

# BATTERY MONITOR 2022

THE VALUE CHAIN IN THE FIELD  
OF TENSION BETWEEN  
ECONOMY AND ECOLOGY





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## Dear readers,

in 2021, the chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University published the Battery Monitor’s first edition. In it, we focused on battery cell production and presented the value chain in terms of economy and sustainability. Moreover, we placed particular emphasis on addressing technologies that have significant added value for resource-saving production. Technologies such as mini-environments or laser and infrared drying were given as examples. In order to continuously develop the Battery Monitor, this new edition is focused more closely on the life cycle phases of the battery. Indeed, we have defined key performance indicators for each life cycle phase of the battery: “Sustainability”, “Technology performance”, “Profitability/Competitiveness”, and “Innovativeness”.

We believe those key performance indicators should provide a statement about the progress of the described objectives. To ensure this is done from all perspectives, PEM of RWTH Aachen University developed the Battery Monitor’s new edition in close collaboration with “Roland Berger”. We are pleased that this community work has enabled constructive, and at the same time critical, reflection on the respective life cycle phases of the lithium-ion battery. Input from different perspectives and access to databases characterize the latest Battery Monitor.

This edition looks at the battery materials required for manufacturing, battery cell production, battery development, battery use, recycling, and reuse of batteries, and offers an overall view of the market. The key performance indicators are applied to these phases. Taken together, this ensures an accurate picture of the technological maturity of the lithium-ion battery.

We would like to use this second edition of the Battery Monitor as a basis to continually review its structure so later editions can be adapted to include latest developments. We are happy to discuss the content at any time and look forward to your feedback. We hope you enjoy reading it.

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# INTRODUCTION

The first gigafactories are starting up, while further cell production facilities are still being built – this is the status of European cell production in 2022. The battery as the main component of the decarbonization of transport and accelerator of the energy transition is currently experiencing further global growth. Production capacities of six to nine terawatt-hours are expected to be reached by the end of the decade. In the competition to meet the projected demand, countries and companies are dueling along the entire value chain.

Companies from Asia, Europe and North America are the primary players in the production of battery cells, modules, and battery packs used in electric vehicles. However, cell production is only one building block in the lithium-ion secondary storage process chain. The process chain already starts with raw material extraction and refining of the active materials. Further components are the engineering and development of the battery systems as well as the period of use of the battery cell, for example in the battery-electric vehicle. Motivated by manufacturing that is as sustainable and CO<sub>2</sub>-neutral as possible, the recycling or reuse of used cells, modules or packs in so-called second-life applications is becoming increasingly important. While Asia, Europe and North America represent the main markets for cell production, South America, Africa and Oceania are other important producers for some components of active materials. The production of batteries is therefore a global issue and cannot be considered on a country-specific basis.

The Battery Monitor 2022 shows the current status of the respective regions based on defined evaluation criteria. These are sustainability, technology performance, economic efficiency and competitiveness as well as innovative strength. These key performance indicators are in turn divided into up to three subcategories in order to allow the most differentiated view possible and to map the relevant issues relating to the value creation of the battery as accurately as possible. The KPI sustainability is becoming more and more important.

Issues around CO<sub>2</sub> emissions and the use of hazardous substances during production often dominate the headlines of critical news platforms. While the sustainability KPI reflects the environmental impact, the other KPIs reflect the technological differences and research work in the respective subareas.

Starting with an overarching market view, this publication then looks at each process step in the battery production value chain. The Battery Monitor concludes with a summary of the values collected and a presentation of the political framework conditions for the respective KPI.



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## 3. OVERARCHING MARKET VIEW

### THE MARKET FOR LIB IS ACCELERATING AND NEW CHALLENGES APPEAR – SUSTAINABILITY AND RAW MATERIAL AVAILABILITY WITH HIGHEST PRIORITY

Today's battery market is unrecognizable from that of a few decades ago. With the rise of power-hungry gadgets and electric vehicles (EVs), the focus has shifted from disposable power cells to ultra-efficient rechargeable devices, high-energy battery packs and fast charging opportunities driven by the battery development, and the infrastructure development. Sustainability, availability of raw materials, the EV market and demand for ever-more powerful lithium-ion batteries (LIB) have been and are still major drivers of the transformation. In this chapter, we assess the key characteristics of the market.

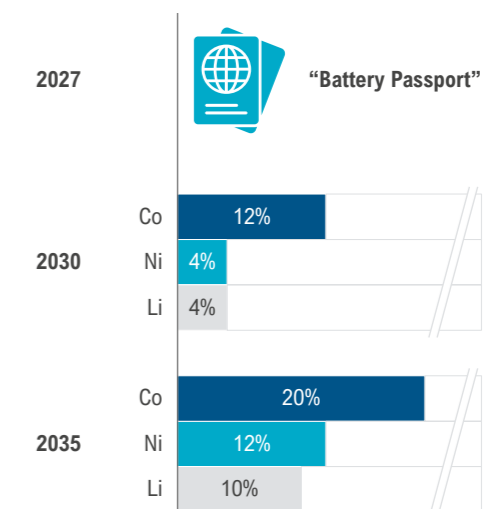
### 3.1 SUSTAINABILITY

**Sustainability of battery production becomes increasingly regulated in the European Union.** There are currently two main issues impacting battery sustainability: the phase out of the internal combustion engine (ICE) and, in Europe, tightening regulations. Fourteen countries have now announced that they intend to ban the sale of new ICE vehicles. For example, Germany, the UK, Canada, and Norway all intend to do this by 2035 or earlier, while the developing nations of Costa Rica and Sri Lanka are targeting 2050 and 2040 respectively. Several US states, such as California and New York, also plan to ban ICE vehicles. Battery-powered vehicles will replace them, leading to increased demand for EVs and, to ensure the move is sustainable, rising shares of renewable energy to power them. This transition is covered in more detail in chapters 5 and 6. Here, we focus on the second issue, regulation.

