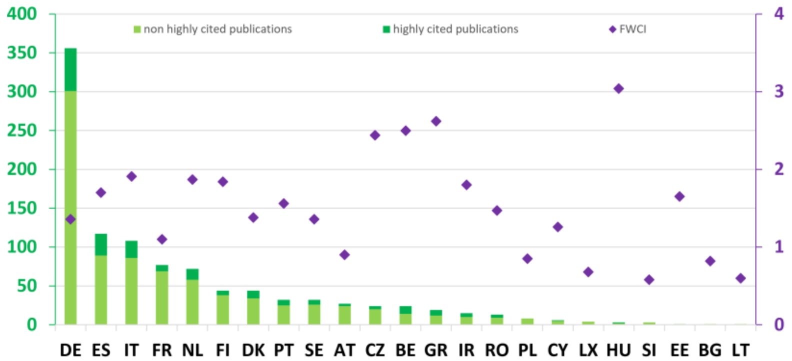
Figure 24. RFB publications and FWCI index for regions.



JRC based on TIM data

The EU leader is Germany, followed by Spain and Italy (**Figure 25**).

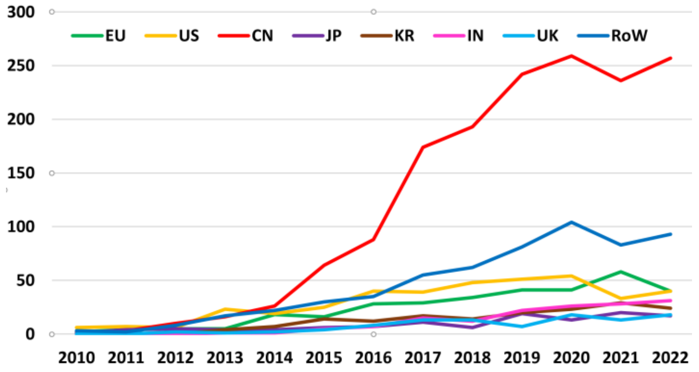
Figure 25. RFB publications and FWCI index for the EU MS.



JRC based on TIM data

The analysis of **Me-air batteries** bibliometric trends (see **Figure 26**) indicate growing interest of China, the current leader, well overpassing the RoW, which in turn passed US and EU. China is clearly a leader with 250 publications·y^{-1}, followed by the RoW (90 publications·y^{-1}), US and EU (both about 40 publications·y^{-1}). The interest of China, after a fast increase in the 2014-19 period, has stabilised. RoW keeps steady increase, while the US and EU probably reached a plateau. India slowly accelerates its publishing rate.

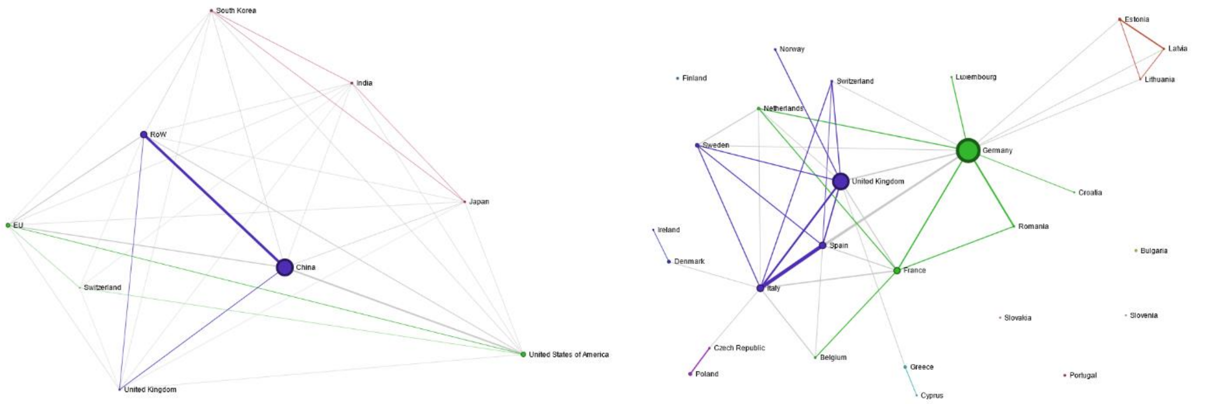
Figure 26. Me-air battery technology publishing activity trends per region.



JRC based on TIM data

As shown in **Figure 27**, globally, the strongest collaboration is observed between China and RoW and also between China and US. A weak cluster is formed around cooperation of China with RoW. For Europe, the strongest links exists with RoW, China and US, a weak cluster is observed around cooperation between EU and the US. Among European countries, the strongest links are observed between Spain and Italy, and together with UK, Sweden, Switzerland and Norway, they form a clearly developed cluster. Another cluster is formed by Germany, Romania, France Netherlands, Belgium and Croatia. The strongest connections between those two clusters are via Germany-Spain, Germany-UK and France-Italy links.

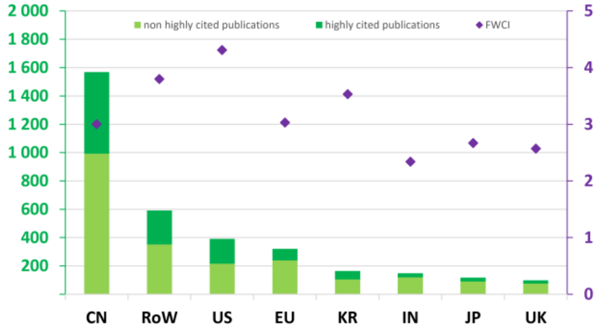
Figure 27. Me-air batteries inter-regional (left) and intra-Europe (right) links.



JRC based on TIM data

Global leader in Me-air battery publications and highly cited publications is China, however the ratio of highly cited to all publication is most favourable for US, while China is third behind RoW (**Figure 28**). The EU is fifth.

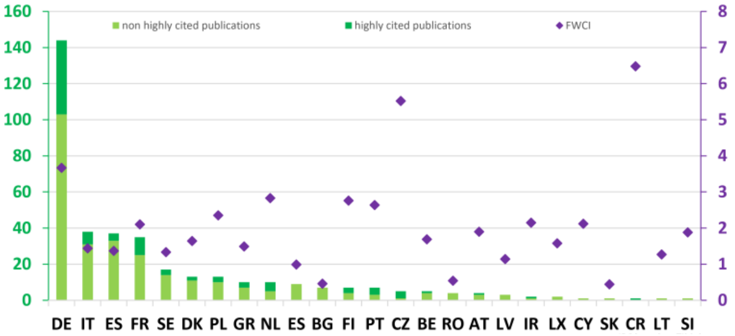
Figure 28. Me-air battery publications and FWCI index for regions.



JRC based on TIM data

As presented in **Figure 29**, the EU leader is Germany, followed by Italy, Spain and France.

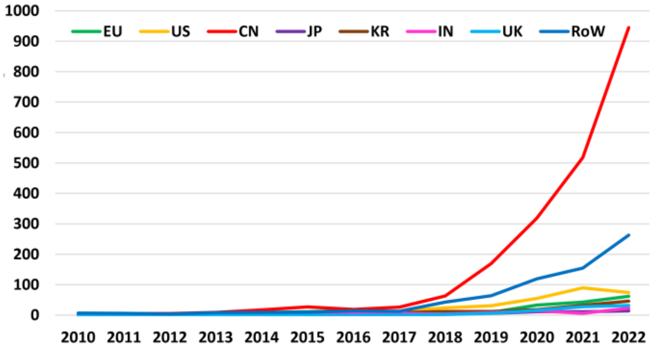
Figure 29. Me-air battery publications and FWCI index for the EU MS.



JRC based on TIM data

The analysis of **Zn batteries** bibliometric trends (see **Figure 30**) indicate exponentially growing interest of China, the current leader, well overpassing RoW (following similar trend to China, but at smaller scale) which in turn passed the US, EU and other regions. The number of Chinese publications is increasing exponentially, and in 2022 reached 950 publications·y^{-1}, while in 2021 it was 500 publications·y^{-1}, noting the 90% increase in one year. The US seems also to follow increasing trend, however in 2022 number of publications has dropped. The EU is also increase publishing activity, however, with number of publications below 100 publications·y^{-1} is grouped together with other regions.

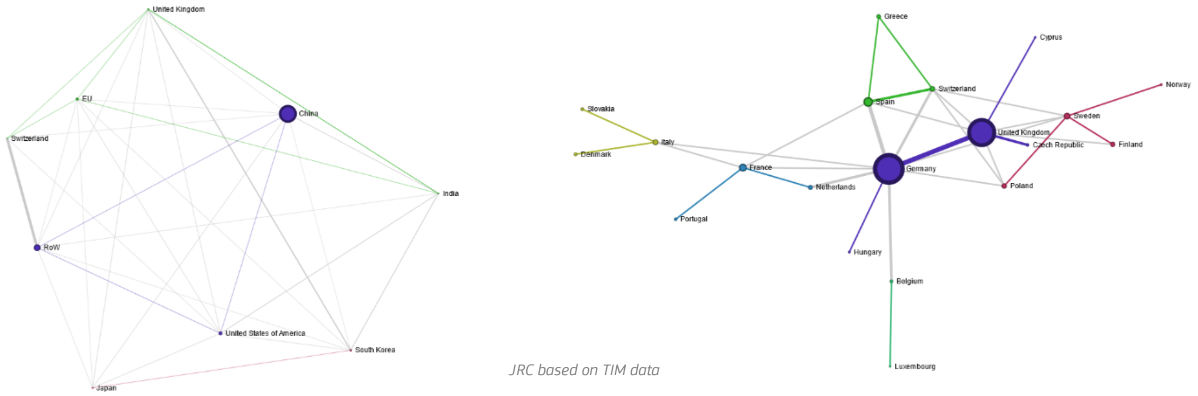
Figure 30. Zn batteries technology publishing activity trends per region.



JRC based on TIM data

The collaborations at global scale are rather limited, slight links are observed between RoW and Switzerland, and also UK and India (**Figure 31**). Weak clusters are formed around cooperation of US-China-RoW and UK-India-EU-Switzerland. Europe’s strongest links are Switzerland, UK and India. Among European countries, the strongest links are observed between Germany and UK, and together with Hungary, Czech Republic and Cyprus, they form a cluster. Other relatively strong links exist between Germany and Spain, Switzerland, Belgium and Netherlands.

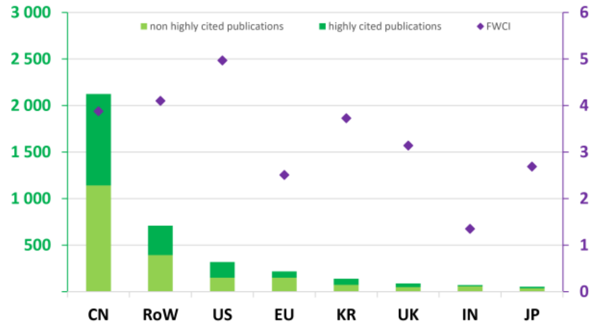
Figure 31. Zinc batteries inter-regional (left) and intra-Europe (right) links.



JRC based on TIM data

The global leader in Zn battery publications is China and again, the ratio of highly cited to all publication is most favourable for US, while China is third behind RoW, see **Figure 32**.

Figure 32. Zn battery publications and FWCI index for regions.



JRC based on TIM data

As presented in **Figure 33**, the EU leader is Germany, followed by Spain and France. FWCI analysis is rather difficult, as only Germany is approaching 100 publications and other Member States have about 20 publications or less. In this situation, the FWCI index is not reliable due to poor statistics.

Figure 33. Zn battery publications and FWCI index for the EU MS.

