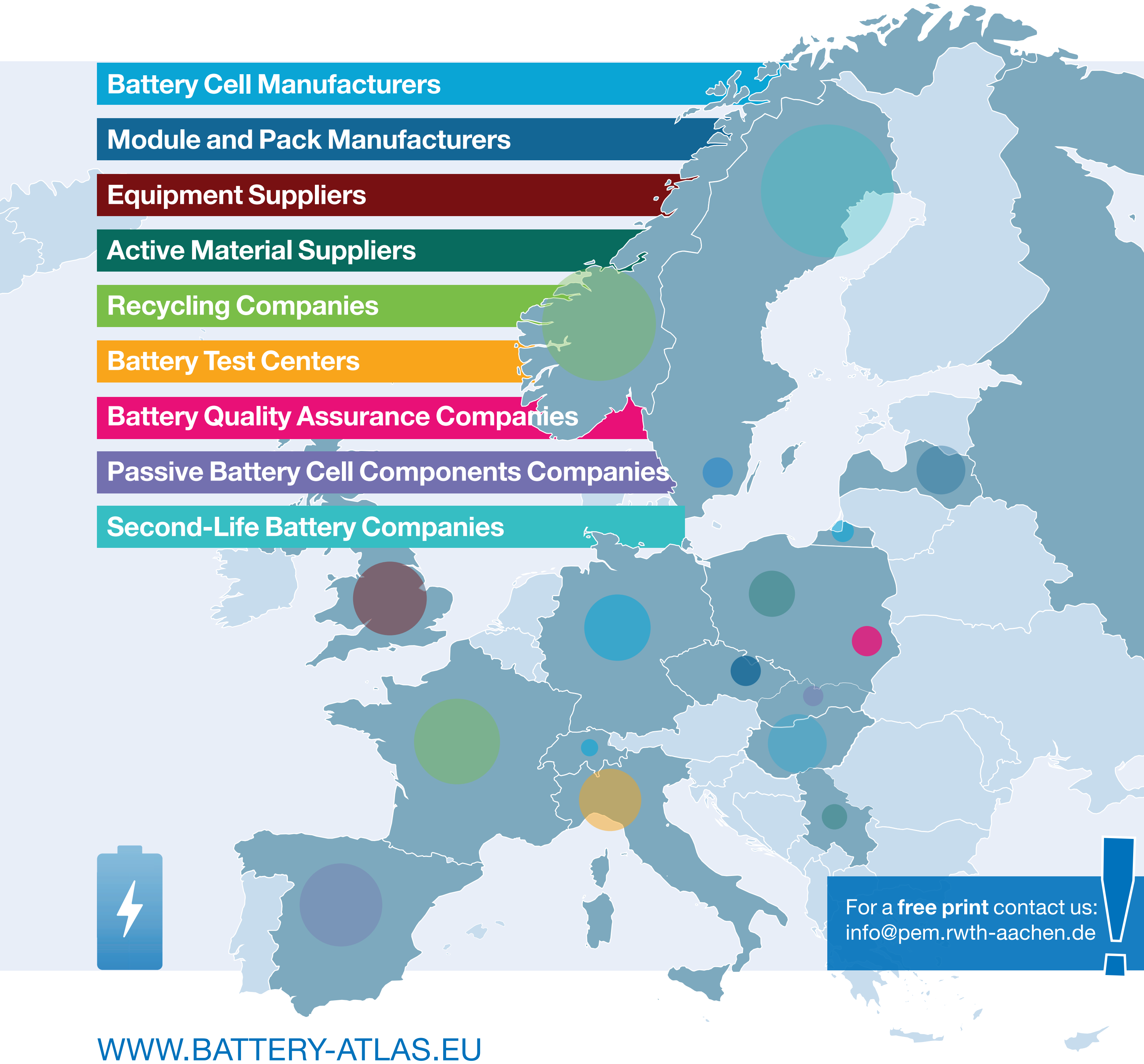
BATTERY ATLAS 2024

SHAPING THE EUROPEAN LITHIUM-ION BATTERY INDUSTRY

Heiner Heimes (editor), 2nd edition



For a **free print** contact us:
info@pem.rwth-aachen.de

WWW.BATTERY-ATLAS.EU

PEM | RWTH AACHEN UNIVERSITY

IMPORTANT NOTICE

Dear reader,

Although our “Battery Atlas” looks at the European battery market from many different angles and business areas, this document does not claim to be exhaustive. The second edition of the Battery Atlas thus once again reflects a snapshot in time. Nevertheless, all readers are invited to contribute to the topicality of this growing work. We will be happy to incorporate suggestions and additions submitted in writing into the next, updated edition.

Sincerely,
Your Battery Atlas Editorial Team

DEAR READERS,

With the second edition of the Battery Atlas, we are taking a new, extended look at the current situation of the European battery industry. It is impressive to see the speed of its growth within two years since the first Battery Atlas. As Europeans, we can be grateful and proud of this development.

The current global political situation demands comprehensive independence from critical components of our daily lives. The lithium-ion battery is one of those. To achieve the greatest possible independence in this regard, the development of various industries around the lithium-ion battery is crucial. Nine thematic maps outline the status quo of today's industry sectors "Battery Cell Manufacturers", "Module and Pack Manufacturers", "Battery Equipment Suppliers", "Active Material Suppliers", "Recycling Companies", "Battery Test Centers", "Battery Quality Assurance Companies", "Passive Battery Cell Component Companies" and "Second-Life Battery Companies".

Networking of the respective market players will be decisive in determining whether Europe can hold its own in global competition. If the various companies succeed in establishing collaborations along the entire value chain, we will be able to offer services as a turnkey solution, jointly exploit economies of scale through economies of scope, and pool financial resources for research and development to bring new technologies to life even faster. Then, Europe will be on a promising path in the expansion of electric mobility as well.

Together, we can make up for the lack of experience in development and production of lithium-ion batteries. In doing so, we must also overcome national borders in Europe. Thus, investments in battery production in one country can strengthen mechanical and plant engineering in another country or lead to the utilization of battery test centers in another one. If we support each other in the development of new projects, we will succeed in making the European battery industry robust and ensuring long-term security of supply with this essential component of our future mobility.

To make this happen, it is necessary that European and national governments continue to support battery research. According to a study by the English portal "Verdict", jobs in the battery sector are the most difficult positions to fill in the technology industry. In Germany, this is exemplified by the fact that individual vehicle manufacturers want to recruit a total of 20,000 skilled workers for battery production by 2030 but have only been able to fill around 1,000 positions so far. Training of such experts usually takes place as part of funded research and development projects. Therefore, it is essential that universities, scientific institutions, and companies are supported in initiating publicly funded research projects.

I also warmly invite you to contribute your experiences. The Battery Atlas is planned to be a continuous publication in which additions and completions are always welcome. Therefore, please do not hesitate to contact us with questions and comments. We will be pleased to be at your disposal.

Best regards,

Prof. Dr. Heiner Hans Heimes

PEM of RWTH Aachen University
Prof. Dr.-Ing. Heiner Heimes
Member of PEM Institute Management

Phone +49 241 80 230 29
E-mail H.Heimes@pem.rwth-aachen.de
Web www.pem.rwth-aachen.de

Are you interested in an exchange of ideas? Feel free to contact us!

INTRODUCTION

The 2024 Battery Atlas covers nine different topics. Thus, this second edition provides an update on the subjects of its predecessor and at the same time is an addition to the initial Battery Atlas. Therefore, it covers a large part of the battery's life cycle, starting with the active and passive cell components up to the recycling or second life of battery cells. The situation of battery cell manufacturers is outlined first. Despite high energy costs, Europe continues to represent a central market in the battery world. Besides Germany, Hungary is developing as a major center of battery production. With increasing capacities in cell production, new opportunities are opening up in module and pack production. This applies to both the automotive sector and the developing stationary storage sector. Due to these circumstances, machine and equipment manufacturers became established in Europe. In this area in particular, you need to be able to provide appropriate references. These can be established much more easily if the customers (battery cell manufacturers) are also located in Europe, so that the advantages resulting from local presence can be exploited. Module and pack manufacturers can also benefit from local proximity. In the direct vicinity, companies dedicated to quality assurance can be found. Innovative companies are developing novel approaches to increase cell quality while more established companies can transfer their experience from Asian factories.

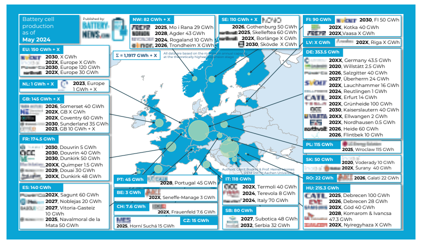
It is also important to note that suppliers of the active material as well as of the passive components of a battery are currently establishing themselves in Europe. These companies have recognized that cell production depends on stable supply chains. The stability of these supply chains can be significantly increased.

Also, many recycling companies are being opened in Europe. With these companies, it may be possible to establish recycling concepts here in the medium term.

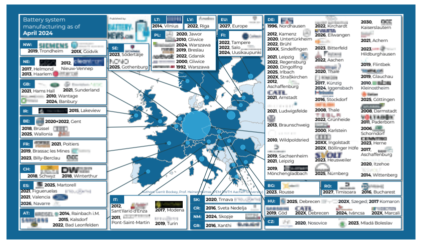
By no means all batteries have to be recycled after their first use. Some cells are often good enough to be transferred to a second-life application.

Once developed, each lithium-ion battery must go through various acceptance and performance tests before it is approved. Since many companies are currently developing batteries at the same time, this leads to a very high testing effort. In conclusion, this Battery Atlas also focuses on battery test centers.