### THE EU'S PUSH FOR SUSTAINABILITY, THROUGH RECYCLING TARGETS AND LEVIES ON CO<sub>2</sub> EMISSIONS, HAS A DIRECT IMPACT ON PRODUCERS

There is a growing number of political initiatives designed to reduce the carbon footprint of batteries in Europe (regulations in other countries tend to focus on competition rather

than sustainability – see subchapter 1.3). In particular, there is a push to lower battery-related CO<sub>2</sub> emissions and increase the share of recycled materials used in battery production. The European Union's (EU) Battery Directive proposes an incremental increase in the recycled share of some key battery materials. This includes targets of 12% and 10% for nickel and lithium respectively by 2035. Technical documentation, described as a "battery passport", will be required from 2027.



**Figure 1:** Targets for share of recycled battery materials in the EU Battery Directive



The directive also proposes shifting the responsibility for collection and recycling of batteries onto producers. However, it is not yet decided if this will be OEMs or cell manufacturers, and specific regulations are not yet defined.

In addition to the directive, the EU's Carbon Border Adjustment Mechanism (CBAM) could also affect the European battery value chain. CBAM is part of a broader legislative package aimed at reducing the EU's greenhouse gas emissions by 50 to 55% by 2030. Beginning in 2023, it will levy an import tax on emissions "embedded" in imported goods, such as metals produced outside the EU. It is not yet known if battery materials will be covered, but if they are, it won't be until 2028 at the earliest. CBAM could push up the price of cathode active materials – one of the main ingredients of batteries (see chapter 2) – by around 1.60 US dollars per kilogram in a worst-case scenario.

### 3.2 TECHNOLOGY PERFORMANCE TECHNOLOGY PROGRESS DRIVES LIB ADAPTATION – AND HIGHER VOLUMES LEAD TO AN INCREASED READINESS TO DEVELOP SPECIFIED CELLS

With the rise in battery demand, technological developments have reached their highest ever levels. The specifics of these advances are covered in detail in chapters 2 through 5. Here we look at several general trends, detached from individual value chain steps.

#### SPECIALIZED PRODUCTS: THE GROWING BATTERY MARKET HAS ENABLED THE DEVELOPMENT OF CELLS FOR SPECIFIC APPLICATIONS, SUCH AS ELECTRIC FLIGHT

First is the opportunity to develop specialized products. To date, most batteries used in new applications have been derivatives of existing cells. But the growing and maturing market now offers a stronger platform to engineer entirely new systems for novel and existing uses. With segments reaching a critical scale of more than 40 gigawatt-hours (fully utilized state-of-the-art gigafactory), development of specific chemistries and cell formats becomes economically attractive. There are several examples.

In its early development stages, the electric vertical take-off and landing (eVTOL) aerospace industry used consumer cells to power its products. But as the technology matures, and demands ever-higher energy and power densities, it has been exploring very different technologies compared to automotive cells. High-performance cells featuring advanced technologies, such as high-silicon anodes and pre-lithiation, have now been specifically developed for eVTOL applications. This is made easier by lower cost pressures in the industry. The same is true for commercial vehicles. Estimates suggest there will be around 315 gigawatt-hours of demand for commercial vehicle applications in 2030. Until now, a limiting factor of battery development in the market, which requires more robust batteries with longer life cycles than in private EVs, has been the utilization and thus economic attractiveness of dedicated production lines for commercial vehicle applications. These require pack manufacturers to source suitable cells from other industries, such as automotive. But this will change as typical production lines today have an output capacity of four to six gigawatt-hours, equaling around 60 production lines to meet demand in 2030.

Finally, stationary energy storage systems (ESS) are a growing market as the need to store power, and ease pressure on grids, grows. ESS cells require far lower energy densities than vehicle batteries but they need to have far longer cycle and calendar lives. In the past this was typically realized with either low-nickel NMC or standard lithium chemistries. However, a new technology is now evolving – sodium-ion batteries. Leading battery producers are now specifically developing these cells for the ESS market as they provide a cost-effective and sustainable solution. Cell manufacturers, like Faradion, CATL, Natron Energy or Tiamat, are developing cells currently 120 to 160 Wh/kg in energy density, with a target of around 200 Wh/kg. Such cells are large and unsuitable for mobility uses, except the entry segment if targets can be reached, but size is less of an issue in stationary storage. In addition, ESS cells typically do not use scarce raw materials. ESS cells are covered in more detail in subchapter 6.2.