JRC based on TIM data

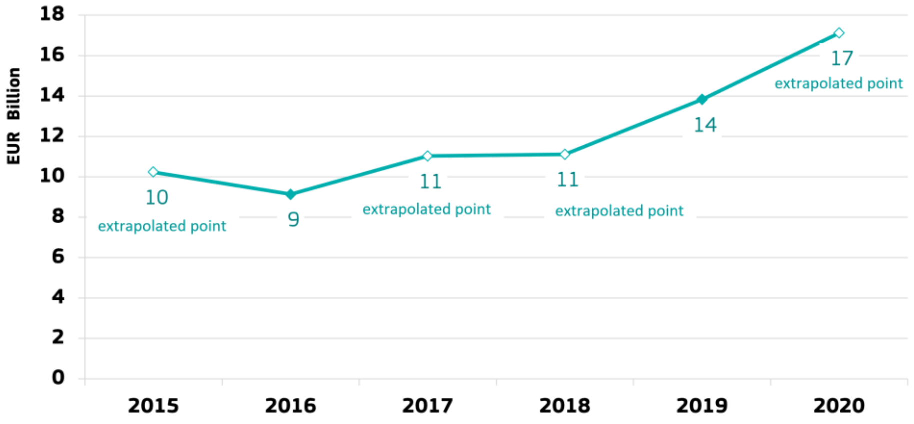
3 Value Chain Analysis

3.1 Turnover

Data on turnover in the battery manufacturing sector is not readily available and not complete. Available data were commissioned by DG GROW and analysed by JRC. The data set is the same as used in the European climate-neutral industry competitiveness scoreboard (CIndECS) (Draft, 2022). Missing or nondisclosed numbers were approximated using available data points and trends observed over longer periods. Most recent data fully available are dating from 2019, 2020 data is only partially available.

The turnover in the EU battery manufacturing sector is presented in **Figure 34**. It remained stable or slightly increased until 2018, but 2019 and 2020 brought dynamic growth of about 55% in two years. This picture is in line with opening of new or extending production in existing battery plants in the last years in EU. This trend is expected to continue. The point for 2020 is extrapolated and might carry a risk of not precise estimation from earlier trends.

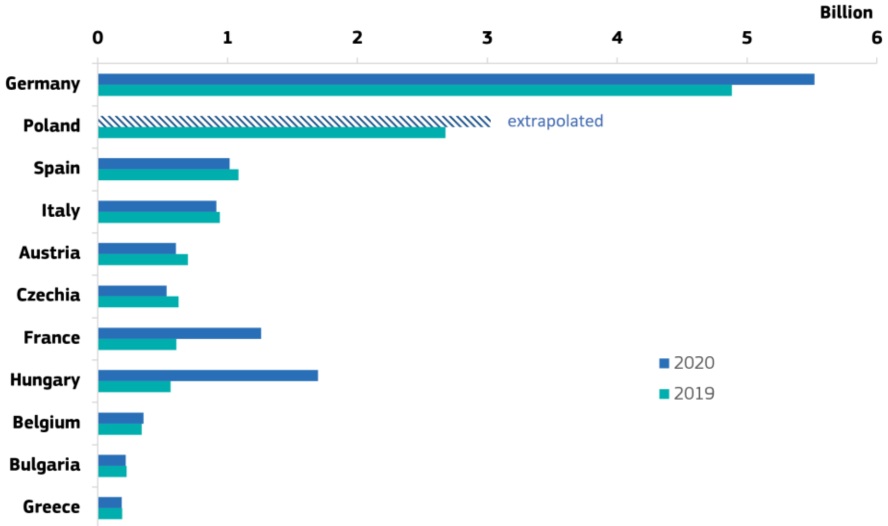
Figure 34. Turnover trends in the EU battery manufacturing sector.



JRC based on Eurostat SBS data

The EU MS with highest turnover in the battery manufacturing sector in 2020 (**Figure 35**) are DE, PL, HU and FR. Especially high dynamic of turnover increase is observed in HU, where SK Innovation and Samsung are developing their production plants, but also in FR. PL did not disclose its statistics while it could profit from high turnover growth due to an expansion of production in the large LG battery plants in Kobierzyce or starting production in the Mercedes plant in Jawor. The conservative approach used to estimate the number for PL using extrapolation of older data trend might not properly capture those changes.

Figure 35. Top 10 EU MS with highest turnover in battery manufacturing sector.



JRC based on Eurostat SBS data

3.2 Gross value added

Statistical data for gross value added is not available.

3.3 Environmental and socio-economic sustainability

As part of the EU Green Deal goals, the production and the adoption of more sustainable batteries in the EU will contribute to decarbonisation of the EU and enhance the independence of the EU from the supply of both raw materials and components from third Countries (Carrara et al., 2023).[125] The Battery Regulation[133] as well as the Critical Raw Materials Act (EC, 2023)[126] confirmed the intention of the EU in reducing the environmental and social impacts through various measures, e.g. the adoption of a carbon footprint declaration for batteries placed in the EU market, as well as ethical sourcing of raw materials; the adoption of ambitious collection and recycling targets, recycled content for targeted raw materials, design for provisions to ensure removability and replaceability of batteries, promotion of circular strategies other than recycling (e.g. repurposing, remanufacturing, reuse of batteries). The 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**), 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 but the exploitation of already existing/new digital skills and the development of circular business models.

3.4 Role of EU Companies

The list of global and EU leaders in assessed technologies is presented in **Table 9**. The EU headquartered companies are marked with green, US – with yellow, China – with red; RoW – with blue.

The global leader in the Na-ion batteries development and commercialisation is China. The big Chinese companies, with CATL at front, showed interest in this technology and its commercialisation advances very fast. The EU with one start-up planning production from 2025 and one already operating cathode material supplier stays far behind. It is expected that in future the dominating position of China will be kept, and it will be followed by RoW (India, UK).

The global leadership in flow batteries technology goes to the US companies, followed by the EU and RoW. There are no giant players investing in this technology like CATL investing in Na-ion batteries, and the rate of development is slower. The EU, despite being strong in RFBs R&D sector, is lagging in the production phase. RFB battery developers prefer to locate production facilities close to their markets and those are the US and RoW countries e.g. Australia, Canada or Japan. It is not expected that the EU will significantly improve its global position in this respect.

In field of Me-air rechargeable batteries (primary Zn-air batteries are excluded), global leader is US, followed by the EU and Canada. The EU perspectives in this technology are not clear. The European companies have a relatively strong position in the R&D phase, but due to better market perspectives in third countries, they might migrate with production to locations close to main markets.

The two companies leading the zinc non-RFB battery market are based in the US and Australia, respectively. They already operate in commercial phase with production capabilities greater than 1 GWh/y each, located on their main markets. The EU is not expected to gain significant percentage in production of batteries in that technology.

---

[125] Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, Á., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D., Christou, M., *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889

[126] COM (2023) 160

Table 9. Global leaders in Na-ion[127], RFB[128], Me-air and Zn battery chemistries.

Company (production capacity or alphabetical order)	Technology	Notes	2030 prod. capacity [GWh/y] expected (possible)
CATL	Na-ion (LO, PBA)	GWh-scale production planned for 2023	10 (30)
Faradion (Reliance)	Na-ion (LO)		10 (15)
Tiamat	Na-ion (PA)	Neogy will produce cells	6 (-)
HiNa	Na-ion (LO)	GWh-scale production started in 2022	5 (10)
Zoolnasm	Na-ion	Building a plant in Jiangsu (CN)	5 (10)
Natron Energy	Na-ion (PBA)	Clarios will produce cells as of 2023	0.6 (6)
AMTE	Na-ion	Building a plant in Scotland (UK)	0.5 (2)
BYD	Na-ion	Might launch Na-ion EV in 2023	- (20)
Farasis Energy	Na-ion	Partnered with JMEV	- (10)
Svolt	Na-ion	Expected to develop Na-ion cells in 2023	- (10)
EVE Energy	Na-ion	Developing cells before production	- (10)
Li-Fun Tech	Na-ion	production planned in 2023	- (5)
Godi Energy	Na-ion	Planning 5 GWh/y Li-ion plant before Na-ion	- (5)
Altris	Na-ion (PBA)		
total in 2030			37 (133)
CellCube (US)	VRFB	over 10 000 charge cycles, 0.5 MW / 3 MWh	
CMBlue (DE)	OSFB	organic solid flow technology	
ESS Tech Inc. (US)	IRFB	designed for 25 years, no (use) degradation, operation range -5 - +50 °C	
Invinity Energy Systems (US, UK)	VRFB	10 kW / 40 kWh system	
Jena Batteries (DE)	organic	100 kW / 400 kWh system	
Largo Clean Energy (CA)	VRFB	1 MW / 10 MWh system	
Lockheed Martin (US)	flow battery	Fort Carson 1 MW / 10 MWh GridStar Flow	
PinFlow (CZ)	VRFB	0.25 MW / 2.5 MWh system	
Primus Power Solutions (US)	ZBFB	EnergyPod 2 – 20 years without degradation	
RedFlow (AU)	ZBFB	ZBM3, 10 kWh 12 h unit with energy efficiency up to 80% and 42 $Wh \cdot kg^{-1}$ specific energy.	
Rongke Power (CN)	VRFB	range: 50 kW / 300 kWh – 0.5 MW / 2 MWh	
Schmid Group (DE)	VRFB	EverFlow – 10 000 cycles, 40 years durable electrolytes, no self-discharge	
Sumitomo Electric Industries (JP)	VRFB	unlimited cycle life, designed for 20 years, 0.25 MW / 1.5 MWh	
UniEnergy Technologies (US)	VRFB	ReFlex – no capacity fade	
ViZn Energy (US)	Zn-Fe	range: 50 kW / 160 kWh – 1.4 MW / 4.2 MWh	
Voltstorage (DE)	IRFB	VDIUM C50, 10 000 cycles, 20 years, in 2022 got M 24 EUR investment from Cummins Inc.(US)	
VRB Energy (CA)	VRFB	world longest lasting VRFB, 0.25 MW / 1 MWh	
AZA Battery (BE)	Zn-air	late R&D / prototyping	
e-Zinc (CA)	Zn-air	late R&D	
Form (US)	Fe-air	plant construction	
Phinenergy (US)	Al-air	open system, “recharging”=Al production	
Polyplus (US)	Li-air	late R&D	
Zinc8 (CA)	Zn-air	pilot / early deployment	

---

[127] Sodium-ion update: *A make-or-break year for the battery market disruptor*, Jan 2023, Wood Mackenzie

[128] https://www.blackridgeresearch.com/blog/top-flow-battery-companies-manufacturers

Zinium (FR)	Zn-air	late R&D / prototyping		
Gelion (AU)	Zn-Br (non-flow)			2
EOS (US)	Zn-Br (non-flow)	1.5 kW / 6 kWh system		1.5
graphical legend:	EU	US	China	RoW

Source: JRC based on Wood Mackenzie, Black Ridge Research and open data in the Internet.

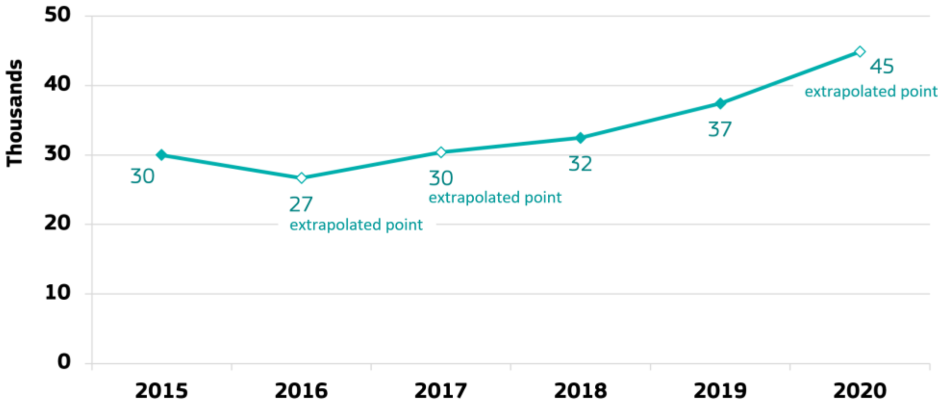
The role of the EU based companies in the value chain of mainstream Li-ion batteries was described in the last edition of CETO report[4] and did not change significantly since that time.

3.5 Employment

Data on employment in the battery sector is not readily available and not complete. Available data were commissioned by DG GROW and analysed by JRC. The data set is the same as used in the European climate-neutral industry competitiveness scoreboard (CIndECS) (Draft, 2022). Missing or not disclosed numbers were approximated using available data points and trends observed over longer periods. Most recent data fully available are dating from 2019. 2020 data is only partially available.