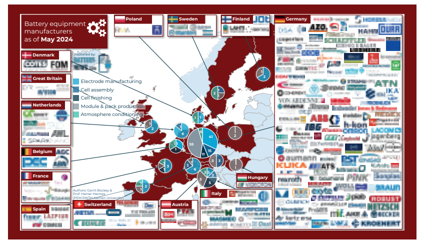
Battery Cell Manufacturers



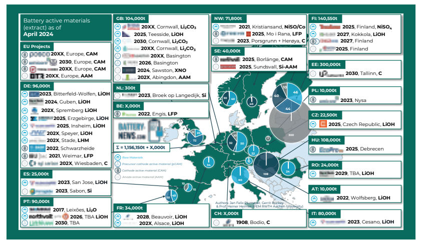
Module and Pack Manufacturers



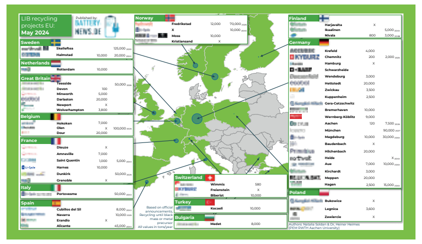
Equipment Suppliers



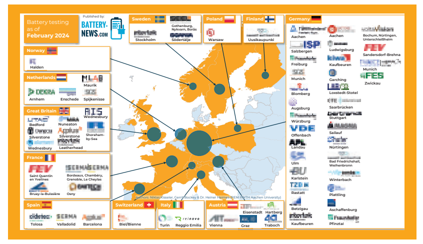
Active Material Suppliers



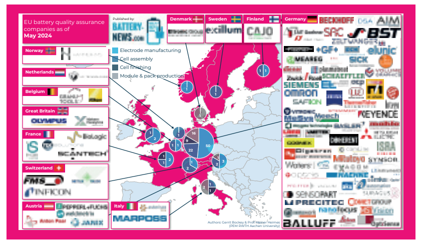
Recycling Companies



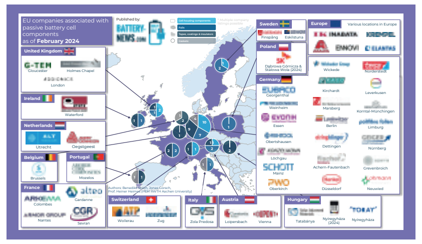
Battery Test Centers



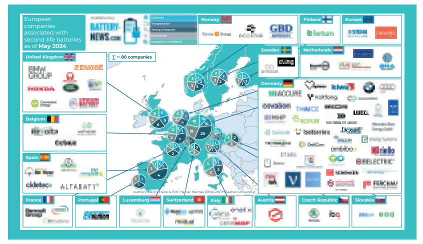
Battery Quality Assurance Companies



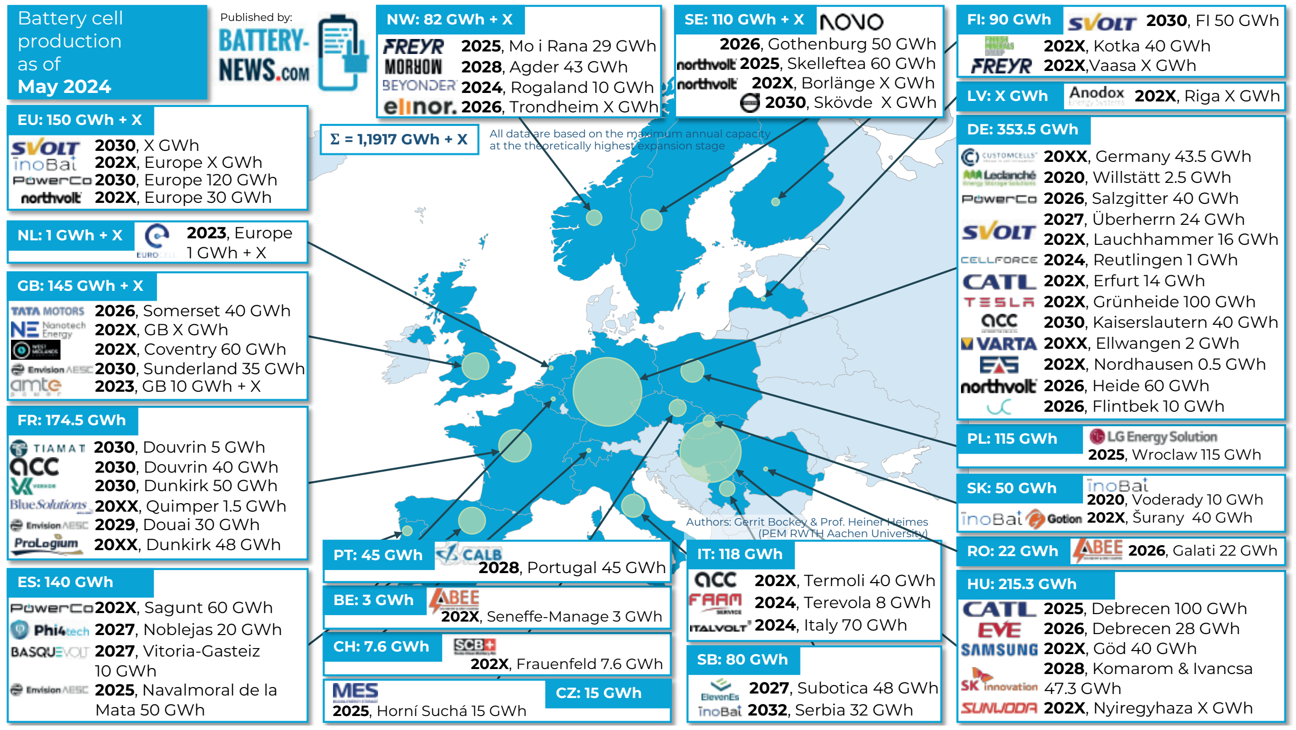
Passive Battery Cell Components Companies



Second-Life Battery Companies



BATTERY CELL MANUFACTURERS



Source: www.battery-atlas.eu; abstract, no claim to completeness

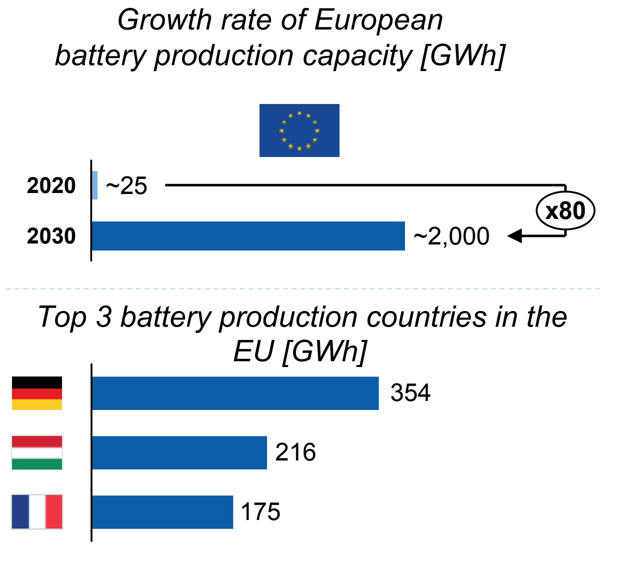
INITIAL POSITION

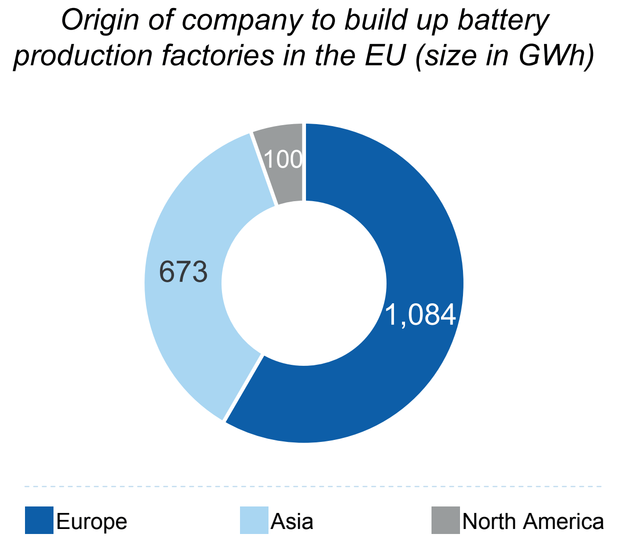
Until recently, Europe has not played a major role as a production location for battery cells – but technical innovation as well as stable and promoting political framework conditions are making Europe more and more attractive as a new market place for battery production. Due to the importance of the battery cell along the process chain of an electric vehicle and Europe's OEM density, Europe will become the next hotspot. In order to meet the increasing demand for battery cells in the automotive sector alone, 900 gigawatt-hours (GWh) of battery capacity could be needed there by 2030. Therefore, around 40 battery cell production factories are being planned or are already under construction. The planned activities are spread all over Europe. In addition to European manufacturers, producers from Asia and America also want to help shape the battery world in Europe. Compared to the Asian cell manufacturing companies who mostly concentrate on the production of cells, the European market sees many collaborations and joint ventures between large car manufacturers and cell producers. In addition, there are new start-ups from Europe. From Asia, it is mainly cell manufacturers already established at home which are entering the European market. The goal of those newly planned battery cell production factories is to decrease further production costs and therefore the cell costs in order to improve competition of electric vehicles against those with internal combustion engines. Important factors are the scrap rate reduction throughout the process, the processing improvement of higher energy material (e.g. nickel-rich cathode material), and the reduction of CO_2 emission within the production process. It is already becoming evident that a characteristic of the European factories will be a high degree of digitization to tackle the addressed goal and to improve the production process. But these activities are also facing some challenges during planning and ramp-up of the production factories. The main challenges regarding building up these battery cell production factories in Europe are the following topics:

- Limited availability of production technologies for gigafactories
- EU environmental standards to be met, including the use of low-carbon power sources as well as standards for sustainable production
- Long-term raw material supply in Europe

UPDATE

Global capacity increases to two terawatt-hours (TWh). While the number of companies fluctuates due to energy costs, more companies are expanding their production facilities outside Germany. Hungary and Poland experience the highest percentage growth. Meanhwile, leading all-solid-state battery (ASSB) companies are considering gigafactories in Europe. Late in 2022, first companies are no longer looking towards the end of the decade, but are planning based on a ten-year program.





ANALYSIS

Compared to 2020 with a 25 GWh production volume per year, an increase to approximately 2,000 GWh is expected to be realized in Europe by 2030. Therefore, the production capacity is increasing by a factor of 50 due to the planned activities in Europe. It is safe to say that the majority of the planned battery cell capacities will be covered by European players. European projects account for around 1,084 GWh of the planned activities.

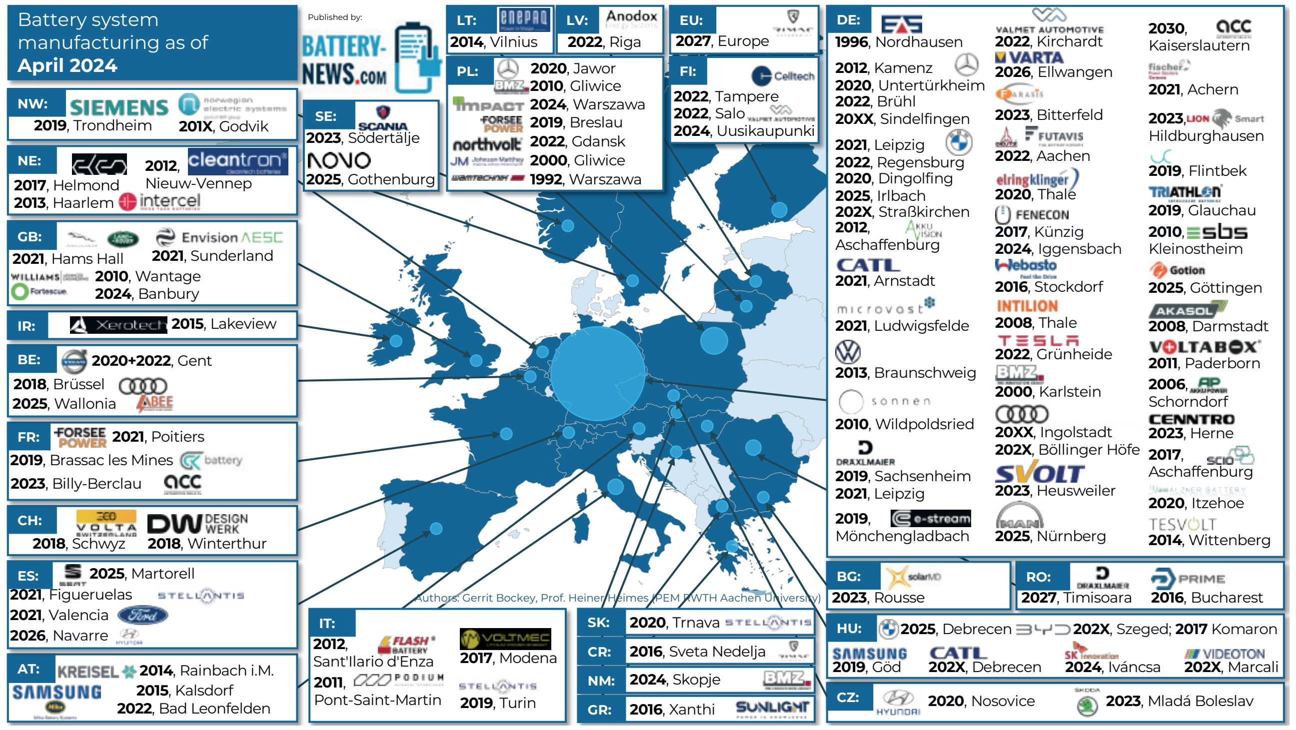
In comparison, Asian and American cell manufacturing companies are planning to install 673 GWh and 100 GWh respectively. Compared to the other areas of origin, European cell manufacturing companies are planning overall smaller production projects in relation to the total capacity to be produced. The planned projects of the Asian and American cell manufacturing companies are characterized by being fewer but larger. Approximately 25 of the 40 projects in Europe are attributable to European players, nine to Asian players and one to an American player. The top three countries where battery cell production factories are being built are Germany with 462 GWh, followed by the UK with 135 GWh and Norway with 125 GWh. Other activities are planned in Italy, France, Hungary, Spain, Poland, Serbia, and Slovakia.