### LOCK-IN BENEFITS: SOME MARKETS ARE DOUBLING DOWN ON THEIR AREAS OF EXPERTISE OR PURSUING CLOSED-LOOP PROJECTS TO EXPLOIT LOCK-IN EFFECTS

With resources at a premium, another general trend is markets' efforts to secure, or lock in, the supply of materials they already have. For example, Europe and North America are currently focusing on nickel-based materials, so will likely stick to the technology as they know they can recycle the nickel in the future. Ecosystems will develop around this model, allowing markets to become more independent. Indonesia, which has legislated to ensure that part of its raw materials can only be processed in country, is another good example. It is setting up closed-loop projects with OEMs such as Honda, battery giants like CATL, LG and ES, and suppliers including Posco and BRUNP, to maximize lock-in effects. These projects are required to process nickel ore within Indonesia to ensure that money stays in the country – for the CATL project, 60% needs to be processed in Indonesia, while the LG ES + Posco project negotiated to 70%.

### 3.3 COMPETITIVENESS ANNOUNCED BATTERY OVERCAPACITY IS A RESULT OF GOVERNMENTAL INCENTIVES AND WILL LEAD TO MARKET CONSOLIDATION

The battery market is overheated. Demand is insatiable, especially from the EV market, and producers are at the limit of their capacity to meet it. However, as more and more players enter the market, overcapacity will become a problem. Missing customers will lead to low utilization will lead to low economics. Combined with the expected undersupply of raw materials, this will present significant challenges for new entrants, and consolidation as well as stranded investments are likely. In this subchapter we look at these issues in detail, along with action battery producers are taking to address them.

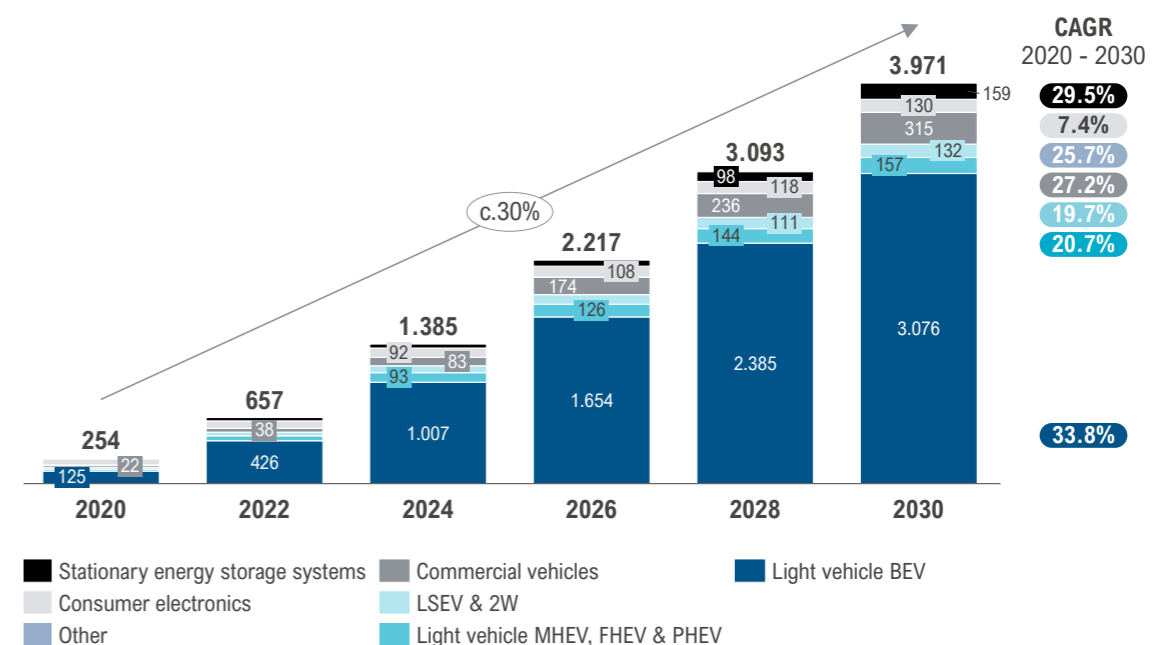


Figure 2: Global market demand forecast for LIB by application [GWh]. Source: IHS Markit, interviews with market participants, Roland Berger

**SUPPLY & DEMAND: OVERCAPACITY IN THE BATTERY MARKET, DRIVEN BY EV SALES PROJECTIONS, COULD RESULT IN MAJOR RISKS FOR NEW PLAYERS**

The EV industry is the main driver of global battery demand. By 2030, it is estimated that all-electric vehicles will comprise up to 45% of the total vehicle fleet in China, up to 68% in Europe, up to 36% in the US and around 38% globally. Once hybrid vehicles are added, the global share of pure ICE vehicles is likely to fall to just 27%. EV penetration will be driven by tightening regulation and reductions in pack costs, with the estimated figures based on the assumption that there will be no significant shortage of raw materials and/or cost increases. In total, the EV industry is forecast to account for 90% of global battery demand in 2030, equivalent to four terawatt-hours.