The number of direct jobs in the EU battery manufacturing (**Figure 36**) 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 PL and FR did not report/disclose their numbers and this missing data was extrapolated with a conservative approach, assuming continuation of trends observed in preceding periods. As both PL and FR, makes strong effort to increase battery production, especially after 2018, a jobs resulting from that efforts might follow non-linear trends and thus be underestimated in evaluation based on pre-2019 data.

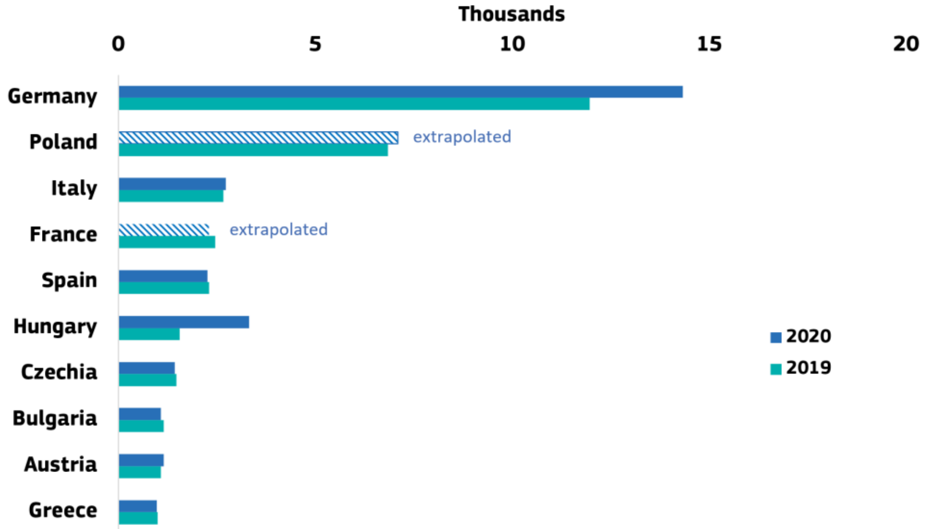
Figure 36. Number of direct jobs in the EU battery manufacturing.



JRC based on Eurostat SBS data

The EU MS with the highest number of direct jobs in battery manufacturing (**Figure 37**) are DE, PL and HU. An especially high dynamics of jobs creation is observed in HU, where SK Innovation and Samsung are developing their production plants. 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 did not report 2020 job data. It was extrapolated from the trend of older data and thus might not properly capture extension of LG battery plants in Kobierzyce.

Figure 37. Top 10 EU MS with highest number of direct jobs in battery manufacturing.



JRC based on Eurostat SBS data

The battery production sector might create more than one million new jobs in EU. This will happen independent of digitalisation and automation of production processes.[129] Those jobs will require workers skilled in electro-chemistry, digitalisation of processes, electronics, programming, etc. The EBA250 Academy is developing a pan-European education ecosystem to cover battery industry's skills needs and provide education to 160 000 workers every year.

Also the Alliance for Batteries Technology, Training and Skills (ALBATTS) will analyse needs of the battery industry and publish a blueprint for competences and training schemes in the battery and electromobility sector.[130]

3.6 Energy intensity and labour productivity

There is no statistical data available that would allow for assessment of the energy intensity and labour productivity of battery production.

3.7 EU Production Data

JRC analysis is based on PRODCOM data.[131] Some countries keep their production data confidential. This production however is included in the "EU total" numbers. That's why the sum of countries' production is lower than the EU total. It should be also pointed that the PRODCOM codes do not distinguish between battery cell, module or system (e.g. EV battery) incorporating cells, thus a double counting may occur.

The total value of batteries produced in the EU in the years 2021 and 2022 was similar and close to 27-28 billion EUR a year. The vast majority of produced batteries are accumulators, while primary batteries accounted for 10-15% of the total production. The trend of value of batteries production is increasing (see **Figure 38**), with a production jump of above 100% y/y in 2021 and stagnation in 2022. Most likely the numbers in 2020 suffered from Cov-19 effects, while in 2022 from disruptions in supply chains that restricted production of electric vehicles. Until 2016 the trend of batteries production rose at a CAGR of 5.2%; between 2016 and 2020 CAGR of 12% and in the last five years it reached 25%.

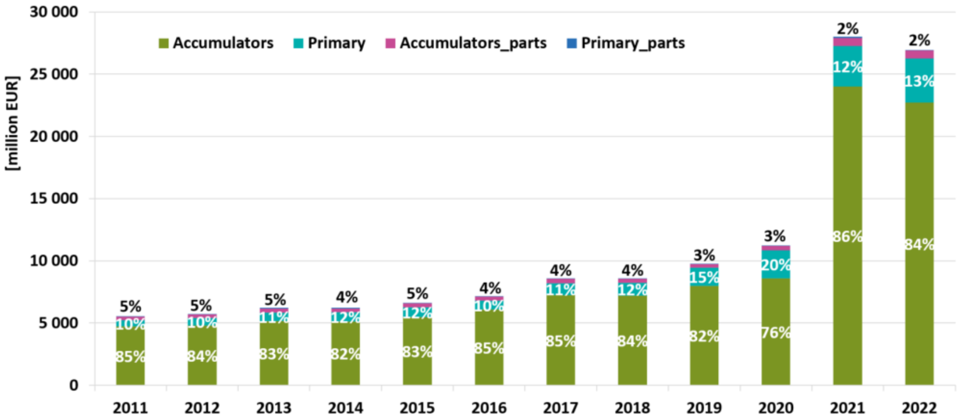
---

[129] Batteries Europe General Assembly 21/06/2022

[130] https://www.project-albatts.eu/en/home

[131] 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.

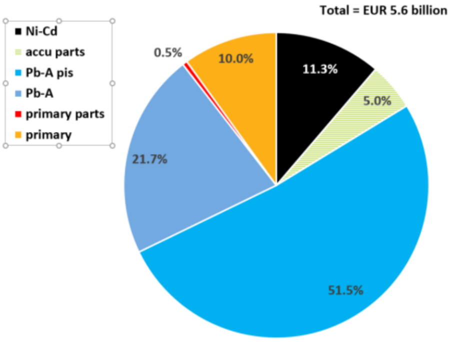
Figure 38. Total value of batteries produced in the EU.



Source: JRC based on PRODCOM data

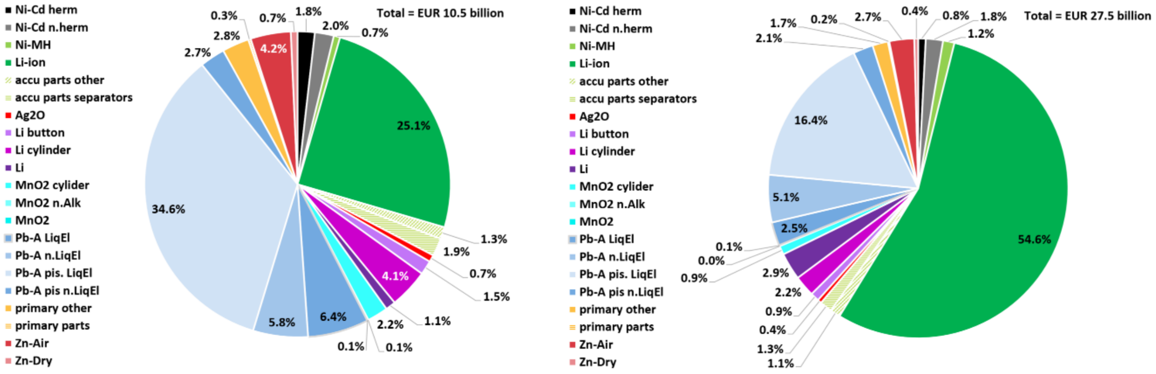
The evolution of structure of the batteries production is illustrated in **Figure 39** and **Figure 40**. A clear shift from Pb-A batteries dominating in 2011-12, to Li-ion batteries in the last years, is observed. The change in the number of battery categories is due to a change in the Eurostat reporting methodology as of 2019.

Figure 39. 2011-12 average structure of the EU batteries production.



Source: JRC based on PRODCOM data

Figure 40. 2019-20 average structure of the EU batteries production, left – in years 2019-2020, right – in years 2021-2022.

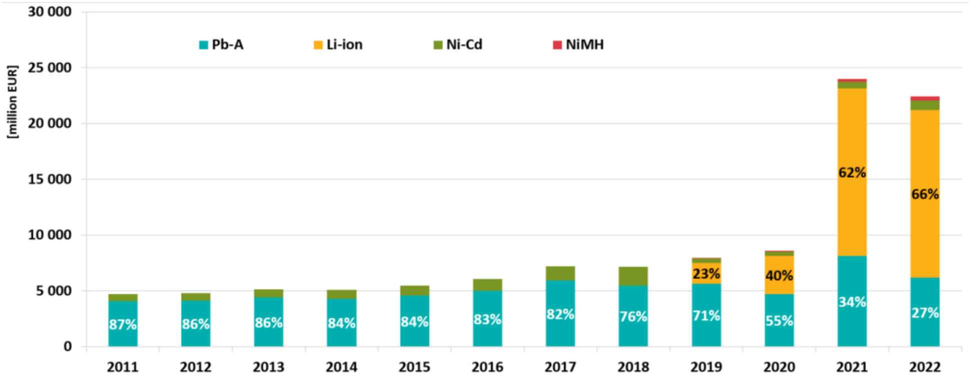


Source: JRC based on PRODCOM data

The data shows that EU production of Pb-A and Ni-Cd accumulators remained stable over a long period, being subjected to short-term fluctuations only, as shown in **Figure 41**. Production of Li-ion batteries emerged at bigger scale in 2019 and since that time is subjected to dynamic changes: almost doubled in 2020, increased more than 4-fold in 2021 and remained stable in 2022.

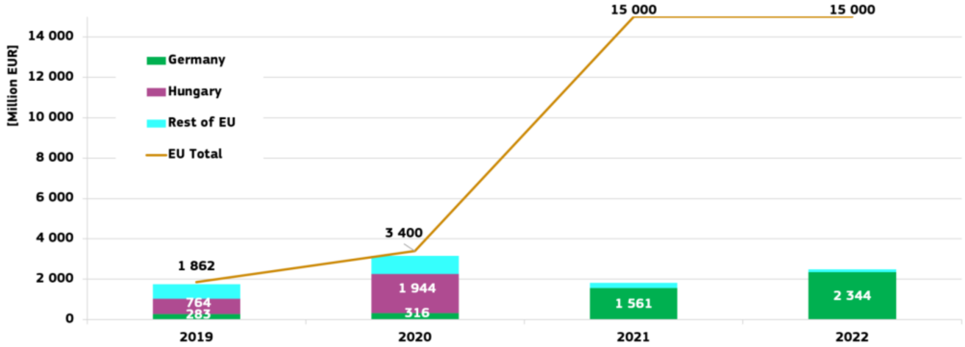
The analysis of Li-ion batteries production trends is very difficult, also due to non-complete data. Production of Li-ion batteries is not disclosed to public domain by some MS. The available data is presented in **Figure 42**. The "Total EU" is a summary production of all MS, including confidential. The difference between the bars and "Total EU" is the production of MS that restricted their statistics, mainly PL (fully-) and HU (partially restricted).

Figure 41. Trends in the EU production of accumulators.



Source: JRC based on PRODCOM data

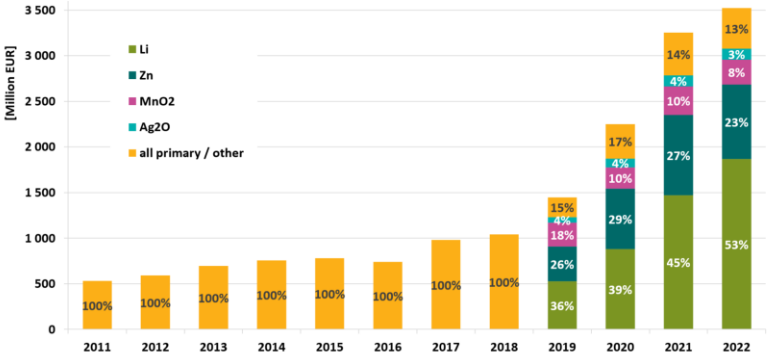
Figure 42. The EU production of Li-ion batteries.