OUTLOOK

Europe is currently in transition on its way to becoming a battery cell production hotspot. In addition to the cell manufacturers and joint ventures already existing in the Asian and American markets, a large number of new companies and joint ventures is being established in Europe. The challenge for European players is to build up the production factories and to achieve a fast ramp-up to keep up with the production speed in Asia. A main price reduction of the European battery cell is to be achieved through the design and optimization of the production process. Digitization and process parameter optimization in particular play a decisive role. Therefore, the production plants have to be designed by including new digitization concepts and strategies. So far, only a minority of European companies has produced a battery cell "made in Europe", and some planning projects in Europe have already been cancelled. The coming years are decisive for the development of Europe as a significant location in the battery sector and thus also for the competitiveness of a battery cell "made in Europe".

Battery cell production in Europe is picking up speed to meet the growing domestic demand for battery cells.

MODULE AND PACK MANUFACTURERS



Source: www.battery-atlas.eu; abstract, no claim to completeness

INITIAL POSITION

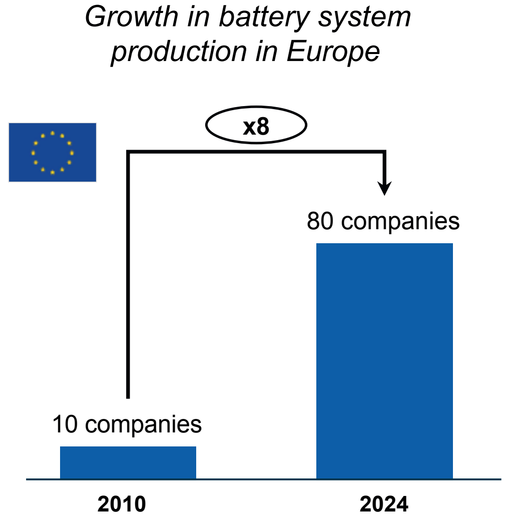
The European market currently has a growing number of cell manufacturers and battery cell plants. As mentioned before, there is a large gap to the Asian manufacturers. In terms of module and pack production, this gap between Asian and European manufacturers is narrowing. This is particularly evident in the automotive groups which have active supply contracts for battery cells from Asia to meet the demand for electric vehicles (EVs). When analyzing the registration numbers in relation to the population of electric vehicles, it becomes apparent that Europe allows significantly more EVs. Since the use of individual cells in electric-powered vehicles is limited, these cells must be bundled into modules and packs. Individual companies, as well as cell manufacturers and direct end users, have specialized in these processes.

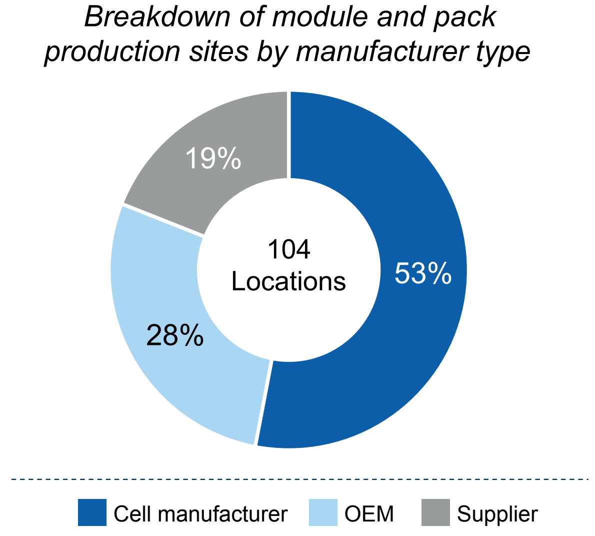
In the map shown above, these end users are manufacturers of cars, buses, and trucks as well as stationary energy storages. Accordingly, it is not surprising that a large number of the companies shown here already have existing plants and are not yet in the planning or design phase. In general, module pack production can be divided into about eleven production steps, ranging from an initial inspection of the cells to an end-of-line inspection.

The processes differ depending on the type of battery cell used. Due to regulations, low-voltage modules are usually handled, from which the packs are ultimately assembled by connecting the modules in series and parallel.

UPDATE

Since the first edition of the Battery Atlas in 2022, some companies have been added to the map. This includes new project announcements from OEMs, newly founded start-ups in the field of module and pack production, and existing projects that were not previously listed. In total, about 30 additional companies or locations were identified.





ANALYSIS

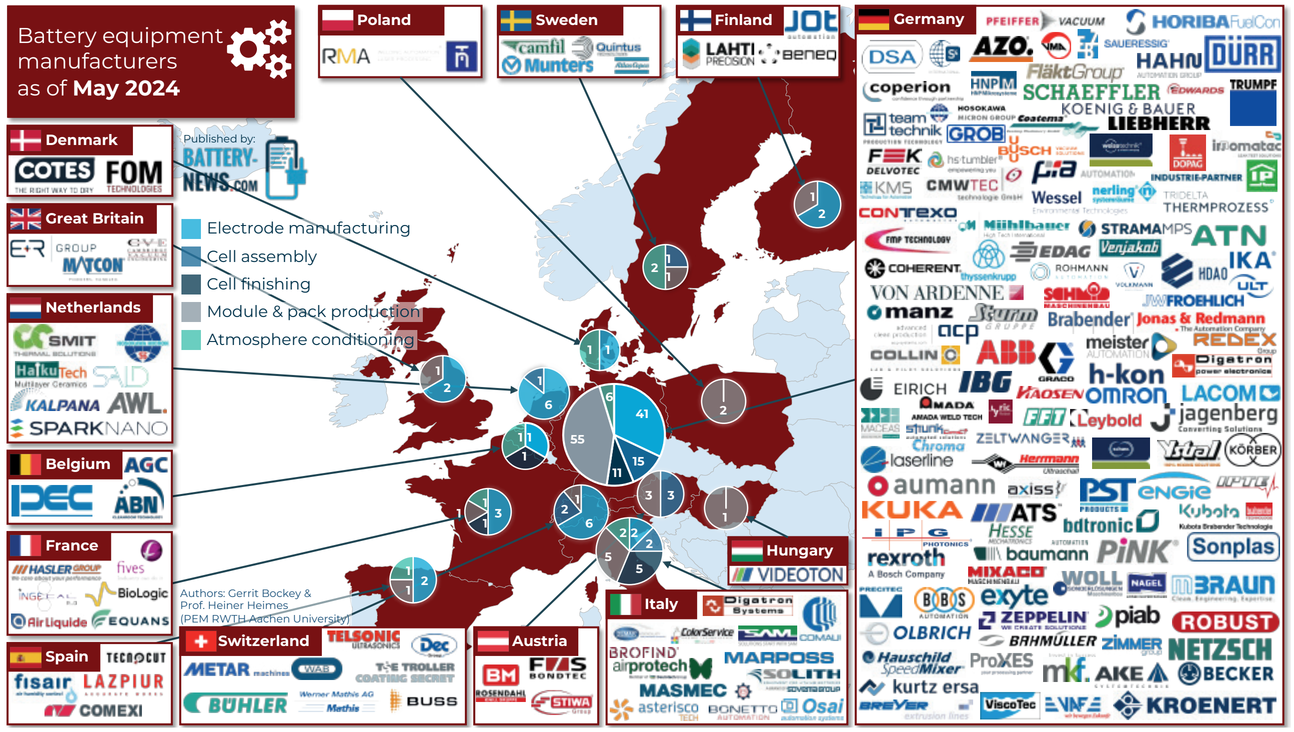
As mentioned at the beginning of this chapter, some companies already have module and pack manufacturing as they source or have sourced their cells externally and are assembling them into modules and integrating them into packs. Some of this manufacturing is done by OEMs. However, it should be emphasized that these have just started manufacturing modules and packs in the last few years or will be doing so in the future. Other companies are or were active here earlier. In 2010, only four companies were active in this area. Since then, the demand but also the supply of manufacturing sites has increased significantly. In 2020, there were already 55 we can identify on this map. By 2024, the total number of manufacturing sites by these companies may grow to over 80. This means that the number of manufacturing sites by these companies has more than quintupled from 2010 to 2020 and more than doubled in the following four years. When looking at the companies, one not only notices the much talked about OEMs, but also battery cell manufacturers that produce their own modules. This takes place both at the direct manufacturing location of the cells and at other locations in Europe. As in other maps, Germany is a center of concentration for many companies, whereas the Scandinavian countries have high potential and in some cases larger plants with higher capacities.

OUTLOOK

Currently the joining to modules and packs is done one after the other. In addition, the topic of "Cell to Pack" or "Cell to Chassis" or even "Cell to Vehicle" is strongly discussed. From this the market of module and pack production can change strongly. When considering large volume cells, any interconnection is no longer necessary or is greatly reduced. The use of cells as an integral component of the electric vehicle can also influence the process sequence and thus affect the market. The direct integration of cells into the vehicle can consolidate the position of the automobile manufacturers, but suppliers could also integrate cells into components and continue to participate in the market. It therefore remains to be seen which trends will prevail in cell formats and what changes such a radical development will lead to. There is no doubt that module and pack production is directly dependent on the battery cell and the respective cell chemistry, which in turn has an influence on a large number of components.

> The number of production sites for modules and packs of automotive and cell manufacturers is steadily growing and is able to further increase the market shares of OEMs through new cell formats.

EQUIPMENT SUPPLIERS



Source: www.battery-atlas.eu; abstract, no claim to completeness

INITIAL POSITION

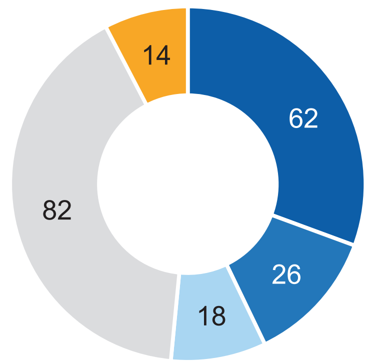
The rising global demand of electric vehicles led to a huge jump in need for batteries. Various battery production sites are ramping up to match these demands. To serve European battery manufacturing, established battery cell companies and emerging start-ups have announced plans to meet the regional growing demands. New battery production facilities will require a large amount of machinery and equipment accounting for about 60% of the total investment. The battery cell production process chain is divided into three sections: electrode manufacturing, cell assembly, and cell finishing. Some of the processes require a high level of technological expertise and high-precision manufacturing equipment.

Beginning with electrode manufacturing, the active material is mixed with the solvent to form a slurry. Subsequent process steps are performed mostly on various role-by-role production systems where large metal foils are coated with the slurry and dried, followed by calendering and cutting the produced electrodes to the desired dimensions.

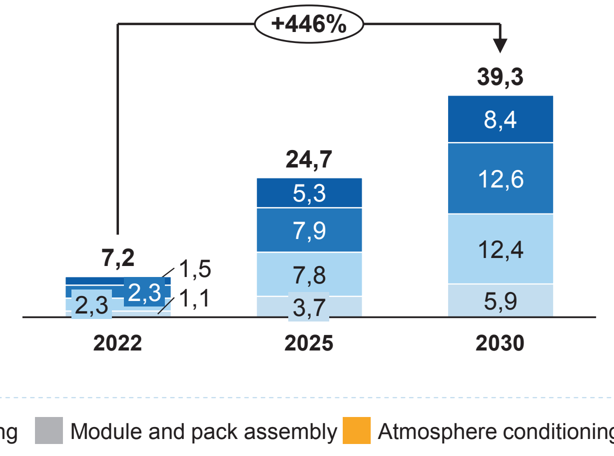
In cell assembly, the fabricated electrodes are formed into a cell roll or stack together with the separator and then placed in the cell housing and wetted with the electrolyte. Given the number of sequential process steps and process atmosphere requirements, the equipment is typically fully interlinked in order to ensure the necessary throughput and product quality. After the battery cell is fully assembled, it is charged for the first time within the formation process and examined in a series of monitoring mechanisms and the end-of-line test. Most electrochemical properties are set during cell finishing, which requires a profound process understanding.

While only a few years ago the majority of machinery was largely provided by Asian equipment suppliers, more and more experts are establishing themselves in Europe to capture a share of the revenue by becoming a key supplier for battery manufacturers. European players seeking to enter or expand into the battery market can leverage their geographic benefits which facilitates installation and ramp-up times as well as support and service for equipment. Suppliers for industries whose operations are comparable to battery cell production are in a particularly advantageous position to capitalize on technological opportunities. Furthermore, suppliers for module and pack production equipment are also focusing on innovative solutions for high automation, increased productivity, and quality management – from cell level all the way to the module and pack.