However, announced global capacity for 2030 is more than 6 TWh, with China alone planning for half of it. In a bid to increase their independence in cell production, Europe fueled huge subsidies of almost every European nation, eager to have its own gigafactory in the country. European players have announced 1.6 TWh and North America 1.2 TWh. The expected overcapacity will have several implications, especially in terms of consolidation:

**Sales security:** Not all players will have enough customers.

**Lack of talent:** There will be too few qualified people.

**Lack of raw materials:** Nickel and lithium, in particular, are expected to be in short supply.

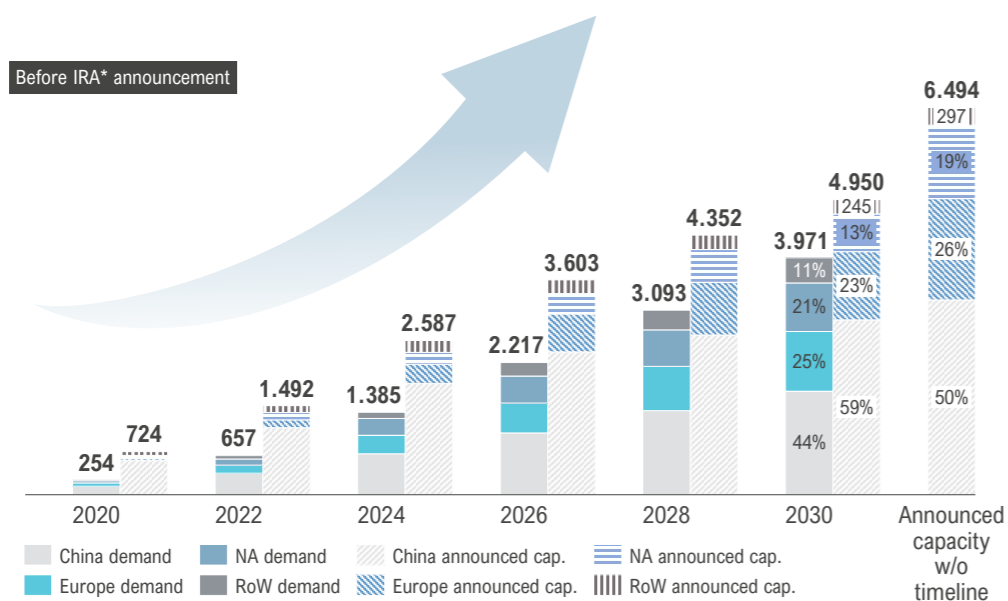
Due to the industry's focus on increasing the nickel share in batteries to improve performance (see subchapter 2.2), the scarcity of nickel will be the most critical risk. Supplies of lithium are expected to be sufficient provided planned mining projects (which have typical lead times of three to seven years) materialize on time. However, 43% of lithium supplies in 2025 are already reserved. Cobalt, another part of major cathode active materials, is expected to be less of a problem as technologies shift away from its use.

**LOCALIZATION PUSH: GOVERNMENTS ARE REGULATING TO EASE BATTERY PRODUCERS' RELIANCE ON CHINESE RAW MATERIALS AND REFINED PRODUCTS**

While huge leaps have been made in battery technology in recent years, producers are still dependent on critical raw materials, such as nickel and lithium. China has long been the global leader in refining, with around 70% of lithium and 30% of

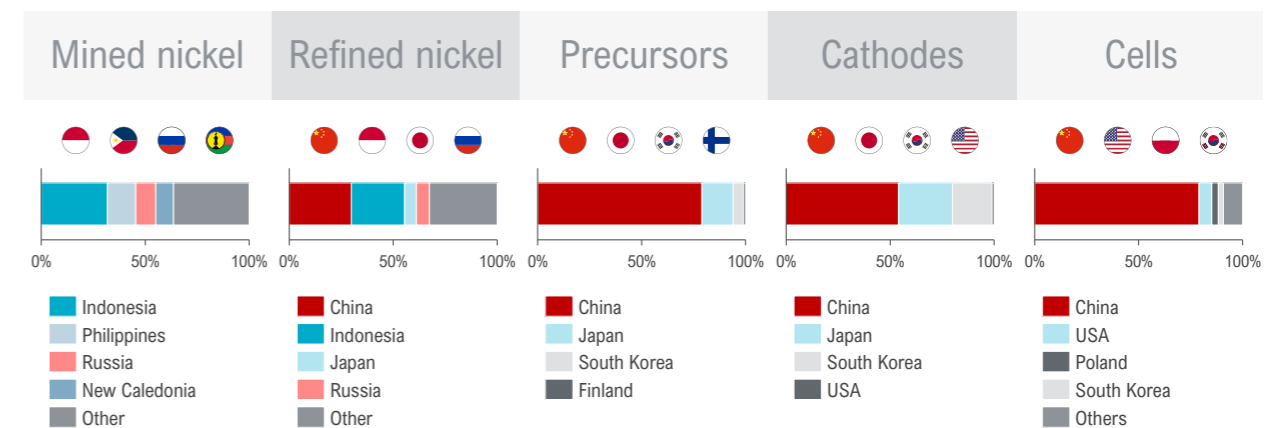
nickel being processed there. This gives the country a significant competitive advantage, especially regarding cathode precursors. But China's dominance is being challenged with the emergence of battery material hubs in Northern Europe, Western Australia and North America (especially Canada), as well as the closed-loop projects in Indonesia. This shift towards localized supply chains is being driven by regulation, especially in Europe and the US. As discussed above, the EU's Battery Directive and CBAM aim to increase the share of recycled materials in batteries and reduce the carbon footprint of the value chain. This is indirectly challenging Chinese material suppliers with higher CO<sub>2</sub> emissions and higher emissions by shipment. Other non-sustainability-related policies could also impact competition. For example, the EU is supporting battery R&D with six billion euros of public funding through an Important Project of Common European Interest (IPCEI) on batteries and others, such as semiconductors. In addition, it is considering classifying lithium as a health hazard following a recommendation from the European Chemicals Agency, a move the industry is opposing. In the US, the focus is on reshoring the battery value chain. A "Buy American" strategy has seen tariffs of between 7.5% and 25% placed