JRC based on PRODCOM data

Production of primary cells exhibited a mild increase at a CAGR of 10% until 2018 followed by very dynamic increase in last four years, at a CAGR of 35%, see **Figure 43**. The most dynamic expansion is observed for Li primary 3.7 V batteries in different form factors. Dynamic increase is also observed for zinc batteries, mostly Zn-Air primary button cells, replacing mercury button cells banned by the battery directive.[132] The production of mercury button cells was reported at a level of 0 EUR since 2021 (no earlier data available). Please note change of the reporting methodology in 2019. Until 2018 all primary batteries were reported under the same PRODCOM code, thus no more granular data on produced battery chemistries is available; as of 2019 Li-air, Zn-air, MnO_2 and Ag_2O are reported under separate codes.

Figure 43. The EU Production of primary cells.



Source: JRC based on PRODCOM data

Production of battery parts and components is dominated by production of accumulator parts (80-99% depending on reporting year), and remained stable at level of 300-400 million EUR in the period 2011-2020. In years 2021-22, it rose to almost 700 million EUR. It is split in about equal parts between production of separators and other parts.

---

[132] 2006/66/EC

4 EU Market Position and Global Competitiveness

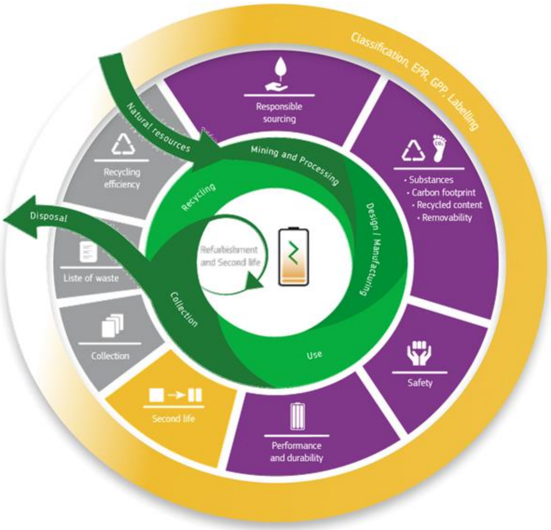
4.1 Global & EU market leaders

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 an innovative, sustainable and globally competitive battery value chain in Europe, which was supported by the Strategic Action Plan on Batteries.[133] In 2019 and 2021, the Commission approved two Important Projects of Common European Interest with a public support of 3.2 billion EUR and 2.9 billion EUR, respectively, facilitating the establishment of many EU production facilities covering the whole Li-ion batteries value chain. In December 2020, the Commission proposed the Battery Regulation aiming to minimise the environmental impact of batteries over their whole life cycle (**Figure 44**). 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. The Battery Regulation[134] is in force as of 17/08/2023. It will apply directly in all EU member states and its provisions will become binding in stages over following years. The regulation will be supplemented by secondary legislation and new harmonized standards.

Figure 44. The life-cycle of batteries as considered in the Battery Regulation.



Source: The Battery Regulation, EU (2023) 1542

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

US adopted several policy measures to support domestic cell and EV production under the Inflation Reduction Act (IRA).[135] It was adopted in August 2022 and has profound impact heavily subsidizing production in the US. It will provide at least 369 billion USD to the US clean energy sector. More than 80 billion USD of new investments is expected in production facilities across the battery supply chain ranging from raw materials to battery cells, modules, electric vehicles and energy storage systems. The effect of IRA has been a clear shift of investments in cell production facilities to US.[136]

---

[133] COM (2018) 293

[134] EU (2023) 1542

[135] https://www.congress.gov/bill/117th-congress/house-bill/5376

[136] I. van Dalwigk, *The Euopean battery supply chain: Status, opportunities and challenges*, AABC Europe 2023, Mainz, Germany

China has strongly supported electric vehicles, the 'New Energy Vehicles' (NEV), with subsidies. A shift towards non-financial motivation such as purchase restrictions for internal combustion engine powered cars in big cities, priority access, discounted or free parking for NEVs, is expected.

In response, the EU started new initiatives in 2023 to rebalance competitiveness. The Temporary Crisis and Transition Framework (TCTF)[137] facilitated the provision of state aid for the production of batteries, matching state aid offered to non-European locations. The Critical Raw Materials Act (CRMA)[126] aims at increasing collection of waste products, increasing domestic strategic raw material extraction and processing and at diversified supply chains. The Net Zero Industry Act (NZIA)[138] aims at scaling up the net zero technologies including batteries by a simplification of the regulatory framework and fast-track permitting for net-zero technologies, such as battery cell production.

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 / expected for battery packs: currently the average EV battery pack in the EU costs 33% more than in China and 8% more than in US. It is expected that IRA could bring down the cost of battery pack in the US to the level of Chinese one while in the EU price could even slightly rise due to increase of energy costs.[135]

A 2022 study showed that currently to set up a battery production plant in the EU an investment of approx. 106 million EUR is needed per 1 GWh/a of production capacity. The same production capacity in the US costs less than 100 million EUR, while in China it is just above 55 million EUR. [139]

Market development: Na-ion

In Dec 2022, the world's first Na-ion gigafactory with an announced production capacity of 1 GWh per year was opened in China by state-owned power company China Three Gorges Corporation.[140] The facility will produce Na-ion batteries in HiNa technology. 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.[141]

CATL and BYD are going to begin production of their Na-ion batteries in late 2023.[142] Globally, there are nearly 30 Na-ion battery manufacturing plants at different development stage (currently operating, under construction or in planning), almost all in China. Their combined yearly production capacity is estimated at over 100 GWh.

The EU leader in Na-ion battery development and commercialisation is Tiamat (FR), a start-up founded in 2017 that raised 5 Million EUR in 2021 and plans to manufacture 18650 cylindrical cells. They developed a 48 V battery pack together with Plastic Omnium Automotive, targeting to start production in 2025 and to ramp up production capacity to 6 GWh/y in 2030.

Altris (SE) is another EU company (founded in 2017, currently about 10 employees) producing Prussian white, a PBA material for Na-ion battery cathodes.

Altech and Fraunhofer plan a 100 MWh/y sodium solid state batteries plant in Saxony (DE), aiming at use in BESS systems. The plant will initially provide 1 600 battery packs per year, each of 60 kWh capacity.[143]

---

[137] 2023/C 101/03

[138] COM (2023) 161

[139] RWTH Aachen University, *Battery Monitor 2022*, 2022

[140] https://www.yicaiglobal.com/news/china-unveils-world-largest-sodium-ion-battery-plant-as-a-lithium-price-hedge

[141] *DOD Releases List of Additional Companies, in Accordance with Section 1237 of FY19 NDAA*, U.S. Department of Defense. August 28, 2020. Archived from the original on 30 August 2020. Retrieved 30 August 2020.

[142] https://pandaily.com/catl-and-byd-plan-to-start-mass-production-of-sodium-ion-batteries-within-this-year

[143] https://www.energy-storage.news/altech-and-fraunhofer-finalise-plans-for-100mwh-sodium-solid-state-ess-battery-plant-in-germany

Market development: RFB

Iron flow battery - the global market is focused in North America, with 1.13 million USD out of 2.14 million USD of global market (2020 data). The expected global market for 2021 was 2.5 million USD and for 2028 was 15 million USD, with a North America share of about 1.2 million USD and 9 million USD, respectively.[144] The projected market development rate was rather moderate until 2023 and significantly increasing after 2024.

Invinity - the world's leading VRFB provider with a portfolio of >65 MWh already deployed or contracted for delivery to 70+ sites in 15 countries. The company is headquartered in London, UK and Vancouver, Canada, with regional representations to the USA, Australia and China. In June 2023 the company has opened production plant in Vancouver that is able to produce 200 MWh of VRFB systems per year.[145]

VRB Energy - a global corporation with a record of >30 MWh of systems installed globally. In 2021 the company decided to set up a VRFB manufacturing facility in China (initially 50 MWh/y finally 1 000 MWh/y) together with a R&D centre and a 100 MW / 500 MWh vanadium flow battery.[146]

ESS Tech Inc. – the US developer of an iron redox-flow battery, company still in the development stage, setting up a factory in Wilsonville, Oregon.[147]

State Power Investment Corp developed the "Ronghe No. 1" IRFB mass production line with independent intellectual property rights. The line can produce 5 000 pieces of 30 kW systems per year (150 MWh/y).[148]

CMBlu – the German developer of Organic SolidFlow batteries, global leader in this technology, founded in 2014 in 2019 exceeded 80 employees. In 2022, the company decided to start the prototype production of their systems within their new Battery Production Center in Alzenau. The company is approaching series production. In 2022, the company established its US subsidiary, CMBlu Energy Inc. in Petaluma, California, to produce systems for the US market.

Elestor (NL), developer of hydrogen-bromine flow battery has currently 50+ employees, and until 2024 plans to grow the above 100 people.[149]

Generally, the community of RFB battery producers observe tendency of locating the production facilities close to their main markets and thus outside the EU.

Market development: Me-air

The global market of metal-air batteries was estimated to 424 million USD in 2021, and is projected to reach 1.6 billion USD by 2031. A CAGR growth of 15% is expected in the period from 2022 to 2031. It is also expected that Asia-Pacific region will provide most of business opportunities for metal-air battery manufacturers. [150]

Polyplus (US), developer of a Li-air battery based on a proprietary protected lithium electrode, employing currently 18 people[151] has installed a pilot manufacturing line for producing their Lithium Seawater Batteries.[152] The same electrode can be used in a Li-air system also patented by the company.

Form Energy, the US developer of Fe-air battery started construction of its first plant in Weirton in May 2023. It is expected that it will produce 500 MW (corresponding to 50 GWh, assuming 100 h storage time declared by the company) of batteries annually and employ 700 people when running at full capacity. The plant represents a total direct investment of 760 million USD, including a financial incentive package from the State of West Virginia worth approximately 290 million USD. First production is expected at the end of 2024.[153]

---

[144] Iron Flow Battery Market Size, share, & COVID-19 Impact Analysis, By Application (Utility, Industrial & commercial, and Off-Grid & Microgrid), and Regional Forecast, 2021-2028, Fortune Business Insights, 2022

[145] https://invinity.com/opens-200-mwh-vancouver-manufacturing-facility/

[146] https://vrbenergy.com/vrb-energy-announces-agreement-for-chinas-largest-solar-battery-a-100mw-solar-storage-project-in-hubei-province/

[147] https://essinc.com/

[148] https://equalocean.com/briefing/20220130230117002

[149] https://www.elestor.nl/affordable-long-term-electricity-storage-key-to-clean-energy-system/

[150] S. Surya, B. Supriya, V. Vitika, *Metal-Air Battery Market Research, 2031 – Report overview,* available at https://www.alliedmarketresearch.com/metal-air-battery-market-A09767

[151] https://polyplus.com/company/

[152] https://polyplus.com/polyplus-achieves-major-u-s-battery-manufacturing-milestone-product-line-established-for-protected-lithium-electrodes-and-lithium-seawater-batteries-that-deliver-record-setting-energy-density-of-200/

[153] https://formenergy.com/form-energy-breaks-ground-on-form-factory-1-in-weirton-wv/

AZA Battery (BE), a developer of Zn-air battery system has opened a new lab for applied research in Paris in Sep 2022.[154] In 2022, the company was employing 20 people.[155]

E-Zinc (CA), a developer of Zn-air batteries, was counting 78 employees in 2022.[156] The company was selected (second year in a row) for the 2023 Global Cleantech 100 List.[157] The company is setting up a 5 000 m^2 manufacturing facility in Mississauga, Ontario. The facility completion is expected by the end of 2023. It will enable the company to commence a revenue-generating pilot program in 2024. Finally, in about two years, the company wants to scale up production and grow internationally.[158]

Market development: zinc batteries (other)

Gelion (AU) – developer of a non-flow zinc-bromine battery called "Endure", has opened a plant in Sep 2022 with an annual production capacity of 2 MWh. This plant is an adapted former Pb-A batteries plant and according to the company about 70% of existing processes were adapted to the new chemistry. They also claim the cost of the plant was about 7-9 times lower than to build new plant of Li-ion batteries with the same production capacity.