Number of European equipment suppliers along the battery production process chain



Market demand for production equipment of lithium-ion batteries [billion €]



ANALYSIS

In Europe, more than 100 established and newly emerging equipment suppliers have already successfully entered the battery market.

The market demand for lithium-ion battery production equipment will increase from around €6 billion in 2022 to a projected €33 billion.

Especially in the area of electrode manufacturing, where some processes such as coating are either unique or specific to battery cell manufacturing, more than 40 companies have been able to transfer their expertise from other sectors like the textile and packaging industry to battery cell production. Specific solutions and technological innovations enable various companies to enter the market.

Germany is playing a pioneering role in the development of battery production systems, where numerous companies in a wide variety of formats are involved in the further development of battery production.

The cell assembly and handling processes are often in scope of general automation and manufacturing, allowing established companies to convert and apply their equipment systems here accordingly.[1]

In Europe, only a few companies are currently able to make a name for themselves in the field of cell finishing for productions on a gigafactory scale.

OUTLOOK

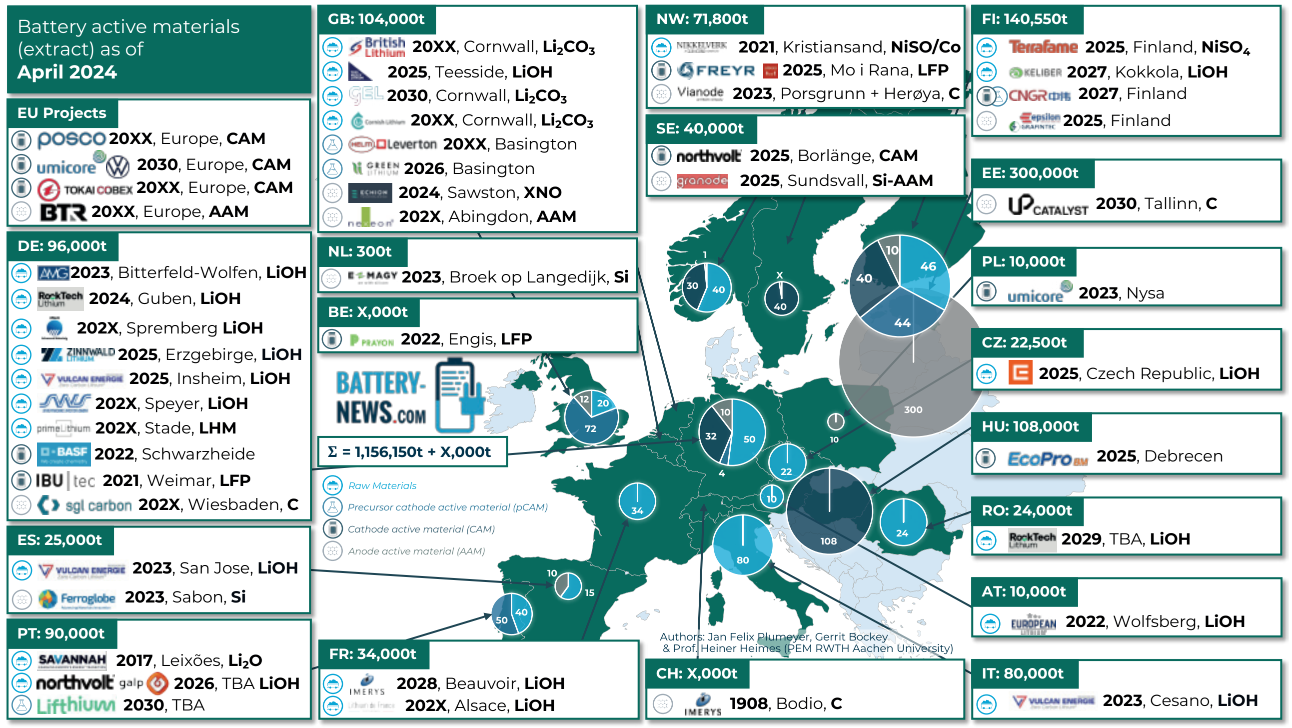
Since most of the Asian battery cell equipment manufacturers are already heavily booked with requests, they may prioritize orders from established customers. As a result, European battery cell manufacturers and OEMs entering the market are likely to face equipment supply shortages that jeopardize their production ramp-up. Securing equipment supplies is a critical success factor while criteria such as sustainability and quality will become more and more important in the procurement process, not just because of the EU Battery Regulation coming into force. The announcements by battery cell and system manufacturers offer great potential for equipment suppliers.

- Cell finishing: This procedure forms a large part of the overall market in cell manufacturing. Only 5-10% of the European companies can serve this market.
- Delivery times: It is expected that equipment manufacturers will not be able to increase their capacities in line with demand. Already now, delivery times for some core processes are more than one year.
- The numerous specialists in the European equipment industry should be able to act as general contractors in the coming years in order not to leave the market to the currently dominant Asian manufacturers.

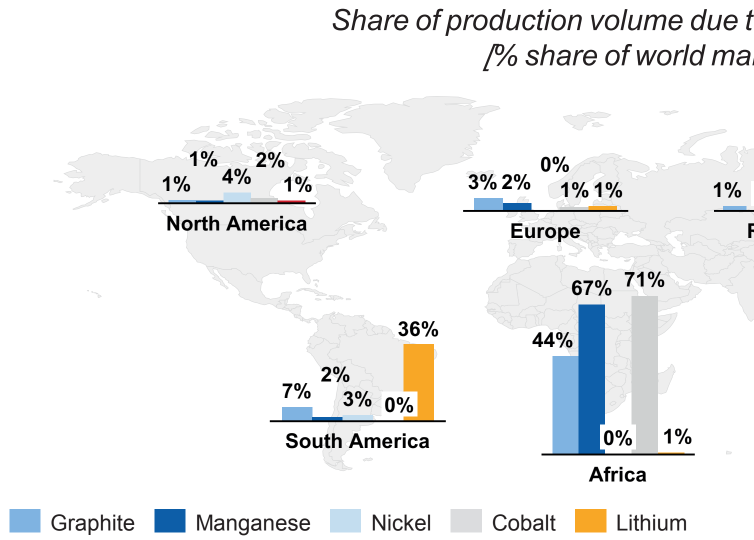
The numerous specialists in the European equipment industry should be able to act as general contractors in the coming years and focus on modular systems in order to shorten delivery times.

1 https://www.mckinsey.com/industries/advanced-electronics/our-insights/unlocking-the-growth-opportunity-in-battery-manufacturing-equipment

ACTIVE MATERIAL SUPPLIERS



Source: www.battery-atlas.eu; abstract, no claim to completeness



Source:
Mineral Commodity Summaries 2023

INITIAL POSITION

A lithium-ion battery consists of several cells, each of which has a negative anode and positive cathode. Both anode and cathode consist of a current collector – which is different for the positive and negative electrode (copper or aluminum foil) – and an active material. This active material can have different compositions and be combined in various ways. Most common material mixtures are Nickel-Manganese-Cobalt (NMC) or Lithium Iron Phosphate (LFP) for the cathodes in combination with graphite anodes. The active material combination determines the cell chemistry of a battery and is decisive for the amount of raw material required in production. The raw materials used in a lithium-ion battery include graphite, manganese, nickel, cobalt, and lithium[2].

- Cathode raw materials obtained through mining and refining or battery recycling
  - Manganese extracted by open pit or deep mining; ore processed by metallurgical/chemical methods
  - Class I nickel mainly derived from nickel sulfide ores
  - Cobalt concentrates (hydroxides): byproducts of nickel and copper mining
  - Lithium: extracted from hard rock mines (processed to lithium hydroxide, lithium chloride, lithium carbonate) or from salars (processed to lithium carbonate and lithium hydroxide).[2]
- The crystals must be processed into precursor cathode active materials (pCAM) for CAM such as NMC or LFP.
- Graphite (most common anode active material): obtained as byproduct of oil refining or from traditional mining; demand for silicon is growing

All the described resources are distributed unevenly among the different countries of the world, resulting in a global supply chain with few suppliers. Combined with the precarious social and political conditions in some countries, this leads to a vulnerable supply chain. These risks play an important role in the assessment and selection of supply chain stakeholders and determine the ecological and social footprint of lithium-ion battery production.[3]

UPDATE

Compared to the previous Battery Atlas, one can find a much more complete picture of European material production above. Besides the main raw materials, electrochemically active additives as well as conducting salts and electrolytes have been added. Together with new announcements and expansion stages, a total quantity of more than 1.1 million tons of active material can be expected.

2 GIZ + BGR, "Rohstoffe für die E-Mobilität", 2021
3 https://www.transportenvironment.org/wp-content/uploads/2022/05/Battery-supply-briefing-2.pdf
4 https://www.energymonitor.ai/transport/booming-ev-sales-challenge-mineral-supply-chains/?cf-view

ANALYSIS

The highly unbalanced distribution of raw materials for lithium-ion batteries means that individual states are de facto single source suppliers of certain resources. The global raw material distribution of the most important active materials in 2022 is shown in the figure above.

- According to the data, 65% of the graphite for the world market is extracted in China as natural graphite in traditional mining.
- Manganese ore is mainly mined in South Africa (67%) from where it is transported to China for further processing.
- Nickel shows the greatest scatter in resource distribution. Nickel laterite and nickel sulfide are mined in more than 30 countries worldwide.[3] However, Indonesia and the Philippines are the two largest nickel producers with 48% and 21% market share, respectively.
- 71% of cobalt is produced in the Democratic Republic of the Congo, making this nation the world's dominant supplier.
- Lithium is mainly available in Australia (47%) and South America (36%). Australia mainly mines hard rock lithium, while South America extracts it from salars.

OUTLOOK

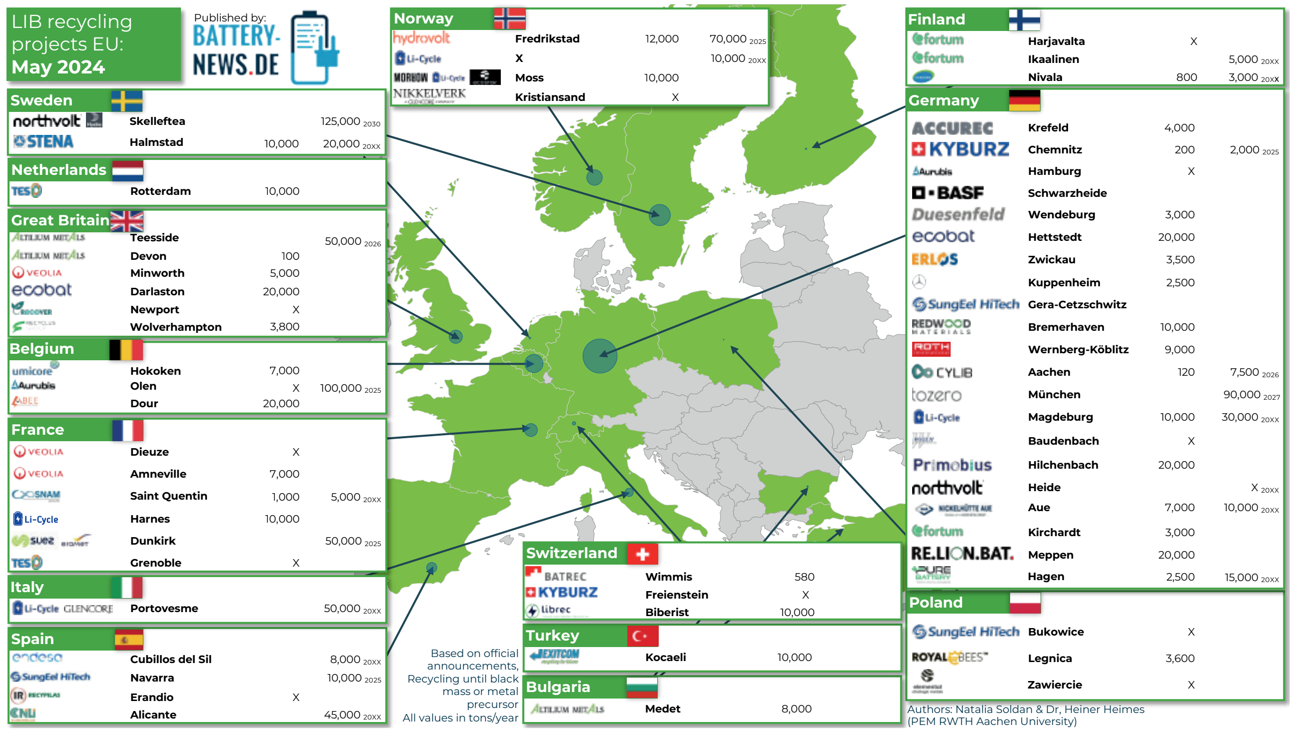
The US and Germany are the most dependent on material supplies for electric mobility from other countries.[4] The demand for NMC and LFP batteries is on a divergent path, with LFP gaining traction due to its lower costs and its safety advantages. This is altering market distribution, leaning towards technologies that offer economic and environmental benefits.[5,6] Direct lithium extraction (DLE) stands out as a promising but immature technology, poised to optimize lithium supply by offering a more efficient, environmentally friendly alternative to conventional extraction methods. This innovation is critical in bridging the projected demand-supply gap for lithium.[7]