on Chinese-produced battery cells, minerals, and other materials, while incentives have been offered for EV producers to source a share of materials from domestic suppliers. The Inflation Reduction Act (IRA) of August 2022 offers further incentives for local sourcing, with up to 12,000 US dollars of tax credits for EVs. The tax credit comprises of two parts: up to 7,500 US dollars if the EV's battery pack components are assembled in the US and if 40% of the value of critical materials come from US-friendly countries (rising to 80% in 2027); and up to 4,500 US dollars depending on the cell size/components and the maker's investment in battery material production. The IRA is expected to massively boost demand for all-electric cars and could result in a significant change in the market shares of battery and EV makers. More widely, the IRA will make the US much more attractive to invest in, with a total of 369 billion US dollars set aside for clean energy and climate initiatives.



**Figure 3:** Global market demand forecast for LIB by region [GWh]. Source: IHS Markit, interviews with market participants, Roland Berger / \*Inflation Reduction ACT

Production countries of nickel-based cathode LIBs



**Figure 4:** Current geographical distribution of mining and processing of nickel battery value chain. Source: Roskill, IEA, Statista, Roland Berger

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# BATTERY MATERIALS

THE COMPETITION ON RAW MATERIALS IS ACCELERATING, AND OEM AND CELL MANUFACTURERS SHOW INCREASING ACTIVITIES IN SECURING NICKEL, LITHIUM, AND COBALT

The materials used in batteries account for 60 to 70% of total cell costs. Value chains to cover this demand are not established in sufficient extend and new projects often take up to seven years to go into operation. As cathode and anode components, such as lithium, have the highest impact on cost and performance, they are the focus of this chapter. Cathode active materials (CAM) together with anode active materials (AAM) determine the efficiency, reliability, costs, cycle and calendar life, and size of batteries, and are the key target of battery technology development. They are therefore the main focus of this chapter.

## 4.1 SUSTAINABILITY CARBON-FOOTPRINT OF BATTERY MATERIALS STRONGLY RELY ON SELECTED PRODUCTION – CELL MANUFACTURERS AND OEMS NEED TO INVESTIGATE VALUE CHAINS TO REACH CO<sub>2</sub> TARGETS PER KILOWATT-HOUR BATTERY CELL

With the increasing importance of the environment, a major challenge for the battery industry is to improve sustainability through new technologies and production methods. The main issues are the CO<sub>2</sub> emissions produced by the highly energy-intensive process of making CAM and the disposal of waste products.

## WASTE PRODUCTS: SODIUM SULFATE TAILINGS ARE BECOMING A GROWING ENVIRONMENTAL PROBLEM AS BATTERY PRODUCTION INCREASES

The cathode active materials in LIBs, such as nickel cobalt aluminum oxides (NCA) and nickel, manganese and cobalt oxides (NMCs), are produced from metal sulfates and sodium hydroxide via a process of precipitation, then heat-intensive calcination (see graphic) to lithiate the material. Precipitation produces around 1.5 kilogram of sodium sulfate per kilogram of CAM. With sodium sulfate production currently at around 650 kilotons per year, this is not yet a hazard. Sodium sulfate can be guided into a

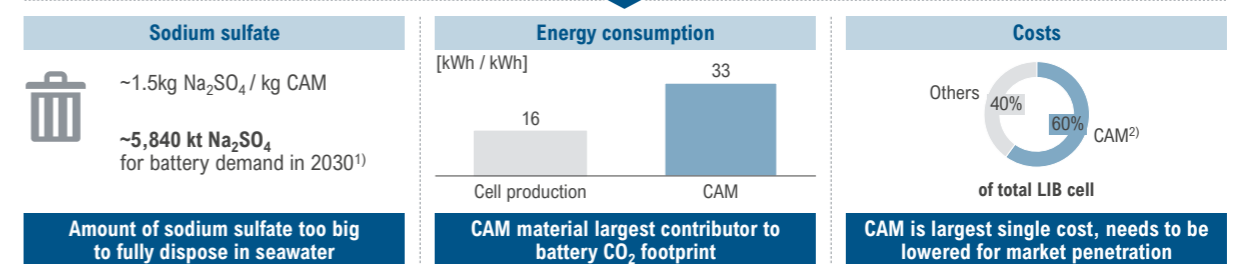
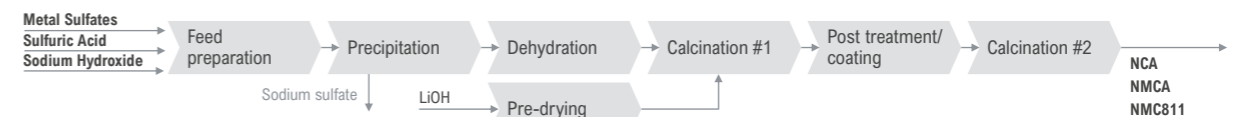


Figure 5: Conventional high-nickel production and implications based on market development. Source: Roland Berger