EOS (US) – developer of Eos Z3 zinc-bromine non-flow battery claimed over 275 employees and 800 MWh of annual production capacity at end 2021.[159] The company also claimed an order backlog of 347 MWh and about 2.2 GWh of binding orders.[160] EOS expect a revenue of 17-20 million USD for 2022 and 30-50 million USD for 2023. The company participates in the Department of Energy Loan Programs Office's due diligence process under the Inflation Reduction Act 2022 implementation phase. They expect a loan of at least 250 million USD, if successful.[161] The company claims that the investment in new manufacturing capacity is low, around 30 million USD per 1GWh of manufacturing capacity.[12]

Market development: Li-ion

The globally leading companies in Li-ion batteries production and sales based on SNE Research data*[162]* are presented below in **Table 10** and **Table 11**.

Table 10. Global top 10 battery manufacturers

	company	change (vs. 2021)	market share (Jul 2022)
1.	CATL (CN)	0	34.8%
2.	LG Energy Solution (KR)	0	14.4%
3.	BYD (CN)	+1	11.8%
4.	Panasonic Holdings Corporation (JP)	-1	9.6%
5.	SK Innovation (KR)	+1	6.5%
6.	Samsung SDI (KR)	-1	4.9%
7.	CALB Group (CN)	0	4.1%
8.	Gotion High-tech (CN)	0	2.9%
9.	Sunwoda Electric Vehicle Battery (CN)	0	1.5%
10.	Svolt Energy Technology (CN)	new	1.3%

Source: JRC based on SNE Research data

A remarkable increase (above 100%) of sales numbers y/y was observed for all listed Chinese companies and only for Chinese companies.

---

[154] https://www.azabattery.com/aza-expands-rd-with-a-new-applied-research-lab-in-paris/

[155] https://pitchbook.com/profiles/company/442372-87#overview

[156] https://pitchbook.com/profiles/company/231861-34#overview

[157] https://www.businesswire.com/news/home/20230112005784/en/e-Zinc-Selected-for-the-2023-Global-Cleantech-100-List

[158] https://businessviewmagazine.com/e-zinc-toronto-ontario/

[159] https://www.eose.com/company/

[160] https://www.bloomberg.com/press-releases/2023-05-09/eos-energy-enterprises-reports-first-quarter-2023-financial-results

[161] https://www.globenewswire.com/en/news-release/2023/02/02/2600477/0/en/Eos-Energy-Enterprises-Inc-Provides-Business-Update

[162] https://www.sneresearch.com/en/insight/release_view/82/page/0?s_cat=|&s_keyword=

Table 11. Global top 10 battery sellers by application

	company	sales 2022 [GWh]			growth rate y/y [%]		
		EV	BESS	total	EV	BESS	total
1.	CATL (CN)	270	53	323	135	212	145
2.	LG Energy (KR)	92	9	101	19	13	19
3.	BYD (CN)	84	14	98	163	180	165
4.	Panasonic (JP)	49		49	4		4
5.	SK Innovation (KR)	36	9	45	89	13	67
6.	Samsung SDI (KR)	44		44	83		83
7.	CALB Group (CN)	24		24	140		140
8.	Gotion (CN)	17	6	23	113	500	156
9.	Sunwoda (CN)	9	9	18	125	800	260
10.	Svolt (CN)	11		11	267		267

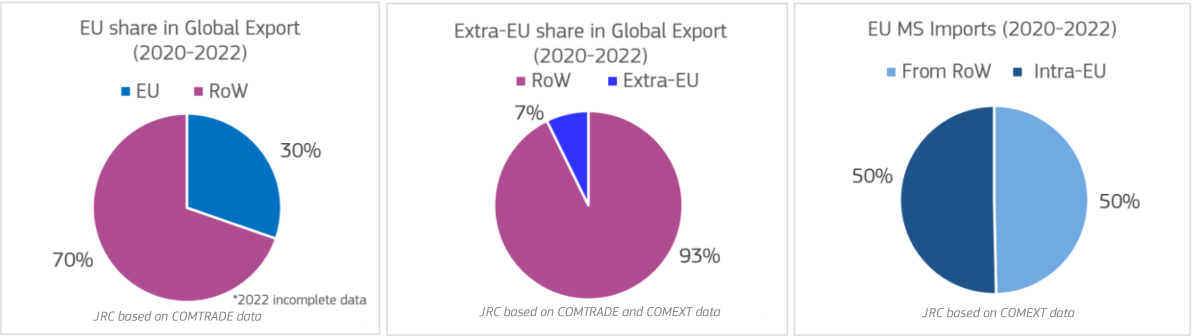
Source: JRC based on SNE Research data

4.2 Trade and trade balance

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

The global export of batteries is estimated at about 183 billion EUR over the period of 2020-22. The EU export to non-EU countries reached almost 13 billion EUR in the same time, which is 7.1% of the global market. Including the EU internal exports, the total EU exports were at level of 55 billion EUR, which corresponds to 30% of the global market. The EU satisfied half of its battery demand by imports from non-EU countries, while another half was produced internally. The EU export and import shares in global export and import of batteries are presented in **Figure 45**.

Figure 45. Share of total and EU-external export in the global market, source of the EU imports.


EU share in Global Export (2020-2022)

JRC based on COMTRADE data

Extra-EU share in Global Export (2020-2022)

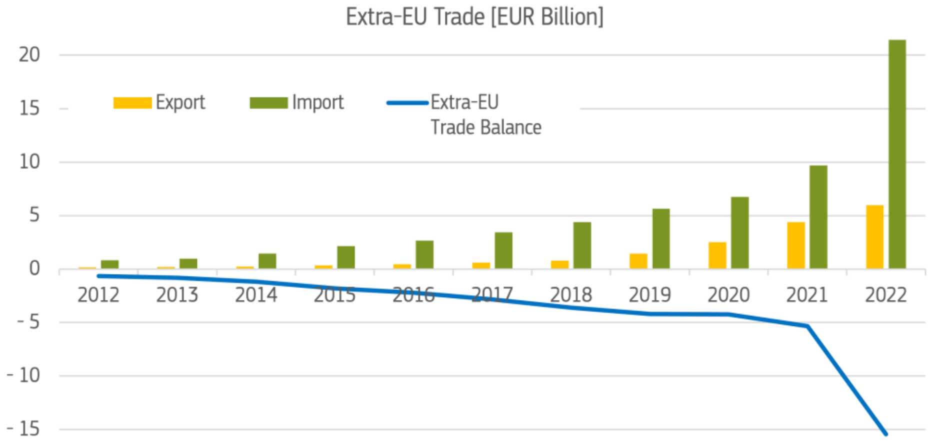
JRC based on COMTRADE and COMEXT data

EU MS Imports (2020-2022)

JRC based on COMEXT data

The evolution of the EU exports, imports and trade balance in the period 2012-22 is presented in **Figure 46**. In 2022, the EU export rose by 36%, however in the same time import rose by 120% leading to record high imbalance in battery trading of the European Union. The EU deficit reached 15 billion EUR, 190% more than in 2021, rising faster than ever before.

Figure 46. The EU exports, imports and trade balance in 2022



JRC based on COMEXT data

On the growing markets[163] during 2019-2021[164], the EU reached 37%, 40% and 44% share in the country's battery imports in the UK, Mexico and Switzerland respectively (see **Table 12**).

Table 12. Growing markets based on a 2-year average of net import change

Country	2-year average of net import change	Total import (2019-2021) [Million EUR]	% import from the EU
China	3 458	9 677	12%
South Korea	1 738	5 384	3%
Japan	1 707	3 872	1%
Vietnam	1 472	6 603	4%
United Kingdom	1 203	2 457	37%
Mexico	638	2 690	40%
Other Asian	390	1 373	3%
Canada	281	1 083	7%
Brazil	258	1 065	1%
United States	208	14 494	9%
Australia	168	1 285	4%
India	166	3 489	1%
Singapore	135	597	17%
Turkey	125	478	3%
Switzerland	86	590	44%
Philippines	80	504	1%
Indonesia	77	789	0%
Russia	43	438	6%
Thailand	40	640	8%

Source: JRC based on COMTRADE data

The top 5 EU partners in battery trading are shown in **Figure 47**. China remains the main importing partner holding 72% of total extra-EU imports, much higher than the 65% limit set by NZIA[165]. Germany, Netherlands and Czechia, the top EU importers for 2020-2022, brought respectively 77%, 58% and 87% of their extra-EU imports from China.

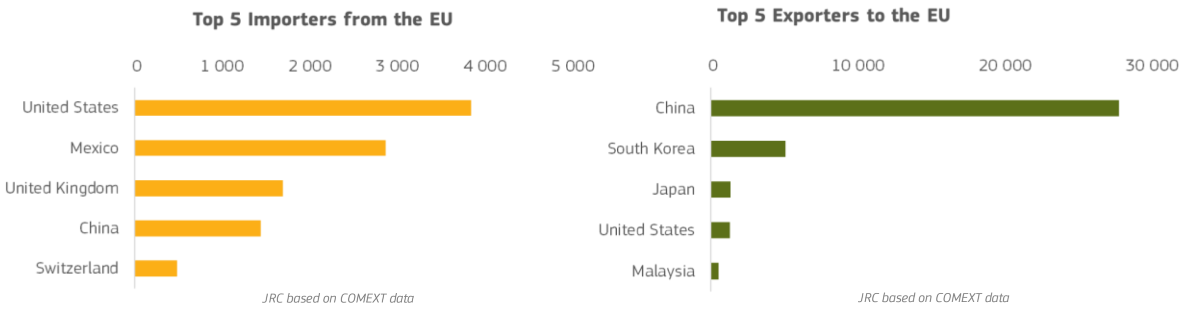
---

[163] Calculated as $net\ import\ change = [(import_{2020} - import_{2019}) + (import_{2021} - import_{2020})]/2$

[164] Last complete data available for 2021; for 2022 comtrade does not provide estimates for the missing values as comext does.

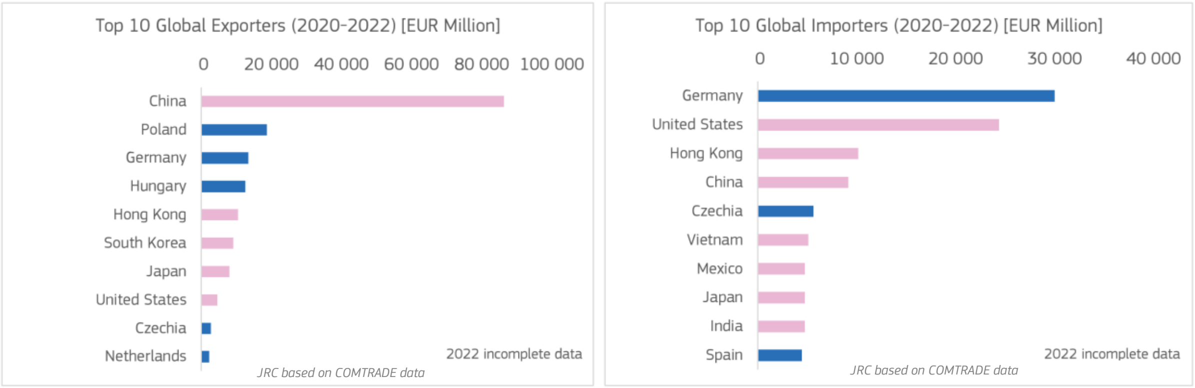
[165] COM(2023) 161 final & SWD(2023) 68, 16th March 2023. Net Zero Industry Act

Figure 47. Top 5 EU partners in battery trade in 2020-22 [million EUR].