Sustainability, cost efficiency, and supply chain resilience are becoming key market aspects. Battery prices have fluctuated considerably over the past two years, with experts observing the impact of local manufacturing expansions in the US and Europe, alongside production incentives and regulations on critical minerals. Localization is expected to introduce new complexities into regional battery pricing. The US Inflation Reduction Act and the Bipartisan Infrastructure Law are driving substantial investments in the battery value chain, mirroring efforts in the EU.[6]

The rising production capacity for battery materials in Europe indicates a shift towards a more balanced global supply chain, potentially mitigating existing raw material availability risks.

5 https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/batterie-rohstoffe-preis-schwankungen-wie-reagiert-automobil-industrie-auswirkungen-zellkosten.html
6 https://www.energy-storage.news/lfp-cell-average-falls-below-us100-kwh-as-battery-pack-prices-drop-to-record-low-in-2023/
7 https://elements.visualcapitalist.com/direct-lithium-extraction/

RECYCLING COMPANIES



Source: www.battery-atlas.eu; abstract, no claim to completeness

INITIAL POSITION

Because of the immense growth rate of electric mobility and the associated high consumption of battery raw materials, the resource-efficient handling of lithium-ion batteries is essential. In terms of the circular economy, recycling processes in Europe can reduce dependence on raw materials for battery production, as these materials are mainly imported from other continents. The location of recycling plants plays a strategic role in terms of economic efficiency, as transport is one of the highest cost factors in the whole recycling process chain.

The new draft legislation of batteries introduced by the EU Commission in March 2022 sets requirements for the future recycling process. The key points here are the overall recycling efficiency of LIBs that is increased from 50% to 65% latest 36 months after the regulation getting into force. After 48 months, the recovery rates should be reached for the individual battery raw materials for lithium (35%), cobalt, nickel, and copper (90% each). The recovery of lithium should be increased after 96 months of regulation coming into effect to 70% imposing a high challenge to recycling companies, as their processes are currently not designed with the focus on lithium recycling. In addition, a minimum proportion of recycled battery raw materials will have to be used in newly produced LIBs.[8]

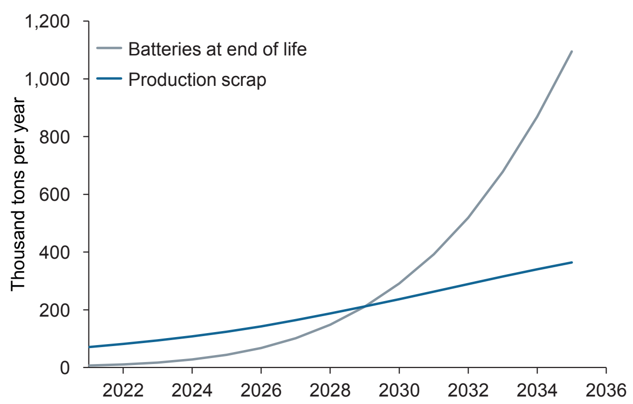
Recycling plants can be distinguished by their recycling process and thereby also by the quality of their end product. While some companies focus exclusively on the recycling process up to the battery active material mixture (BAMM) which is also known as the black mass, others recycle up to the individual metal precursors. There is not yet a fixed definition in which quality the recycled intermediate product must be present to be called BAMM. BAMM designates a mixture of anode and/or cathode and/or electrolyte and/or other components, obtained during the recycling or recovery process of batteries, possibly containing contaminants. Contaminants are all materials that have a negative impact regarding quality on the further recycling process and consequently on the final product.

The fast market development and new innovations of battery design and cell chemistry cause further challenges for recycling companies. They must be able to quickly react to the new battery technology and, if necessary, make modifications to the recycling process.

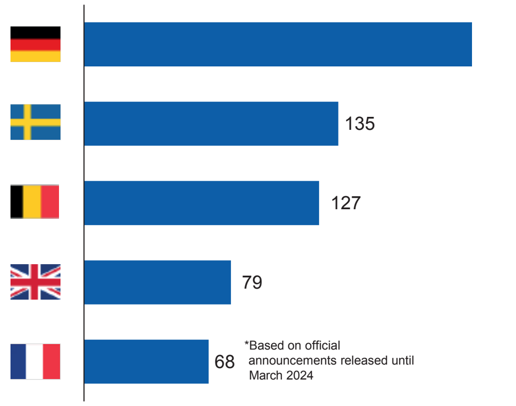
ANALYSIS

In 2023, about 17,000 tons of batteries from electric vehicles in Europe have been returned to the market for

Estimated return rates of lithium-ion batteries and amount of battery production scrap in Europe



*Top 5 recycling markets in the EU by 2030 in thousand tons per year**



recycling and other approaches such as remanufacturing and reuse. The number of end-of-life batteries will increase significantly reaching the mark of 290,000 tons by 2030 underlying the need of recycling capacity in Europe (Figure 1).

The main recycling source of lithium-ion batteries currently is scrap from battery production, outweighing the volume of end-of-life batteries until 2029. The country with the most recycling players on the European market is Germany. The reasons for this development lie in the high number of automotive companies as well as in the increasing battery production. Germany's location in the center of Europe provides great advantages for recycling companies in terms of short transport routes and good logistics infrastructure.

A strong increase in recycling of lithium-ion batteries can be observed in the north of Europe, according to actual recycling capacities and announcements. Based on announcements until the end of 2022, Sweden will take over the leading position in terms of recycling capacity in Europe by 2030 with a capacity of 135,000 tons per year. In the same year Great Britain would be positioned on the third place with 78,900 tons per year (Figure 2).

OUTLOOK

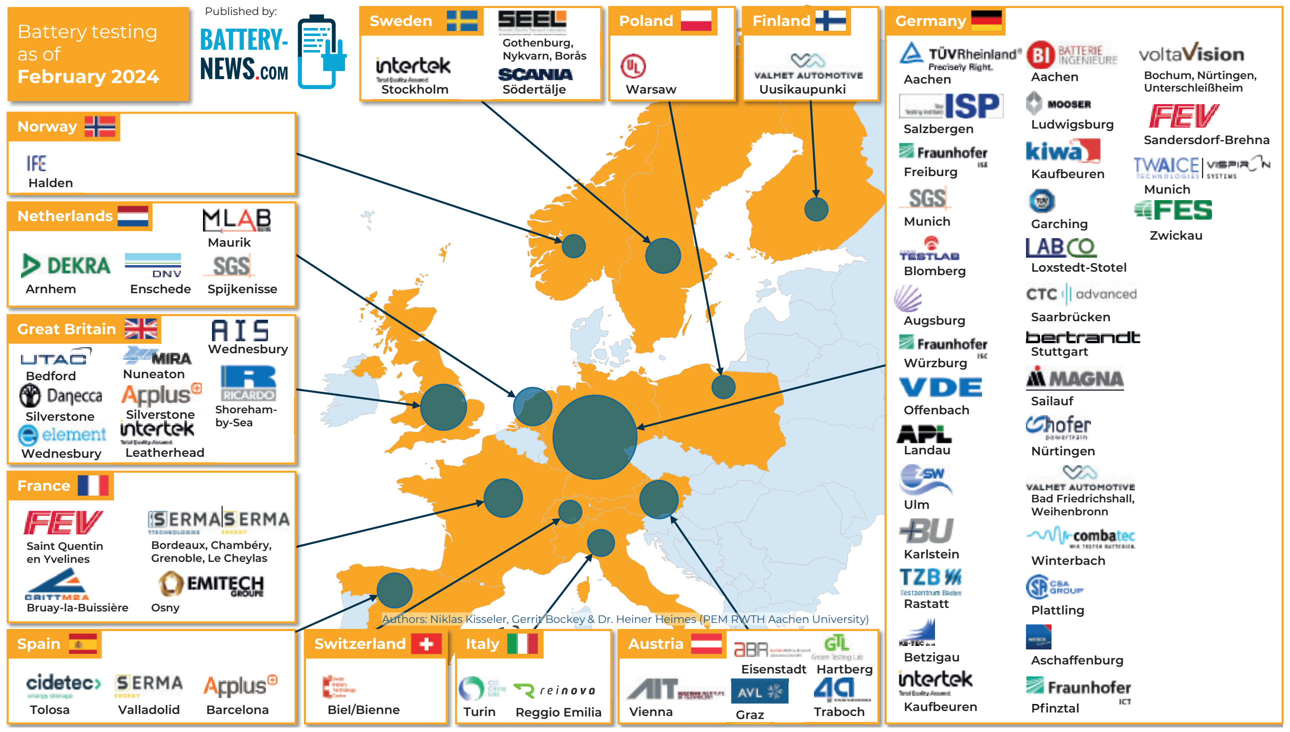
It has become evident that there is an urgency to address and adequately handle the rise in lithium-ion batteries after their use in the market. Because of its strategic location and growing know-how, Europe can set the benchmark in battery recycling. The aim is to establish a circular economy to ensure that waste from batteries is reused in a way that makes battery production less resource-intensive overall. For this to happen, battery manufacturers must also partake in battery return systems to ensure battery materials are not lost, collected efficiently and recycled in a sustainable way.

In addition, there is a need for battery recycling plants that recover not only the active materials such as nickel, cobalt and lithium, but also other metals such as aluminum and copper. To be able to have a high recycling quote of all materials, the recovery process needs to be profitable. For that, battery manufactures should adapt the design and materials used in the battery production for a better recyclability. If European nations can establish a circular economy where lithium-ion batteries are reused and reapplied, we can expect an increase in jobs within the sector, a lower environmental footprint, and overall economic growth.

The increasing use of electric vehicles in Europe has been generating 17,000 tons of recyclable batteries at the end of 2023, rising to 290,000 tons by 2030, requiring a significant expansion of recycling capacity, with Germany currently leading the way in battery recycling.