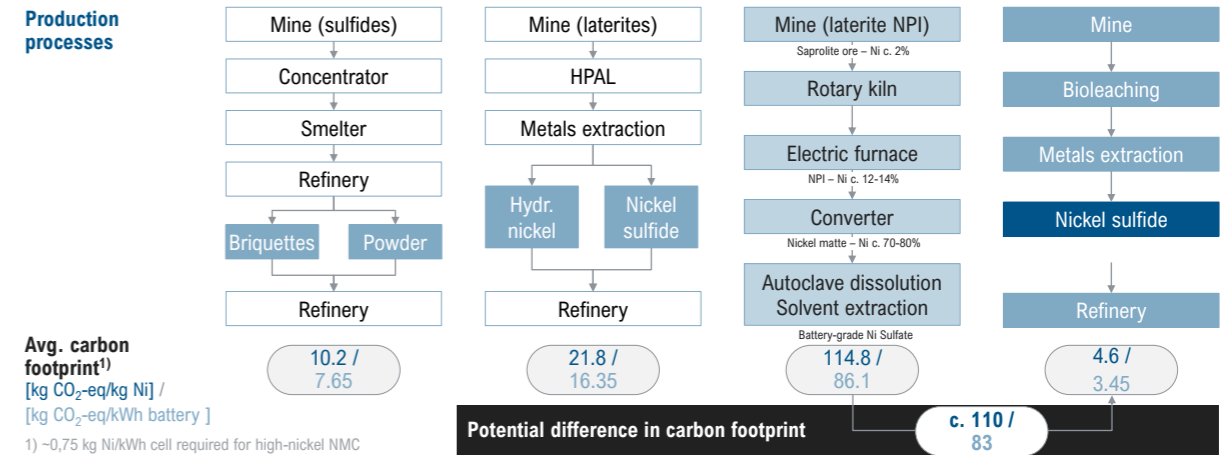
salt water body, provided it is evenly distributed to avoid changes to the seawater pH level. The dumping of tailings is normally tightly regulated. But with production expected to hit 4,170 kt in 2030 (based on around four terawatt-hours market demand for LIBs in 2030, assuming 70% are nickel-based), sulfate tailings need better management to limit environmental strain. Indeed, some countries have now banned the dumping of tailings. New processes that avoid sodium sulfate production are in development, as are after-treatments that can recycle the chemical (see subchapter 2.4). Toxic residues present another waste problem. Calcination is usually carried out in ceramic boxes (saggars) in roller-hearth kilns, and materials such as cobalt seep into the ceramic when baked. This hazardous waste must be disposed of. The use of more energy-efficient rotary-hearth kilns can avoid this problem. However, these are not yet fully industrialized due to problems with degradation of the equipment and maintenance. Once this technology is established, it also can provide a more energy-efficient calcination.

#### ENERGY AND CO<sub>2</sub> EMISSIONS: EMISSIONS ARE HIGHLY DEPENDENT ON THE SETUP OF THE VALUE CHAIN AND AVAILABILITY OF RENEWABLE ENERGY

From mineral extraction to calcination, CAM production is energy-intensive. Some CAM players, such as Northvolt in Sweden and Umicore in Poland, have even moved to co-locate with green energy production sites to ensure supplies and lower their carbon footprints. But overall CO<sub>2</sub> emissions depend on more than just the local availability of renewable energy – the entire value chain setup plays a critical part. Depending on the setup, CO<sub>2</sub> emissions from battery cell production are currently between 42 kilograms CO<sub>2</sub> equivalent per kilowatt-hour (cleanest) and 142 kilograms CO<sub>2</sub> eq/kWh (worse case). Typical emissions are between 60 and 80 kilograms CO<sub>2</sub> eq/kWh. Of these, CAMs account for 40 to 60 kilograms CO<sub>2</sub> eq/kWh. This can be further broken down into three main parts:

- Mining/refining of metal sulfates: 36 – 45 kg CO<sub>2</sub> eq/kWh battery cell for all required metal sulfates (with nickel being the vast majority; this varies considerably depending on the nickel production process – see graphic. As depicted, the NPI conversion process is, as expected, combined with high CO<sub>2</sub> emissions, making it unsuitable for sustainable battery production)
- Production of precursor CAM (P-CAM): 0 – 4 kg CO<sub>2</sub> eq/kWh battery cell (where the zero figure represents the green EU setup using 100% renewable energy and the higher figure the setup used in China)
- Production of CAMs: 0 – 14 kg CO<sub>2</sub> eq/kWh battery cell (green EU vs. China setup)

Some OEMs have set a target of below 30 kilograms CO<sub>2</sub> equivalent per kilowatt-hour at a cell level, with CAM making up less than 20 kilograms CO<sub>2</sub> equivalent per kilowatt-hour. To achieve this, it is clear that OEMs and battery producers need to overhaul their supply chain to lower their overall footprint. The extraction and refining of nickel is a particular target for reducing emissions, and relocating to production sites that are close to renewable sources is another lever. But even then, the target will only be achievable if recycling technologies are introduced. While recycling has a dedicated chapter in this report, further innovation processes to increase sustainability in CAM production are outlined in subchapter 2.4.