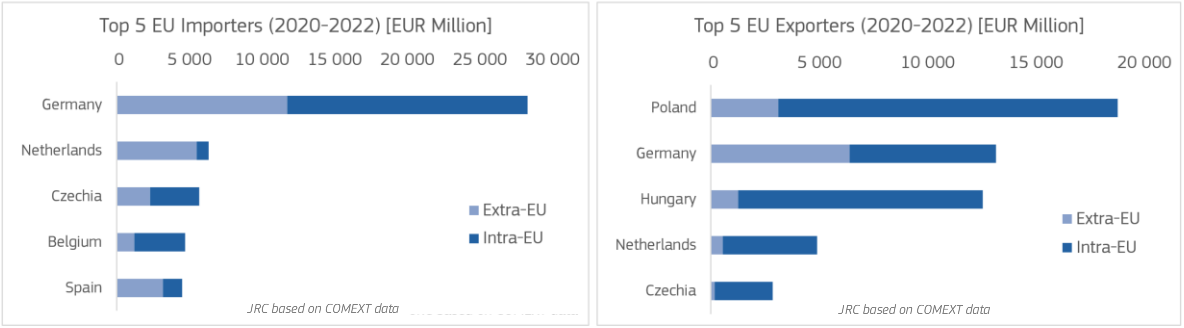
The global top 10 countries in battery exports and imports are presented in **Figure 48**. In global top 10 of battery exporters China remained the biggest global exporter by far, Poland, Germany and Hungary are listed at place two, three and four respectively. Analogically, Germany is the global importer number one keeping the position from last year. Czechia appeared in both ranking lists, while Poland and Netherlands went off the top 10 global importers.

Figure 48. Global top 10 countries in battery trade in 2020-22



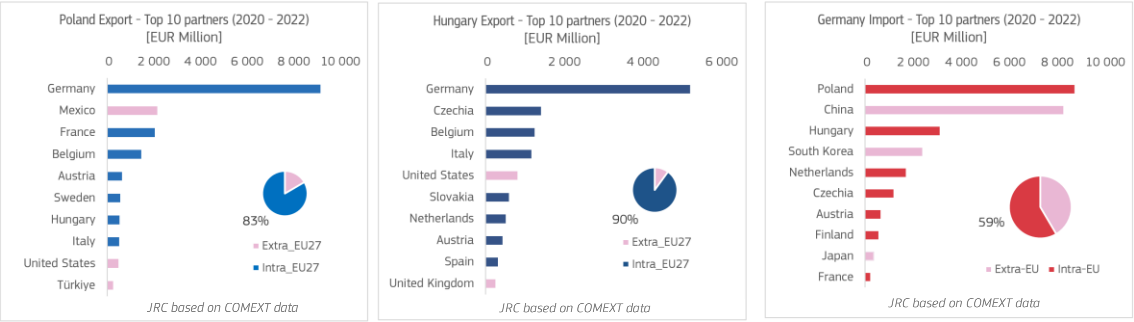
The top 5 EU exporters and importers are shown in **Figure 49**. Poland, Germany and Hungary were the top EU exporters for 2020-2022, and only Poland and Hungary reached a positive trade balance. The biggest importer is Germany.

Figure 49. Top 5 EU MS in battery imports and exports in 2020-22



Main directions of export from Poland and Hungary, as well as main sources of import to Germany are presented in **Figure 50**.

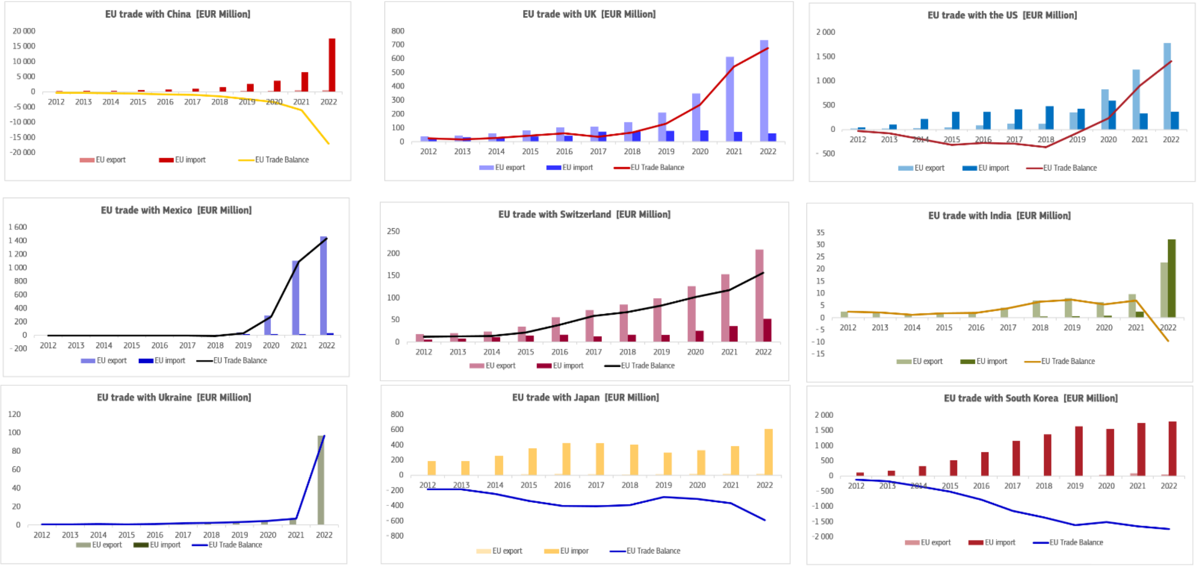
Figure 50. Top 10 destinations of PL and HU exports as well as top 10 sources of DE imports in 2020-22



Analysing the time trends in the EU trade (see **Figure 51**), it should be noted that:

1. EU imports from China increase very fast, in 2022 it was over 170% bigger than in 2021, causing 185% increase of the negative trade balance in 2022 relative to 2021.
2. 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).
3. In the same period, the EU strongly increased exports to the US reversing its earlier slightly negative trade balance.
4. EU is steadily increasing export to Switzerland, although at still rather limited level.
5. Imports from South Korea and Japan increase at limited pace with almost no export to those countries, generating significant (KR) or limited (JP) deficit.
6. In 2022, export to Ukraine jumped, remaining however at still low level.
7. In 2022, export to India rose fast, more than doubling within a year. However, import in the same period multiplied, reversing the earlier observed positive trade balance. Still the trade with India remained at low level.

Figure 51. 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. However, the existing cell production facilities attract their suppliers and a development of local supply chains around those production centres is already observed. The EU imports also most of cell manufacturing equipment.

4.3 Resource efficiency and dependence in relation to EU competitiveness

The EU depends heavily on third countries for battery raw materials and also battery production equipment. This topic was broadly presented in the 2022 edition of CETO[4] and will not be repeated here, as the situation in the sector cannot change quickly. Here a short summary:

China currently holds 37%, 72%, 67% and 75% shares in raw materials, processed materials, components and cell production global markets, respectively, in the value chain of Li-ion batteries. The EU holds 2%, 4%, 3% and 6% share in those markets respectively.[125]

European supply of graphite for 2030 is likely to remain well below 5% of total European demand. European projects for cobalt and nickel mining that are under way have the potential to satisfy up to 4% and 2% of the European demand, respectively. According to EBA250, Europe should be able to cover up to 20% of the battery ecosystem's needs for lithium by 2025.

Industrial projects for production of cathode active materials, electrolyte or separators in the EU are on the way, so improvement in the EU production is expected in the next few years.

The EU share in global cell production is expected to improve with opening of production facilities currently in development stage. However, competition from Asian and American companies is very strong, especially after IRA was announced in the US.

EU remains strong in the application field, holding above 25% of global EV production. However, also here competition from Chinese companies is very strong. In the field of stationary energy storage systems the EU is not a strong player, and it should not be expected that it will become.

As of July 2023, there were battery recycling plants installed in Europe with an overall recycling capacity of 116 kt per annum. It is expected, that this capacity will increase to 400 kt per annum by 2030.[166] The battery recycling facilities very often are located in the direct neighbourhood of cells production plants as this process is associated with high yield of production scrap. In the first period after factory commissioning the scrap rate can reach even 40-60% by weight. In the period of 5-6 years after starting the new factory the production processes are stabilised enough to bring the scrap yield down to about 5-10%.[167] Currently, Germany holds the highest number of battery recyclers in the EU.[168]

Battery recycling is one possible way to reduce EU's dependence on the supply of battery raw materials. There are three main recycling methods that are commercially available: mechanical, pyrometallurgical and hydrometallurgical:

- Mechanical – involve (often manual) separation of batteries based on chemistry, disassembly and separation of cells and other components, shredding of cells (or full batteries, sometimes in inert atmosphere), physical separation of materials based on physical state, grain size, density, magnetic properties, etc. Products of this process are: plastics, metals (Cu, Al, steel), electrolyte (if recovered) and black mass (fine powder containing mixed and contaminated anode and cathode materials). Usually, a mechanical process is followed by a hydrometallurgical process.
- Pyrometallurgical – this process requires little pre-treatment or separation of batteries. Basically, it involves burning and smelting of batteries in a single process. Metals (except Li, Al and Fe) are recovered in the form of a multi-metallic alloy; Li, Al, Fe and eventual ceramics are contained in the slag and usually not recovered. Graphite, plastic and electrolyte solvents are burned and also not recovered. Products of the process (alloy and slag) must treated further in a hydrometallurgical process to recover materials in battery-grade quality.
- Hydrometallurgical – this process can accept black mass after mechanical treatment or an alloy (and slag) after pyrometallurgical process to separate metals, purify and transform them into useful battery grade chemicals. It involves wet chemistry processes of dissolving, leaching, solvent extraction, precipitation etc. It is relatively costly, chemical- and water-intensive, but it is the only commercially available process to recover battery-grade materials.
- Direct recycling – this process is still in the development phase, not available commercially yet. It involves physical processes (like in the mechanical process, it can be also seen as continuation or phase II of mechanical recycling) able to separate black mass into single components, e.g. graphite and NMC.

---

[166] RWTH Aachen University, *Battery Monitor 2022*, 2022

[167] Strat Anticipation, *Battery demand & supply forecasts & analysis*, Paris, 9th March 2023

[168] RWTH Aachen University, *Battery Atlas 2022*, 2022

> If successfully applied and recovered materials are of high purity and quality offering not deteriorated durability of batteries produced using them, this would be most economical method of recycling.

Currently, the most of commercial scale recyclers in Europe and US offer only mechanical or pyrometallurgical recycling and thus cannot produce battery-grade secondary raw materials for further use in battery manufacturing. Usually the black mass containing most valuable metals is sent to recyclers in the Asia-Pacific region for a hydrometallurgical process to obtain battery-grade materials. This, however, is changing and also recyclers in Europe and US are expanding their capacities to cover also hydrometallurgical processes, e.g. Fortum has recently started commercial operation of its plant in Harjavalta, (FI), the first commercial-scale facility in Europe for hydrometallurgical recycling. In the US, Li-Cycle is setting a hydrometallurgical plant too.[169] It is expected that by 2025, the EU recycling capacity will reach 400 000 t/y due to setting up new and expansion of existing plants.[170]

The rate of Na-ion batteries commercialisation in China is extremely high. There are about 30 production projects ongoing, at different development stage. The summary production capacity of over 100 GWh/y is expected from those projects. In this light, it should be expected that the EU will develop dependence from China in this technology.

---

[169] https://www.idtechex.com/emails/view.asp?emailtypeid=15279

[170] https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-kapazitaeten-bedarf-akteure-markt-analyse.html

5 Conclusions

5.1 Status of non-Li technologies

Na-ion batteries are being commercialised and their production is scaled up extremely quickly, mostly by Chinese companies. The position of the EU is rather weak with only one start-up aiming to start production of Na-ion batteries and one small cathode material supplier.

With specific energy comparable to LFP, similar or better performance, increased safety and lower price, Na-ion batteries are very likely to enter the market of EVs, just as LFP chemistry has already established a place there. Furthermore, in stationary energy storage market Na-ion batteries will most likely play a role as well.

Na-ion batteries are exposed to geopolitical risks to a very limited extent, as they do not contain CRMs and generally use less costly materials.

Analysing the CETO 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 those technologies will be dominated by China.

Redox-flow batteries represent a wide range of technologies at different stages of development, of which the most advanced are commercially available. The rate of commercialisation is much lower than that for Na-ion batteries. The global leader is the US, while several countries from the RoW group also have a strong position.

The EU has several producers, but the EU market of flow batteries is not large due to well-developed energy grid (lower market for energy storage in general), price currently higher than competing technologies, lower maturity (thus higher risk), lack of positive record of past use at large scale (typical for new technologies). It is not expected that the EU will became a global leader in the future. There is a visible trend to locate production facilities close to main markets and thus outside the EU.

Redox-flow batteries are not expected to enter the EV market, but would be a valuable technology in stationary energy storage.