8 Vorschlag für eine Verordnung des Europäischen Parlaments und des Rates über Batterien und Altbatterien, zur Aufhebung der Richtlinie 2006/66/EG und zur Änderung der Verordnung (EU) 2019/1020, März 2022

BATTERY TEST CENTERS



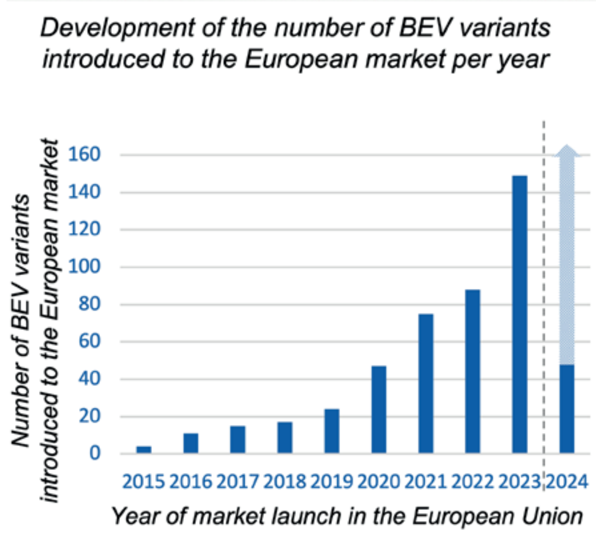
Source: www.battery-atlas.eu; abstract, no claim to completeness

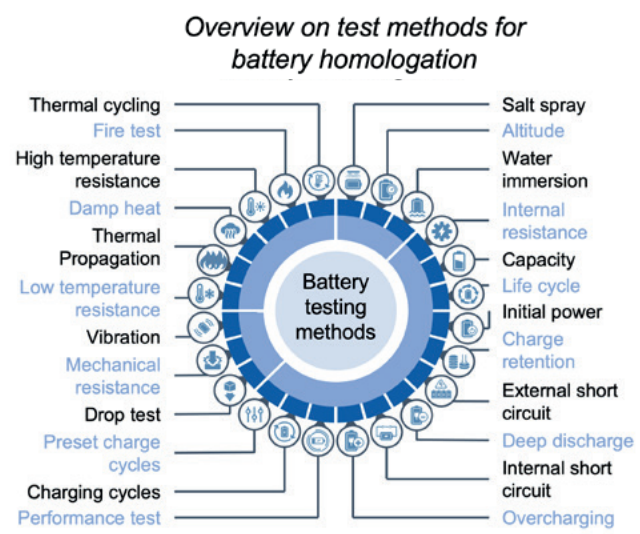
INITIAL POSITION

Before it is approved for use within specific applications, each lithium-ion battery must pass various abuse and performance tests after completion of its initial development. These tests are performed depending on the respective performance and safety requirements from standards or additional extensive manufacturer requirements at battery cell, module and/or system level.

For example, the approval of energy storage systems for electrically powered vehicles according to ECE-R100 requires the successful completion of a total of ten tests including thermal, mechanical and electrical stress investigations. These include vibration and mechanical shock tests as well as tests to ensure thermal shock and fire resistance, and verification of protection against overcharging and deep-discharging. In revision 3, a test for overcurrent safety and a documentation requirement for thermal propagation have been added. A selection of other standard specifications particularly relevant to battery storage applications include UN T 38.3 as a requirement for transporting battery storages by road, rail, sea, or air as well as GB 38031-2020 as a safety standard for traction batteries of electric vehicles for the Chinese market and is therefore also of particular relevance for European manufacturers. In addition to the tests defined in standards and homologation requirements, test capacities are also needed to carry out further quality-relevant performance tests on battery systems. This includes, for example, the (long-term) characterization of battery systems during different product development phases.

At the current time, it can be observed that the number of companies which are simultaneously developing new lithium-ion battery systems is increasing rapidly. As a direct consequence, there is a correspondingly high demand for testing capacities. Often, the required test capacities exceed those available on the market. There is a risk that a lack of testing capacity will result in inefficiencies in the product development. In addition to fulfilling the test scopes required for the approval of battery systems in Europe, there is also a need to cover additional test requirements in order to be able to approve products in other regions of the world (e.g. China). In this context, the map of test centers is intended to help visualize the availability of potential test capacities as well as the establishment of upcoming service providers in Europe.





ANALYSIS

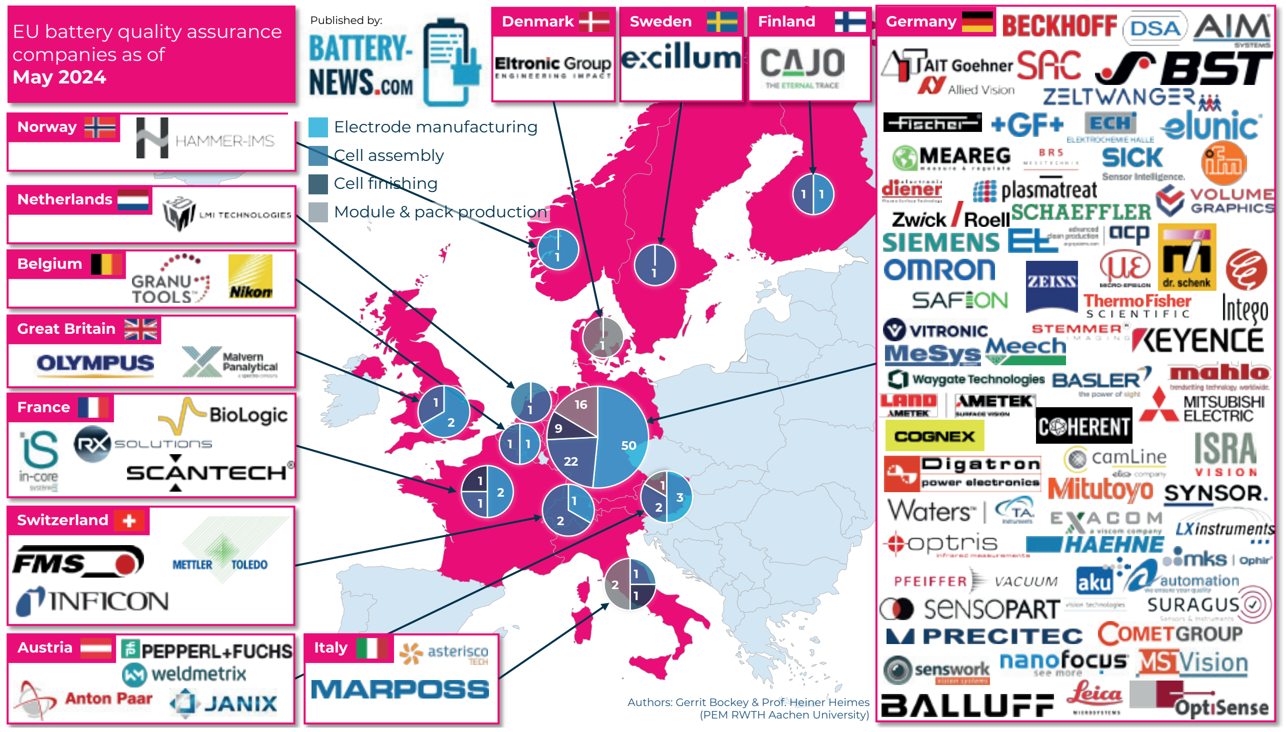
The existing test capacities for lithium-ion battery systems are currently concentrated in central Europe, especially in Germany. A predominant share of the currently overall available test capacity is still limited to the testing of battery cells and small-format battery modules. In particular, abuse testing of large-format battery packs with high-energy content has so far only been possible at a comparatively small number of test centers due to the high-performance and safety requirements for the test infrastructure and test environment as well as the high initial investment costs. European test providers are also increasingly offering tests to validate batteries against non-European test standards, such as GB 38031-2020, in order to address the requirements of the Chinese market for European battery manufacturers. Against the background of the expected further increase in energy content at system level, challenges arise here in particular for the existing test capacities, which are limited in their applicability to battery systems with comparatively low energy content. Another challenge is the centralized availability of test capacities in order to be able to perform all test scopes of corresponding standards bundled in one place.

OUTLOOK

The foreseeable further increase in demand for test infrastructure for lithium-ion battery systems represents a central requirement along the development of a fully integrated battery value chain in Europe. Due to the rapid development in the field of battery technology and the updating of standards, this trend is foreseeably intensified. This opens up the opportunity for companies to position themselves strategically within this field and to build up know-how, as can already be increasingly observed at the present time. In this context, it is important for existing and upcoming test centers to anticipate developments in the product area as well as to be able to design test capacities that meet requirements and are economically efficient. This requires intensive monitoring of developments on the market for battery system applications as well as collaborations between battery test centers and manufacturers of battery systems in order to be able to address future demands efficiently. The further development of the relevant international standards for testing battery systems represents an additional challenge for the operators of battery test centers.

The increasing number of battery development projects in Europe requires the establishment of sufficient test infrastructure in order to be able to cover the demand efficiently and to meet developing requirements from safety standards.

BATTERY QUALITY ASSURANCE COMPANIES



Source: www.battery-atlas.eu; abstract, no claim to completeness

INITIAL POSITION

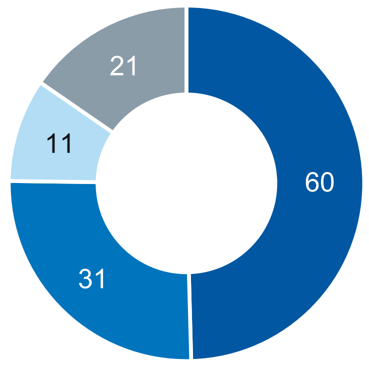
The production of battery cells comprises a large number of individual process steps. These range from dosing and mixing in electrode production to end-of-line inspection after pack assembly. Depending on the process step and the networking of the production facility, the processes are carried out in a reel-to-reel process or as a batch. Optimal interaction of the processes is crucial for high quality and safety in the subsequent operation of the cell. To ensure this interaction and the quality of the battery, there is a number of quality assurance systems, sensors, cameras, and concepts in the field of artificial intelligence and the networking of equipment and systems.

Based on public announcements, production capacities of up to two terawatt-hours will be created by the end of the decade. In addition to the uncertainty of the actual construction of these plants, there is also a difference between theoretical plant capacity or throughput and the actual production volume. This is mainly guaranteed by quality assurance systems. For this purpose, different systems exist for the respective process steps to check individual factors. This check can be performed inline or by offline measurements. Exemplary quality checks or systems to ensure quality in battery production are

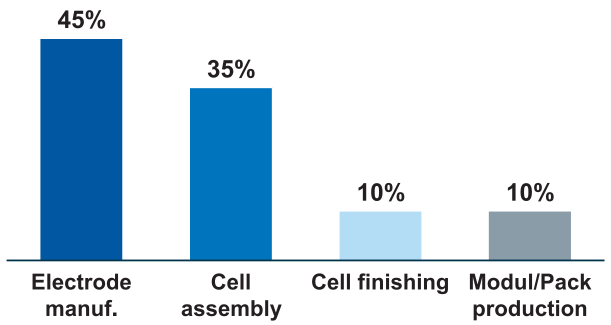
- determining agglomerate size and viscosity after mixing,
- checking the wet film thickness after coating,
- maintaining the web tension in the drying process,
- checking the porosity after calendering.

Early detection of defects or irregularities allows early identification of faults or even countermeasures. Depending on the cell shape and module as well as pack design, battery production comprises up to more than 15 manufacturing steps. In a very simplified view and in a fictitious scenario, quality assurance measures would reduce the scrap per process step by one percent, so output would be increased by up to 20 percent.

Number of European quality equipment suppliers in battery production



Strongly generalized quality monitoring distribution, derived from PEM projects



Electrode manufacturing | Cell assembly | Cell finishing | Module and pack assembly

ANALYSIS

Based on research by the PEM chair of RWTH Aachen University, there is an approximate distribution of about 45 percent of quality assurance equipment needed for electrode manufacturing, 35 percent for assembly, and ten percent each for cell finalization as well as module and pack assembly. A similar picture emerges when evaluating the manufacturers of such equipment within Europe. Especially in the area of electrode manufacturing, companies offer solutions or components. Due to non-existing scaling of the sales of the individual companies, this reduces the informative value of the pie chart shown here. The same evaluation was deliberately chosen for the equipment manufacturers and the quality map, illustrating the relationship in an exemplary manner. However, the discrepancy in the number of solution providers within the module and pack production compared with the plant engineering map should be emphasized. It should be noted here that a conventional pick-and-place has different quality assurance requirements than the web-based process. A large number of the companies in module and pack production specialize in automation. Identifying an exact differentiation for battery manufacturing among manufacturers, when they do not accurately advertise such an application, is a challenge.

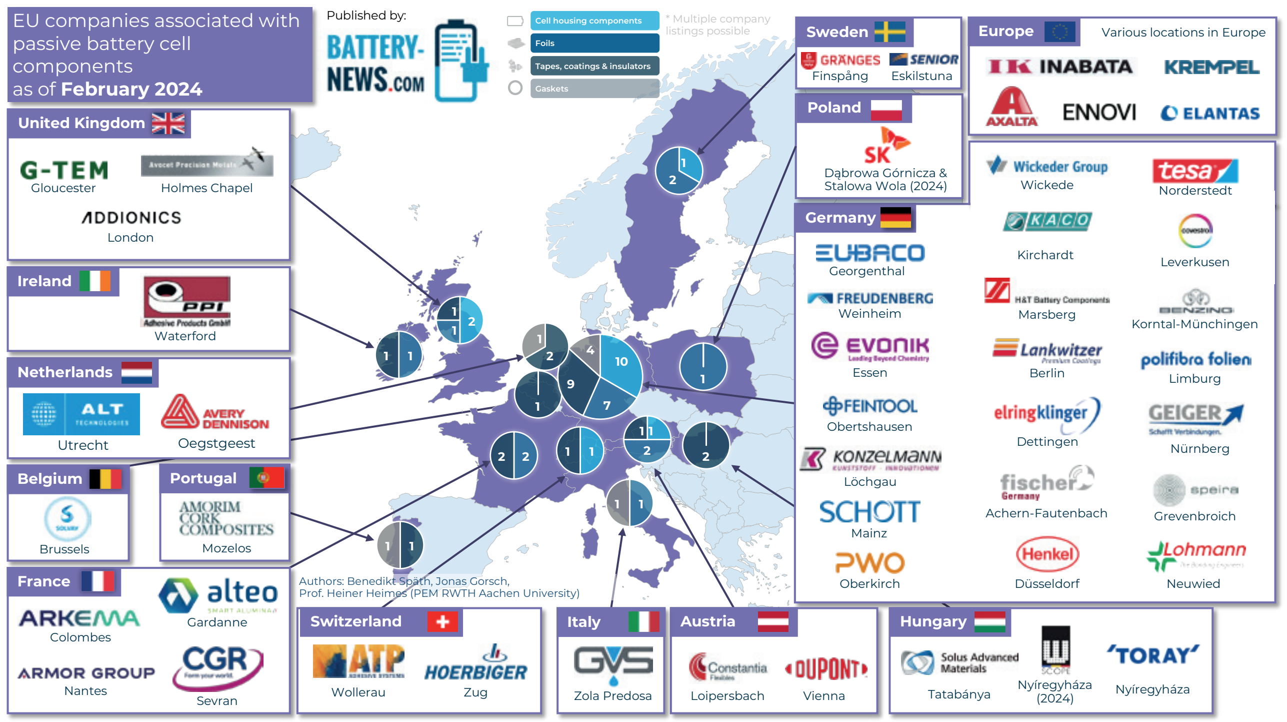
OUTLOOK

As more gigafactories are gradually implemented, newer assurance concepts are evolving along with them. One of the most important topics in this field is quality assurance using artificial intelligence and the application of digital twins. Already today, companies advertise to equip their production with such data-based systems. All the exact interrelationships in the production of battery cells are not yet known. Interviews with leading industry experts support the statement that the expansion of knowledge and the analysis of the process as well as the associated interdependencies will lead to a reduction in the necessary quality assurance equipment in the medium term.

Over the long haul, it is not yet clear what the minimum of measuring equipment will be and what it will look like. Whether this will be a surface inspection supported by exposure techniques or a porosity analysis of the entire web will only become clear as further production lines are set up. However, it is already becoming clear that companies want to know and track more about their product. The exact transfer of information about the product and thus the collected measurement values within the production, i.e. data, are becoming increasingly valuable for the industry.

In the future, plant manufacturers can continue to build on the experience of quality assurance experts based in Europe and collaborate on further developing battery production.

PASSIVE BATTERY CELL COMPONENTS COMPANIES



Source: www.battery-atlas.eu; abstract, no claim to completeness

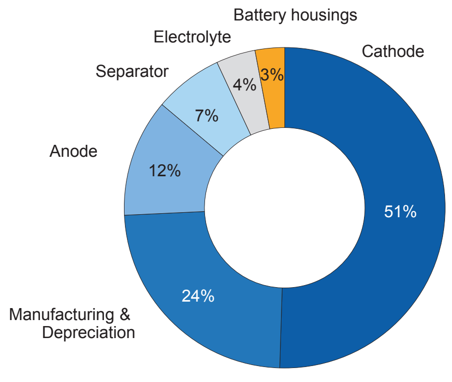
INITIAL POSITION

Battery cell components can be distinguished between active and passive components. The active components are defined as materials which are intended to store or transport lithium ions. Therefore, all other materials fall within the category of passive materials.

In the automotive industry various types of batteries are applied, which primarily differ in geometry and utilized passive components. Established in the consumer market, the cylindrical cells offer good safety standards and comparably the most advanced industrialization, resulting in the lowest manufacturing costs. Packaging density on module or pack level and high relative weight of the robust, deep drawn nickel-plated steel housing can be counted as disadvantages of this cell type. Meanwhile, prismatic cells use housings made of aluminum in a prismatic shape. High possible energy densities and flexible size opposes the lower level of industrialization. The housing of pouch cells on the other hand consists of an aluminum composite pouch foil with a lower weight and volume including a lower structural integrity compared to the other cell types. Pouch cells are characterized by their high energy density but more difficult mechanical, electrical and thermal module integration.

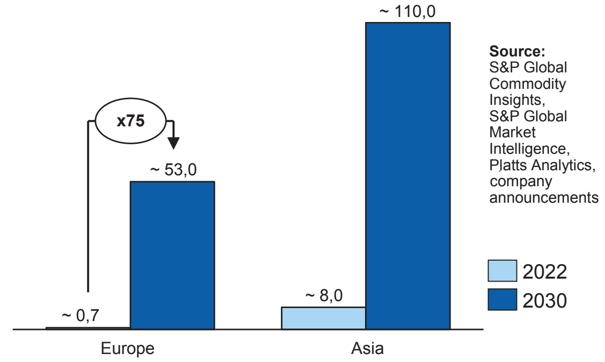
The cell housing assembly of the prismatic and the cylindrical cell includes multiple components. Besides the actual casing such as overpressure vents, terminals, and current interrupt devices, the pouch cell housing only consists of the pouch foil and the cell tabs. The current collector foils and separators can be found in all three cell formats. Tapes, coatings and insulators can also be used in all cell formats. Adhesive tapes are applied in pouch cells for holding the electrode stack in place as well as creating an electrical insulation. Due to its shape, insulation rings are utilized in cylindrical cells along with insulation sleeves for its lateral surface. Insulator bags and tapes are used in prismatic cells. Gaskets find application as lid-to-can gaskets in cylindrical cells and terminal-to-busbar gaskets in prismatic cells. The sealing of pouch cells is instead done by impulse or contact welding, so that no additional gaskets are required.

Breakdown of the cost of an EV battery cell



* Percentages may not add up to 100 due to rounding.
Source: Visual Capitalist, BloombergNEF

Maximum market volume for passive cell materials based on production capacity [in billion €]



Cell cost 100 €/kWh
* 28% of cell cost for passive materials

ANALYSIS

The approximated maximum market potential in Europe of currently 700 million euros is small in comparison to eight billion euros in Asia. The vast majority of the passive component suppliers today is based in Germany, followed by France and the United Kingdom.
While there is already a value chain for materials – such as aluminum for casings, singular components, or collector foils – to supply the Asian battery market in place in Europe, there are still gaps to fill to be able to support the growth of a European value chain for passive components. For example, not a single company with large-scale can manufacturing experience could be identified offering deep drawn aluminum cans for prismatic cells in Europe.
To analyze the passive battery component market, the upstream supply chain for these passive components needs to be considered. Depending on the component and applied processes, specific material is needed as input. The required key materials are:

- **Cell housing components:** aluminum alloys, copper alloys, and nickel-plated steel
- **Foils and separators:** aluminum alloys, copper alloys, polypropylene (PP), polyethylene (PE), polyethylenterephthalat (PET), and ceramics
- **Tapes, coatings, and insulators**: polypropylene (PP), polyethylene (PE), polyethylenterephthalat (PET), and ceramics
- **Gaskets and sealings:** electrolyte resistant rubber

OUTLOOK

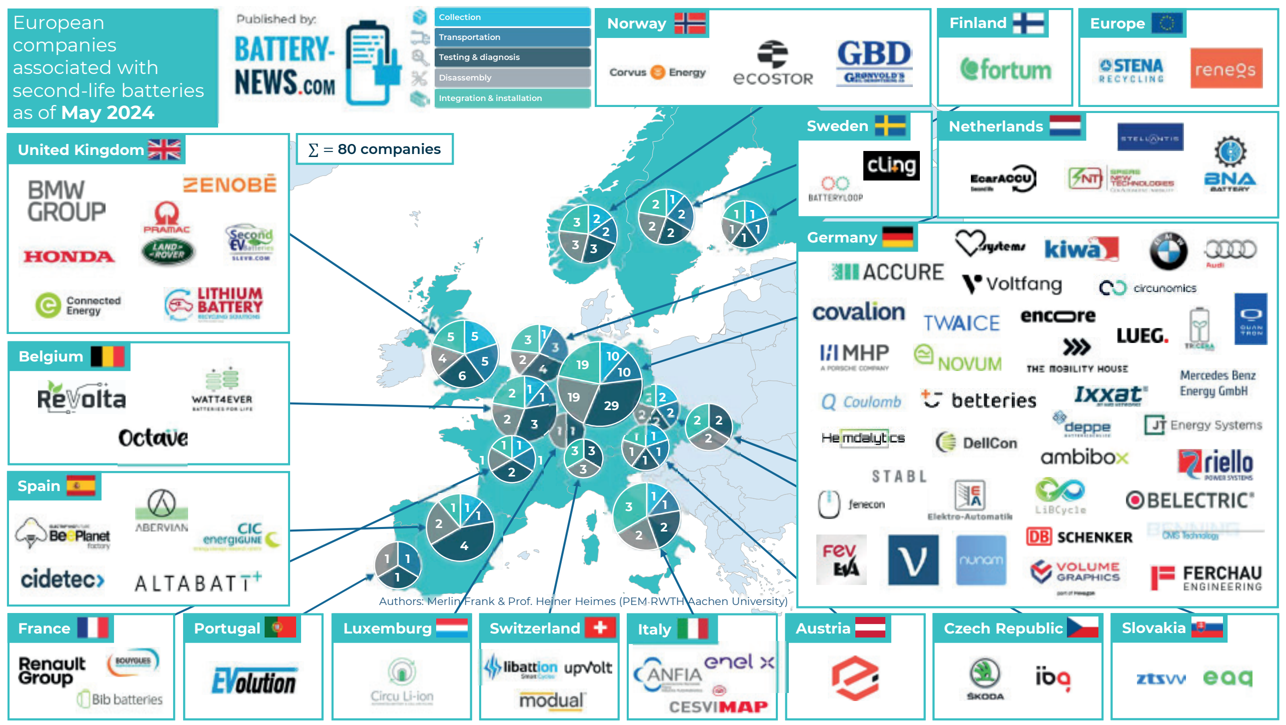
Even though the passive components of a battery cell make up less than 15% of the cost of a lithium-ion battery, to meet the European battery market's expected growth of more than 70 times by 2030, increased focus on the passive components is needed. Beside the components themselves, the upstream supply chain needs to be considered to be able to support the need for battery- and process-specific alloys and materials.

As of now, there are few suppliers able to provide complete assemblies or packages of passive components for a specific cell type. Therefore, a way forward could be more integrated suppliers of passive battery cell components. A challenge for this integration and the growth in general is the trend towards more individual battery sizes and formats requiring each component to be customized for a specific cell design. This challenge is amplified by the extensive upfront tooling cost needed for most of these components.

Commitments of European cell manufacturers to European passive cell component suppliers in early development phases could enable a parallel scaling of the manufacturing capabilities. This would also enable a European supply chain growth and competitiveness with larger and more integrated players from Asia.