Redox-flow batteries are also exposed to geopolitical risks to a very limited extent, as they do not contain CRMs and generally use less costly materials (with exception of vanadium redox-flow batteries).

Scaling up the production to achieve the effect of scale and a resulting cost reduction, which would allow flow batteries to compete with technologies well settled in the market remains a significant challenge.

Analysis of CETO indicators leads to the conclusion that the redox-flow battery technology is not a subject of focus in the EU, leaving a lot of space for others to develop and strengthen their position in the market. RFB technologies will likely be dominated by the US and a few RoW countries, but not by only one country alone.

Metal-air batteries are at the last stages before commercialisation by the technology leaders. The most advanced systems are built using Fe, Zn, Al and Li. The rate of development is lower than that of redox-flow batteries. The global leaders are the US, Ca and EU. An EU market does not exist yet (except for primary batteries).

The market for Me-air batteries likely will be in stationary energy storage. Me-air batteries are not exposed to geopolitical risks, with the exception of Li-air systems, and are generally made of cheap and non-toxic metals. Nonetheless, commercialisation of the technology remains a challenge, while upscaling the production to a level which will allow them to compete with other established technologies is demanding. Analysis of CETO indicators leads to the conclusion that the Me-air battery technology is not a subject of focus in the EU.

Zinc batteries (non-flow and non-air) are already commercially available and few more technology variants are still being developed. The rate of development is high. The EU has one technology developer, however the leaders are the US and AU. The EU market is not large, and it should not be expected that it will become a leading global market in the future. Zn batteries are not expected to enter the EV market, but could be a valuable technology in stationary energy storage. They are not exposed to geopolitical risks, nor supply issues as zinc is rather cheap and a non-toxic metal. The production process has synergies with the production of lead-acid batteries and requires low investment. The technology needs to compete with other technologies established in the market.

Analysis of CETO indicators leads to the conclusion that the Zn battery technology is not a subject of focus in the EU. It is likely that the US and AU will develop and strengthen their position.

5.2 Overall battery technology and market status

Li-ion batteries market and especially the EV market advances fast in the EU, however China significantly strengthened its position and overpassed the EU in respect of EV share in the vehicles market.

The main market demand continues to be for transportation. The stock of EVs in the total EU fleet is increasing, but is still at level <3%, thus no large effects on conventional fuels markets is observed yet. It should be expected to see increasing effects in the coming years. Currently the Chinese EV producers experience fastest growth in the global scale, significantly faster than that of the EU and US producers. Buses are the most electrified sector of transport with the share of EVs in the fleet at about 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. This ranking of market size is expected to remain the same in the future.

The average cost of batteries increased by 7%, breaking the decreasing trend. It is expected that prices in 2023 will be at the level of 2022 and that the decreasing trend will continue in the future. In the long perspective prices of stationary storage and truck batteries will converge and remain about doubled compared to EV batteries.

R&D funding in the EU remains high, however it is difficult to estimate the amount of support given especially to the Chinese companies in form of low environmental standards, cheap electricity, doted demand, waived taxes, etc.

The EU is also quickly developing its battery production capacities, however there have been shifts of international investments from the EU to the US after adoption of the IRA law. The EU experienced stagnation of battery production in 2022, and a very high deficit in battery trade balance. It still depends heavily on third countries for raw battery materials and battery production equipment.

Li-ion batteries are exposed to different levels of geopolitical risk depending on exact chemical formulation; this ranges from medium (for LFP) to high (for NCA and NMC). The materials are rather costly and prone to high price variability. Their production is linked with sustainability risks thus the Battery Sustainability Regulation was adopted to control these.

Analysis of CETO indicators leads to the conclusion that only the high performance Li-ion battery technologies closely related to the high performance automotive sector are a subject of focus in the EU. New technologies are being developed including production, use and recycling stages. The development of new production capacity is also advancing and is on a good track to cover EU needs in 2030. The cheaper, lower performing LFP technology is not a subject of focus in the EU. China and other countries keep a dominating position in production of LFP batteries, which is however a key technology for stationary energy storage applications.

List of abbreviations and definitions

18650 - one of standard formats of cylindrical batteries; 18 mm diameter, 65 mm length
AA - common format of portable battery cell
AABC - Advanced Automotive Battery Conference
AAA - common format of portable battery cell
ACEA - European Automobile Manufacturers' Association
ALBATTS- Alliance for Batteries Technology, Training and Skills
APS - Announced Pledges Scenario of IEA
ARPA-E - Advanced Research Projects Agency–Energy, a United States government agency
AU - Australia
BE - Belgium
BESS - battery energy stationary storage
BEV - battery electric vehicle
BMS - battery management system, electronic circuits managing battery state
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
CRMA - Critical Raw Materials Act
CZ - Czech Republic
DE - Germany
DG - Directorate General
DK - Denmark
DMC - dimethyl carbonate
DME - dimethoxyethane
EAFO - European Alternative Fuel Observatory
EASE - The European Association for Storage of Energy
EC - ethylene carbonate
EMMES - European Market Monitor on Energy Storage
ENER - The Directorate-General for Energy, a Directorate-General of the European Commission
EoL - end of life
EOS - company name
ES - Spain
EVE - company name
EU - European Union
Fi - Finland
FR - France

FWCI - Field Weighted Citation Impact
GAC - company name
GM - General Motor
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
ICRFB - iron-chromium redox-flow battery
IEA - International Energy Agency
IRFB - iron redox-flow battery
IN - India
IRA - Inflation Reduction Act
IS - Israel
ISO - International Standardisation Organisation
IT - Italy
JP - Japan
JV - joint-venture
JRC - Joint Research Centre
kWh - kilowatthour, energy unit = $3.6 \cdot 10^{6}$ J
KR - South Korea
L - litre, volume unit = 1 dm^3
LCA - Life Cycle Assessment analysis
LEAG - German energy provider
LFP - lithium iron phosphate
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. $Na_{0.75}Ni_{0.82}Co_{0.12}Mn_{0.06}O_2$
Me-air - metal-air
MS - Member State, country belonging to the European Union
MW - megawatt, unit of power = 10^6 W
MWh - megawatthour, energy unit = $3.6 \cdot 10^{9}$ J
NA - not available
Na-ion - sodium-ion
Na-S - sodium-sulfur
NASA - National Aviation and Space Agency, (US)
NCA - nickel cobalt aluminium oxide
NEV - New Energy Vehicles
NG - natural gas
NGK - Nandha Gopalan Kumaran, company
NIB - sodium-ion batteries
NL - Netherlands
NMC - nickel manganese cobalt oxide
NVP - sodium vanadium phosphate, battery chemistry based on $Na_3V_2(PO_4)_3$

NZIA - Net Zero Industry Act

OECD - Organisation for Economic Co-operation and Development

ORR - oxygen reduction reaction

OSFB - organic solid flow battery

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

PBA - Prussian blue analogues, group of compounds based on iron hexacyanide, e.g. $Na_2Mn[Fe(CN)_6]$

PC - propylene carbonate

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

PRODCOM - PRODuction COMmunautaire, provides statistics on the production of manufactured goods

PSB - polysulfide-bromine battery

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

RTE - round trip efficiency – ratio of energy drought from battery during full discharge to energy needed to fully charge it prior discharge

SBB - sulfur-bromide battery

SE - Sweden

SET - The European Strategic Energy Technology Plan

SETIS - SET Plan information system

SI - specialisation index

SK - Slovakia

SLI - starter-light-ignition, standard 12 V (24 V) battery in a car

STEPS - IEA scenario

SWOT - strength-weakness-opportunity-threat analysis

TCTF - Temporary Crisis and Transition Framework

TEA - tetraethylammonium

TIM - Tools for Innovation Monitoring

TM - transition metal

TRL - technology readiness level

UK - United Kingdom

US - United States of America

UPS - uninterrupted power supply

VRFB - vanadium redox-flow battery

VW - Volkswagen

WiS - water-in-salt

Wh - watthour, energy unit = $3.6 \cdot 10^3$ J

ZBB - zinc based batteries

ZBFB - zinc-bromide flow battery

ZIB - zinc-ion batteries

List of figures

List of tables

Annexes

Annex 1. Summary Table of 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	EC – GROW (CIndECS)
	Gross Value Added	not available
	Environmental and socio-economic sustainability	internal LCA analysis, scientific literature
	EU companies and roles	IDTechEx, other reports, Internet
	Employment	EC – GROW (CIndECS)
	Energy intensity and labour productivity	not available
	EU industrial production	PRODCOM
Global markets and the EU positioning	Global market growth and relevant short-to-medium term projections	IDTechEx, other reports, Internet
	EU market share vs third countries share, including EU market leaders and global market leaders	IDTechEx, other reports, Internet
	EU trade (imports, exports) and trade balance	COMEXT, COMTRADE
	Resource efficiency and dependencies (in relation EU competiveness)	IDTechEx, other reports, Internet

Annex 2. Sustainability Assessment Framework

Parameter/Indicator	
Environmental	
LCA standards, PEFCR or best practice, LCI databases	LCA is a standardized methodology to estimate the environmental impacts of products/services, and various LCAs of both batteries and their adoption in different applications are already available. In the framework on the Product Environmental Footprint (PEF)160, the "Product Environmental Footprint Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications"161 were published back in 2018. These rules provide the necessary information to develop reproducible, comparable and verifiable LCA of different types of batteries. Currently, in the framework of the Regulation (EU) 2023/1542, Article 7 states that "*for electric vehicle batteries, rechargeable industrial batteries with a capacity greater than 2 kWh and LMT batteries a carbon footprint declaration shall be drawn up for each battery model per manufacturing plant*" and such a declaration shall be developed in accordance with the methodology set out by specific delegated act for the different batteries' categories. The report with the possible CFB rules for EV batteries prepared by the JRC is available.[171]
GHG emissions	Based on the PEFCR of batteries[172], the benchmark Climate Change (kg $CO_{2eq.}$) values for four different representative batteries are the following: • 0.95 kg $CO_{2eq}{\cdot}kWh^{-1}$ for CPT-Li-ion batteries (excluding the use phase) • 0.57 kg $CO_{2eq}{\cdot}kWh^{-1}$ for ICT-Li-ion batteries (excluding the use phase) • 0.80 kg $CO_{2eq}{\cdot}kWh^{-1}$ for ICT-NiMH batteries (excluding the use phase) • 0.42 kg $CO_{2eq}{\cdot}kWh^{-1}$ for e-mobility Li-ion batteries (excluding the use phase) Such values are now under revision to support Article 7 of the Regulation (EU) 2023/1542 which requires the declaration of the carbon footprint of batteries that are put in the EU market, to promote the adoption of more sustainable batteries.
Energy balance	Energy (electricity mix) is used in manufacturing cells/assembly the battery pack are reported below according to the PEFCR (2018): • 41.20 $MJ{\cdot}kg^{-1}$ of battery for CPT-Li-ion batteries • 12.90 $MJ{\cdot}kg^{-1}$ of battery for ICT-Li-ion batteries • 41.20 $MJ{\cdot}kg^{-1}$ of battery for ICT-NiMH batteries • 41.20 $MJ{\cdot}kg^{-1}$ of battery for e-mobility Li-ion batteries For the use phase, the losses of energy are considered in the PEFCR: • 6.9 $kWh{\cdot}kg^{-1}$ of battery for CPT-Li-ion batteries • 11.7 $kWh{\cdot}kg^{-1}$ of battery for ICT-Li-ion batteries • 11.6 $kWh{\cdot}kg^{-1}$ of battery for ICT-NiMH batteries • 9.6 k $Wh{\cdot}kg^{-1}$ of battery for e-mobility Li-ion batteries Similarly, some energy is also used for the EoL treatment (in this case recycling is considered): • 0.3 $MJ_{electricity}{\cdot}kg^{-1}$ of battery and 0.9 MJ from natural gas$\cdot kg^{-1}$ of battery for CPT-Li-ion batteries • 0.42 $MJ_{electricity}{\cdot}kg^{-1}$ of battery and 1.24 MJ from natural gas$\cdot kg^{-1}$ of battery for ICT-Li-ion batteries • 0.41 $MJ_{electricity}{\cdot}kg^{-1}$ of battery and 1.23 MJ from natural gas$\cdot kg^{-1}$ of battery for ICT-NiMH batteries