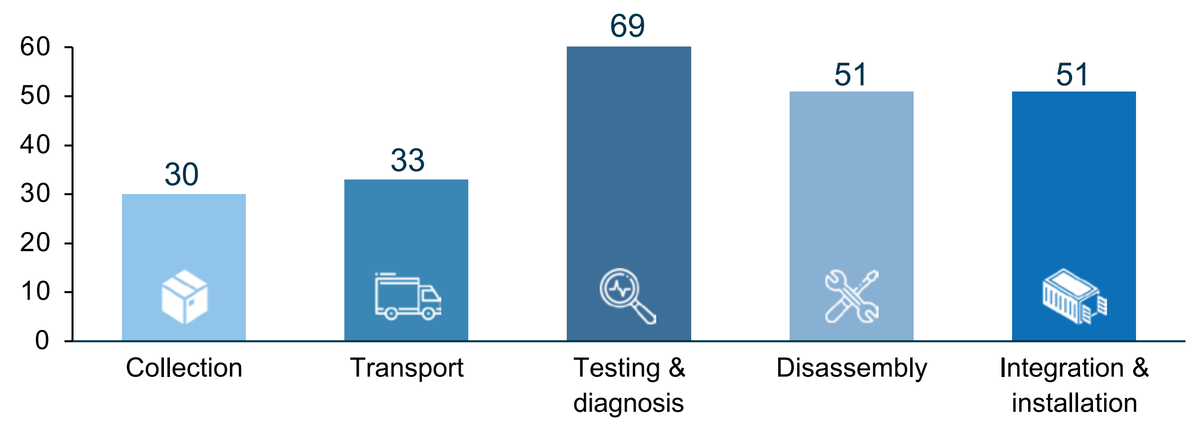
The passive component market in Europe needs significant upscaling to reach the expected and announced growth rates of cell manufacturers.

SECOND-LIFE BATTERY COMPANIES



Source: www.battery-atlas.eu; abstract, no claim to completeness

Number of companies associated with the second-life supply chain



INITIAL POSITION

Based on the manufacturers' descriptions and the existing literature, once electric vehicle (EV) batteries reached 70% to 80% of their nominal capacity, their role as EV first-life batteries ends due to degradation effects. The associated drop in performance of the battery system depends on numerous factors – such as power load, number of cycles, climatic conditions, etc. – and can vary greatly. The individual cells also generally age at different rates, with the performance of the modules being determined by the weakest cells and the performance of the overall battery system by the weakest modules.[9] This degradation is estimated to be happening after about eight years of usage or equivalent to 100,000 miles (160,000 kilometers) of travelling. However, the retired EV batteries, even with lower state of health (SOH), could still be repurposed in other applications such as grid-scale photovoltaic plants, peak shaving, production smoothing, or frequency containment reserve (FCR). In those less requiring applications, batteries are estimated to have another six to ten years before reaching the "End of Life" (EOL).[10]

Beside this typical "second life" case, there are several other cases for EV battery repurposing, such as recalls, R&D batteries, and production scrap of battery modules and packs. Thus, the market provides much higher amounts of returning batteries for stationary second-life applications than expected. This is why second-life business cases are starting to gain traction, with companies commercializing second-life storage systems or making them a part of their supply chain. However, the decision-making process for transitioning from primary, first-life applications to second-life usage is not well understood. Several studies have been conducted that consider the benefits of repurposing EV batteries in stationary applications before recycling. An economic value of second-life batteries cannot be confirmed in general terms since each battery system has a different degradation condition due to individual usage phases, cell chemistries, and system architectures. At the same time, there are multiple application areas that a stationary storage system could serve, generating varying levels of revenue streams. Also, individual application areas can be combined flexibly in some cases, resulting in unique revenue structures which are influenced by the dynamic energy market. Against this background, the individual assessment of the economic benefits of second-life battery systems is necessary to increase the attractiveness of repurposing scenarios.

ANALYSIS

A supply chain of aged batteries from their first use to their second-life application consists of five steps. After the batteries have reached the end of their first use, they must be collected and further transported to a suitable reprocessing plant. After transportation, the batteries' condition is diagnosed based on different tests. Currently, there are no standardized test procedures for second-life batteries, which means that different test scopes can be carried out for condition diagnosis, also depending on battery pack or module level. However, in many cases it is more efficient to disassemble the battery pack before testing to obtain more accurate test results, even if this leads to higher repurposing costs. After these steps, second-life batteries are offered on the market and transported to the customer for integration.

As the figure above shows, all parts of the supply chain are covered by different companies. Most of the companies in the EU are associated with the testing and diagnosis of second-life batteries as well as disassembly and storage integration. Both processes are primarily performed by companies that provide storage systems, but these services are not always outsourced. Fewer companies, on the other hand, focus on the collection and transport of aged battery systems. However, most companies are serving multiple parts of the second-life supply chain in parallel. Hereby it must be considered, that even though many companies can be associated with "second life", only a small number of them operate exclusively in this area.

OUTLOOK

While both the registration and the production numbers of electric vehicles in Germany are increasing continuously, the processing of obsolete battery systems is only in development and still offers a lot of uncertainty about future business models. Focusing on battery repurposing, uncertainties related with the state of the battery, the different ways and requirements for adapting the battery to a new application, and difficulties in analyzing the economic and environmental benefits complicate the transition from first to second life. In addition, there are several potential pathways for batteries once they reach the end of their first life. Beside repurposing in second-life applications, a common pathway is to build a refurbished battery from aged modules which is then reused in mobile applications such as vehicles. Beside the slowly increasing return flow rates, the aforementioned uncertainties represent a barrier to the replicability and scalability of the implementation of second-life batteries.

At the same time, it should be considered that the second-life market is just beginning to develop. Continuously increasing return volumes will force the market to evolve and form economically stable supply chains – finally improving the sustainability of traction batteries while in parallel increasing their technological value.

Batteries returning from electric vehicles will create a separate market, as many systems are still functional and can be used in stationary applications with lower requirements.

9 Hossain et al. (A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies), 2019

10 E. Martinez-Laserna et al., Battery second life: Hype, hope or reality? A critical review of the state of the art, Renew. Sustain. Energy Rev. 93 (February 2017) (2018) 701–718.

SUMMARY

BATTERY CELL MANUFACTURERS

1. To meet the demand for battery cells in the automotive sector in Europe, 900 GWh of battery production capacity are needed in 2030.
2. Main players on the European cell production market are Asian cell manufactures, European cell manufacturers/start-ups, and joint ventures between car manufacturers and cell producers.
3. To improve the production process, digitization will be an important characteristic of European factories.

MODULE AND PACK MANUFACTURERS

1. The module/pack manufacturer market consists of cell manufacturers, automotive manufacturers, and suppliers.
2. Cell manufacturers are planning to increase module and pack production, while automotive manufacturers are converting existing production facilities.
3. In module and pack production, vertical integration is currently taking place in some cases, but classic supplier relationships still exist.

EQUIPMENT SUPPLIERS

1. Germany is playing a pioneering role in the development of production equipment for future battery production.
2. European equipment manufacturers should focus on modular systems in order to shorten delivery times and adapt to customer demands.
3. The numerous specialists in the European equipment industry should be able to act as general contractors in the coming years.

ACTIVE MATERIAL SUPPLIERS

1. Global distribution of battery raw materials is uneven, leading to supply chain vulnerabilities and a strategic need for diversified sourcing to enhance stability.
2. With a focus on cost reduction, manufacturers are shifting their attention to active materials that are readily available and cost-effective, which influences market preferences and production strategies.
3. The EU is scaling up its production capacity for active materials, signaling a push towards self-reliance, with a projected annual output now surpassing one million tons.

RECYCLING COMPANIES

1. In 2023, approximately 17,000 tons of electric vehicle batteries in Europe will have to be recycled or repurposed.
2. By 2030, the number of end-of-life batteries in Europe is expected to reach 290,000 tons, highlighting the need for increased recycling capacity.
3. Germany currently has the most recycling companies on the European market due to its high number of automotive companies and increasing battery production.

BATTERY TEST CENTERS

1. The high demand for battery test capacities leads to capacity bottlenecks and delays development.
2. The increasing number of battery development projects and evolving battery standards require additional testing capacity.
3. At the present time, there are only a few test centers that can offer all the necessary certification tests from a single source.

BATTERY QUALITY ASSURANCE COMPANIES

1. Europe can secure the entire process chain through resident companies.
2. The number of companies that can actually cover every single process and support them with AI will increase.
3. By building a broad process understanding, the amount of quality equipment for plants can be reduced.

PASSIVE BATTERY CELL COMPONENTS COMPANIES

1. Every battery cell format needs custom-designed and format-specific passive battery cell components.
2. The European market for passive battery cell components has an approximated growth potential of 75 times until 2030.
3. Partnerships between cell manufacturers and passive component manufacturers in Europe could enable simultaneous scale-up of production capacities.

SECOND-LIFE BATTERY COMPANIES

1. The second-life supply chain can be divided into five different steps: collection, transportation, testing and diagnosis, disassembly, and final integration.
2. Even though many companies can be associated with the “second life” sector, only a small amount of them operate exclusively in this area.
3. The industry is slowly preparing for a strong increase in battery return volumes expected for the next decade.

IMPRINT

PEM | RWTH AACHEN UNIVERSITY

The Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University was founded in 2014. In numerous thematically organized research groups, the PEM team is dedicated to all aspects of the development, production, and recycling of battery systems, electric motors, fuel cell technologies, and their respective components as well as their integration, especially in heavy-duty commercial vehicles.

At the time of publication of the 2024 Battery Atlas, a total of 80 researchers, 36 non-scientific employees and 140 student assistants are employed at PEM's headquarters in the German-Dutch Avantis industrial park as well as at the Electric Mobility Laboratory (eLab) on RWTH Aachen Campus and at an e-truck research workshop in the East of Aachen. The PEM team is active in teaching as well as in nationally and internationally funded research projects, also collaborating with renowned industrial partners. The focus is always on sustainability and cost reduction – with the aim of a seamless "Innovation Chain" from basic research to large-scale production in the immediate vicinity.

WWW.PEM.RWTH-AACHEN.DE

AUTHORS

Prof. Dr.-Ing. Heiner Heimes
Member of PEM Institute Management
PEM of RWTH Aachen University

Prof. Dr.-Ing. Achim Kampker
University Professor & Founder
PEM of RWTH Aachen University

Moritz Frieges
Chief Engineer
PEM of RWTH Aachen University

Gerrit Bockey
Research Associate
PEM of RWTH Aachen University

Natalia Soldan
Group Leader
Circular Economy & Materials
PEM of RWTH Aachen University

Niklas Kisseler
Group Leader
Battery Engineering & Safety
PEM of RWTH Aachen University

Merlin Frank
Research Associate
PEM of RWTH Aachen University

Benedict Späth
Research Associate
PEM of RWTH Aachen University

Jan Felix Plumeyer
Research Associate
PEM of RWTH Aachen University

Artur Scheibe
Research Associate
PEM of RWTH Aachen University

Editor
Heiner Heimes,
Production Engineering of E-Mobility Components (PEM) | RWTH Aachen University

Bohr 12 | 52072 Aachen
Phone +49 241 80 230 29
E-mail info@pem.rwth-aachen.de
Web www.pem.rwth-aachen.de

The authors are solely responsible for the contents of the publication.

Primary content research Gerrit Bockey
Editing Mischa Wyboris
Concept and layout Patrizia Cacciotti

Cover/back
PEM | RWTH Aachen University

Freepik.com (pages 2 and 3)
Adobe Stock | KanawatTH | #526620639 (page 4)
Battery-News.de (maps)
PEM | RWTH Aachen University (diagrams, page 26)
VDMA collage: Maschinenfabrik Gustav Eirich GmbH & Co. KG und
TRUMPF SE + Co. KG (page 26)

Disclaimer
Information from the Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University is obtained from selected public sources. In providing this service/information, PEM and its affiliates assume that the information used come from reliable sources but do not warrant the accuracy or completeness of such information which is subject to change without notice, and nothing in this document should be construed as such a warranty. Statements in this service/document reflect the current views of the authors of the respective articles or features and do not necessarily reflect PEM's views. PEM disclaims any liability arising from the use of this document, its contents, and/or this service. Image rights remain at all times with the respective creator. PEM is not liable for any damage resulting from the use of the information contained in the "Battery Atlas".

PEM of RWTH Aachen University (own print), 2nd edition, EN, ISBN: 978-3-947920-33-4

PEM of RWTH Aachen University (own print), 2nd edition, EN, ISBN: 978-3-947920-33-4

www.Battery-Atlas.eu