---

[171] https://eplca.jrc.ec.europa.eu/permalink/battery/GRB-CBF_CarbonFootprintRules-EV_June_2023.pdf

[172] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

	- 0.69 $MJ_{electricity}·kg^{-1}$ of battery and 2.07 MJ from natural gas·kg^{-1} of battery for e-mobility Li-ion batteries
Ecosystem and biodiversity impact	Impacts of biodiversity mainly relates site-based practices. Supporting studies to the PEFRC have not identified specific hotspots therefore the impact of batteries on ecosystem and biodiversity "is not at the moment of concern".
Water use	Water is used in manufacturing processes of batteries. Default water quantities used in cells and battery pack manufacturing are reported in the PEFCR of batteries. For instance, the amount of water needed in manufacturing the battery is: - 11 kg·kg^{-1} of battery for CPT-Li-ion batteries - 11 kg·kg^{-1} of battery for ICT-Li-ion batteries - 5.5 kg·kg^{-1} of battery for ICT-NiMH batteries - 11 kg·kg^{-1} of battery for e-mobility Li-ion batteries
Air quality	
Land use	No significant impacts on land use have been identified by the supporting PEFCR. Main concerns derive from the size of manufacturing plants and the possible increase of such an industrial sector.
Soil health	
Hazardous materials	As already stated in the Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, the Regulation (EU) 2023/1542 confirmed the prohibition of putting into the EU market batteries and accumulator containing hazardous materials, with specific reference to mercury and cadmium (and lead from 2024) above specific thresholds. Also, in case of mercury, cadmium and lead content, this needs to be reflected through labelling[173].
The Economic	
LCC standards or best practices	Life Cycle Costing (LCC) is a methodology that can be used to estimate the total costs of batteries along their life-cycle. LCC on batteries are already available for different type of applications; among others, a LCC analysis is provided by the Preparatory Study on Ecodesign and Energy Labelling of Batteries (Hettesheimer et al., 2019) [174].
Cost of energy	An LCC analysis was developed for the Ecodesign Preparatory study (Hettesheimer et al., 2019). The study provides the Capital Expenditure (CAPEX), the Operational Expenditure (OPEX) and the Levelized Cost Of Energy (LCOE) for batteries used in BEV, PHEV, truck and ESS applications (residential and commercial).
Critical raw materials	Several materials belonging to the Critical Raw Materials List for the EU[175] 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) (JRC, 2023)[176],[177]. Among the used CRMs, cobalt and lithium are mainly used in cathodes (e.g. nickel-manganese-cobalt cathodes) and natural graphite in anodes (JRC,2023[175]). 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

---

[173] https://echa.europa.eu/legislation-profile/-/legislationprofile/EU-BATTERIES

[174] https://www.eceee.org/static/media/uploads/site-2/ecodesign/products/Batteries/ed_battery_study_task5_v3_20190823.pdf

[175] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

[176] https://publications.jrc.ec.europa.eu/repository/handle/JRC132889

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

	term, even though global supply of these materials will be increasingly diversified[175]. 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[175,178].
Resource efficiency and recycling	The adoption of more resource-efficient batteries and the increased flows of secondary materials obtained from batteries recycling has potential to maximize the value of materials and to keep them within the EU, hence decreasing the EU dependency from imports. The Regulation (EU) 2023/1542 foresees progressive minimum recycling efficiencies for lead-acid, Li-based, nickel-cadmium batteries and other waste batteries. In addition, specific materials recovery levels need to be achieved for cobalt, copper, lead, lithium and nickel. JRC is currently leading the work related to the definition of measurement rules and related targets to maximize the collection of portable and light means of transport waste batteries as well as the calculation rules of recycling efficiency and material recovery levels. 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[179]. Key aspects to promote circularity are: 'design for circularity', traceability of batteries along their value-chain, development of business cases related to circular economy strategies, maximisation of waste batteries collection and development of high-quality recycling technologies.
Industry viability and expansion potential	*Yes, see markets section*
Trade impacts	*Yes, see markets section for volume and import/export balance*
Market demand	*Yes, see markets section*
Social	
S-LCA standard or best practice	The Social LCA methodology can be used to identify social hotspots and impacts along the batteries supply chain. Comprehensive life cycle-based studies on social impacts of batteries are scarce and the methodology is still under development (Batteries Europe, 2021),[180] (Shi et at., 2023),[181] (Koese et al., 2022).[182] Concerning data, uncertainties are high also due to the lack of primary data, the low granularity of available secondary data, and the limited possibility to generalize results from specific case studies/assessments. Hence, interpretation of results can be challenging (Batteries Europe, 2021). Analyses identifying social hotspots along the battery value chain are provided by (Bobba et al., 2018)[183] and (Eynard et al., 2018).[184] Moreover, an analysis

---

[178] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661

[179] https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749

[180] https://ec.europa.eu/energy/sites/default/files/documents/sustainability_task_force_position_paper.pdf

[181] Y. Shi, X. Chen, T. Jiang, Q. Jin, *Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials*, Sustainable Production and Consumption, 35 (2023) 525, doi:10.1016/j.spc.2022.11.021

[182] M. Koese, C.F. Blanco, V.B. Vert, M.G. Vijver, *A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage*, Journal of Industrial Ecology, 27 (2023) 223, doi.org/10.1111/jiec.13347

[183] S. Bobba, A. Podias, F. Di Persio,M. Messagie, P. Tecchio, M.A. Cusenza, U. Eynard, F. Mathieux, A. Pfrang, *Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB)*, Final technical report: August 2018. EUR 29321 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-92835-2; doi:10.2760/53624, JRC112543.

[184] U. Eynard, S. Bobba, M.A. Cusenza, G.A. Blengini, *Lithium-ion batteries for electric vehicles: combining Environmental and Social Life Cycle Assessments,* in: Life Cycle Thinking in Decision-Making for Sustainability: From Public Policies to Private Businesses, Messina, 11-12 Jun 2018

	of social risk in battery raw materials supply is provided in (Mancini et al., 2020)[185] while (Mancini et al., 2021)[186] investigates the social impacts of responsible sourcing initiatives in artisanal cobalt mining sites in the Democratic Republic of the Congo. Several other studies focused on human rights and other social impacts in the Katanga region in DRC, also considering the prominent role of the artisanal mining sector (e.g. OECD, 2019).[187]
Health	Few information on health effects of batteries are available, even though some considerations can be provided by S-LCA studies (e.g. (Bobba et al., 2018)(Mancini et al., 2020)). It is noticed that studies on health effects on specific battery raw materials are already available in the literature, e.g. on specific risks of artisanal mining of cobalt in specific mines (Lubaba Nkulu et al., 2018),[188] (Mancini et al., 2021), (Arvidsson et al. 2022).[189]
Public acceptance	Few information on social acceptance is available on public acceptance of batteries,[190],[191] even though study addressing the topic are ongoing (e.g. Baur et al., 2022[192]; Petavratz et al., 2022; Dunlap A. and Riquito M., 2023).
Education opportunities and needs	Few information on education opportunities is available, even though some considerations can be provided by S-LCA studies (e.g. (Batteries Europe, 2021).
Employment and conditions	Several studies have been published on the working conditions of the mining sector, especially in the case of cobalt extraction in the DRC. Additional information can be derived by S-LCA studies (e.g. (Batteries Europe, 2021)(Eynard et al., 2018; Mancini et al., 2021, 2020)).
Contribution to GDP	*see VC analysis section*
Rural development impact	Few data are available on the effect of the impact of batteries in rural development even though projects on the adoption of batteries in energy storage systems in rural areas (including second-used EV batteries) already exist to increase energy self-sufficiency and the share of renewable energy (e.g. battery storing solar or wind energy). E.g. (Ambrose et al., 2014),[193] (Kessels et al., 2017).[194]
Industrial transition impact	The industrial battery sector is a strategic sector for the EU, with a significant potential on both short and long term to decarbonize the EU (e.g. mobility sector and increasing the share of renewable energies). The battery technology is rapidly evolving and both R&D&I activities as well as industrial initiatives are currently engaged to build a more competitive and sustainable European battery industry (EBA250, BatteriesEurope, Battery2030+, etc.).
Affordable energy access (SDG7)	The battery industry development can have a key role in "ensuring the access to affordable, reliable, sustainable and modern energy for all (SDG 7)". Chemistries and type of batteries can be used in multiple applications, increasing the consumption of renewable energy (e.g. in combination with PV

---

[185] L. Mancini, N.A. Eslava, M. Traverso, F. Mathieux, *Responsible and sustainable sourcing of battery raw materials. Insights from hotspot analysis, company disclosures and field research*, 2020, JRC Technical Report. Doi:10.2760/562951

[186] L. Mancini, N.A. Eslava, M. Traverso, F. Mathieux, *Assessing impacts of responsible sourcing initiatives for cobalt: Insights from a case study*. Resour. Policy. 71 (2021) 102015, doi:10.1016/j.resourpol.2021.102015

[187] https://mneguidelines.oecd.org/interconnected-supply-chains-a-comprehensive-look-at-due-diligence-challenges-and-opportunities-sourcing-cobalt-and-copper-from-the-drc.htm

[188] C. Banza Lubaba Nkulu, L. Casas, V. Haufroid, T. De Putter, N.D. Saenen, T. Kayembe-Kitenge, P. Musa Obadia, D. Kyanika Wa Mukoma, J.M. Lunda Ilunga, T.S. Nawrot, O. Luboya Numbi, E. Smolders, B. Nemery, *Sustainability of artisanal mining of cobalt in DR Congo,* Nat Sustain 1 (2018) 495, doi:10.1038/s41893-018-0139-4

[189] R. Arvidsson, M. Chordia, A. Nordelöf, *Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery*. Int J Life Cycle Assess 27 (2022) 1106, doi:10.1007/s11367-022-02084-3

[190] A. Dunlap, M. Riquito, Social warfare for lithium extraction? Open-pit lithium mining, counterinsurgency tactics and enforcing green extractivism in northern Portugal, Energy Research & Social Science 95 (2023) 102912, doi:10.1016/j.erss.2022.102912

[191] E. Petavratzi, D. Sanchez-Lopez, A. Hughes, J. Stacey, J. Ford, A. Butcher, The impacts of environmental, social and governance (ESG) issues in achieving sustainable lithium supply in the Lithium Triangle, Mineral Economics 35 (2022) 673, doi:10.1007/s13563-022-00332-4

[192] D. Baur, P. Emmerich, M.J. Baumann, M. Weil, *Assessing the social acceptance of key technologies for the German energy transition* Energy. Sustain. Soc (2022) 12:4. doi:10.1186/s13705-021-00329-x

[193] H. Ambrose, D. Gershenson, A. Gershenson, D. Kammen, *Driving rural energy access: a second-life application for electric-vehicle batteries*, Environ. Res. Lett. 9 (2014) 094004, doi:10.1088/1748-9326/9/9/094004

[194] K. Kessels, B. Mantels, C. Hussy, M. Bons, F. Comaty, M. Goes, F. Wiersma, A. Kshemendranat, C. Christensen, P. Hochloff, D. Schledde, *Support to R&D strategy for battery based energy storage. Costs and benefits for deployment scenarios of battery systems,* BATSTORM project - D7, 2017

	panels), decreasing the life-cycle impacts of the mobility sector, supporting the transition towards a climate-neutral Europe.[195]
Safety and (cyber)security	
Energy security	Cost-effective batteries (including second-used EV batteries) can contribute in increasing the self-consumption and self-sufficiency, especially in rural areas. They hence contribute to energy security and quality[196].
Food security	
Responsible material sourcing	The Battery Regulation proposal states that rechargeable industrial batteries and EV batteries with a capacity above 2 kWh are accompanied by a documentation reporting the due diligence policies adopted along the batteries value chain. Information on specific materials related risk embedded in batteries are available in Mancini et al. (2020)

Source: JRC, 2023

---

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

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

lex.europa.eu).

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

Open data from the EU

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
joint-research-centre.ec.europa.eu

@EU_ScienceHub
EU Science Hub - Joint Research Centre
EU Science, Research and Innovation
EU Science Hub
@eu_science

Publications Office
of the European Union