**Figure 6: CO<sub>2</sub> footprint of different nickel sulfate production routes.**

Source: Skarn Associates, Terrafame, Roland Berger

#### 4.2 TECHNOLOGY PERFORMANCE HIGH-NICKEL CATHODES ARE CLOSE TO REACH MAXIMUM PERFORMANCE, WHILE THE SILICON ANODES STILL HAVE ROOM FOR IMPROVEMENT

**Key development areas: Higher nickel contents, nickel alternatives and sodium-ion technology are in focus, with priorities varying by region and application**

The current focus in battery development is on reducing the cost of cells, improving energy densities and increasing charging/discharging speeds, with energy densities already considered good enough for most applications. Once again, cathode and anode technologies are the key areas of interest. In the former, the main push is towards ever-growing nickel contents in NMCs to increase energy densities, which however are nearly at their limits with technologies of more than 90% Nickel being introduced. However, with the recent increase in nickel prices, producers are also exploring the use of manganese as a compromise between standard lithium ferrophosphate (LFP) cells and high nickel-content NMCs. The substitution of lithium ions with cheaper sodium ions is another key area of research. In anode technology, the race is on to develop better graphite and silicon solutions to increase energy densities and improve power capabilities, and thereby charging/discharging capabilities. Other advances, such as in separators, electrolytes

and current collectors, enable new technologies, and arise mainly as a result of cathode, anode and cell design developments.

#### CATHODE TECHNOLOGIES: FOCUS AREAS VARY BY REGION, WITH CHINESE AND OTHER ASIAN PRODUCERS OUT IN FRONT IN TERMS OF PERFORMANCE IMPROVEMENT

Each regional market has its own particular focus:

#### CHINA AS LOW-COST MARKET WITH LFP AND SODIUM-ION TECHNOLOGY

Asia is currently the leading battery market, and it is expanding rapidly. The Chinese are primarily working on pushing down the costs of already low-cost cell variants, such as LFP cells. This follows a shift away from nickel-based technologies due to price increases. CATL, the world's biggest maker of batteries for electric cars, was also the first battery giant to announce a major push into sodium-ion batteries. The cells are expected to reach an energy density close to that of LFP cells.

#### REST OF ASIA/PACIFIC INCLUDES THE LEADING HIGH-NICKEL CAM PRODUCERS

In South Korea, one of the most advanced battery markets, manufacturers are leading the way in developing cells with ever-growing nickel contents and therefore higher energy densities.



SK Innovation with material supplied by EcoPro BM was the first company to announce a battery – the NCM9, used in the Ford F-150 pickup vehicle – with a nickel content of 90%, for example, and were also one of the first to use NMC 811 for the 2019 Kia e-Niro and Hyundai Kona.

**EUROPE WITH ESTABLISHED HIGH-QUALITY PRODUCERS, NOW TARGETING HIGH-MANGANESE CHEMISTRIES**

The production capacity and number of producers in Europe is still limited. But developments are still underway, with a focus on combining low costs and high-energy densities with new approaches. To compensate for the expected shortage in nickel, BASF and Umicore are looking at materials rich in manganese, for example. Meanwhile, major UK-based player Johnson Matthey sold its battery materials business to Australia-based EV Metals Group and Canada-based Nano One Materials, leaving BASF and Umicore as the only European-headquartered CAM producers.

**NORTH AMERICA AS HIGH-NICKEL MARKET WITH CAM INDUSTRY EVOLVING**

Currently, no major CAM player is headquartered in the US. However, the LIB recycler Redwood Materials is ramping up production and expects to produce 100 gigawatt-hours of cathode and anode components by 2025 – enough for one million electric vehicles (EVs). Other big manufacturers, including BASF, Posco, and EcoPro have also announced production capacities in North America. Demand is driven by the fact that the North American market is a leading user of high nickel-content batteries, especially in EVs. For example, Tesla’s 92%-nickel NCA battery helps its cars to achieve longer ranges. However, Tesla too announced a shift towards nickel and manganese chemistries for a large share of its production.

**ANODE TECHNOLOGIES: GRAPHITE REMAINS THE STANDARD, BUT SILICON TECHNOLOGIES ARE EVOLVING, OFFERING IMPROVED POWER CAPABILITIES**

While less high-profile than developments in cathode technologies, anode technologies are

evolving at a similar rate. Anode active materials (AAM), such as graphite and silicon, dictate the speed at which a battery can be charged and discharged. The main development focus is therefore on increasing the energy density and power capabilities of AAM to improve charging and discharging times. In short, this means developing materials with high reversible capacities (measured in milliamp-hours per gram). There are four approaches:

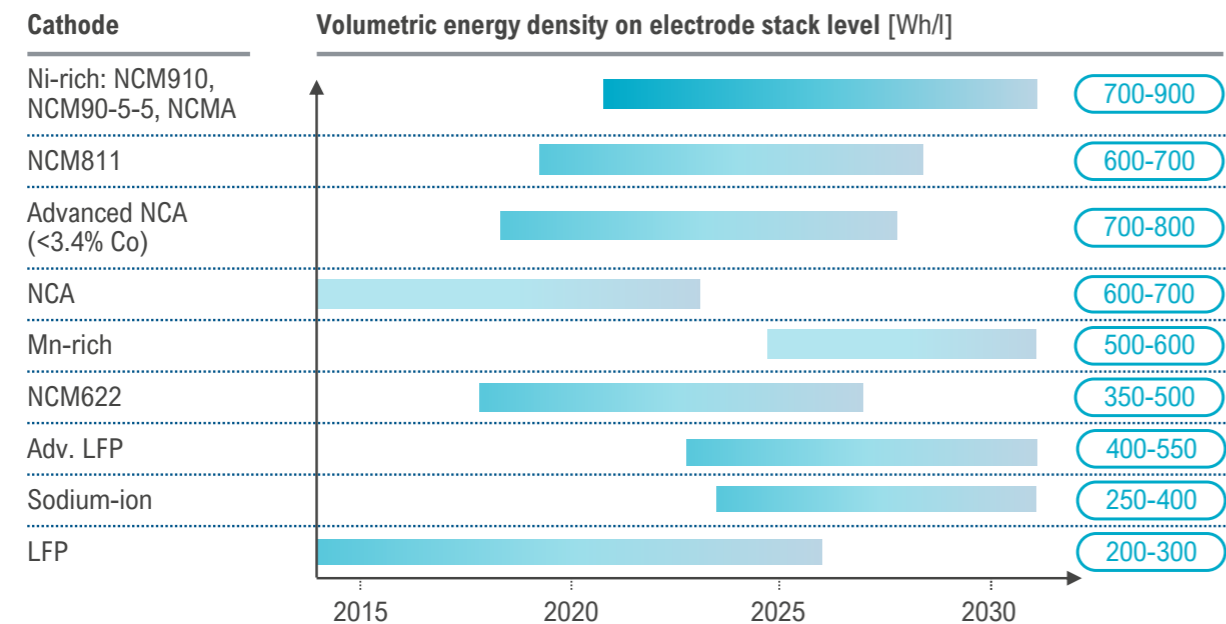
**Graphite AAM (natural, synthetic or mix):** Graphite is the gold standard in LIB anodes, offering a long life cycle and low volume expansion (performance-reducing battery “swelling”). However, its capacity is limited. Pure natural graphite is currently favored due to its lower costs, while synthetic graphite provides better performance, but comes with a much higher carbon footprint. Reversible capacity – around 350 mAh/g.

**Graphite plus silicon oxide additives:** State-of-the-art C + Si(O) anodes incorporate 10 to 20% silicon oxide to boost power and energy density. While silicon is abundant, the additives cause more swelling than in pure graphite anodes. Graphite + Si(O) additives are used in the

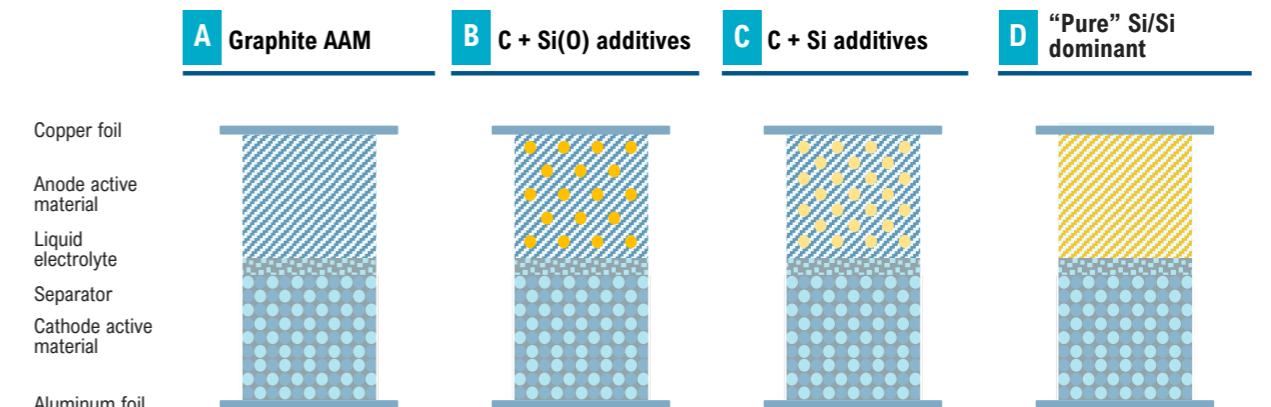
cells of high-end EVs, such as Tesla’s Model 3 and Porsche’s Taycan. Reversible capacity – around 525 mAh/g (10% silicon).

**Graphite plus silicon additives:** These anodes have a 30% share of silicon to further increase energy density. However, more silicon means more swelling, so they also incorporate technologies to overcome volume changes. These include nano-sized particles with graphite scaffolds and protective shells. This makes C + Si additives more expensive, and they have a shorter cycle and calendar life than alternatives. Reversible capacity – up to 900 mAh/g.

**Pure Si/Si dominant:** Here, the active material is 100% silicon, combined with swelling-reducing aids such as void spaces, polymer coatings or additives. These anodes maximize energy and power potential, but currently suffer from up to 400% volume expansion, poor cycle as well as calendar life, and limited conductivity. Reversible capacity: 1,200 to 1,600 mAh/g.



**Figure 7:** Energy densities of batteries from different cathode chemistries (not exhaustive). Source: Desk research, Roland Berger



**Figure 8:** Main anode technology clusters and exemplary players. Source: B3 report 2021, company information, desk research, Roland Berger

### 4.3 COMPETITIVENESS

#### RAW-MATERIAL PRICES HAVE GONE THROUGH THE ROOF IN EARLY 2022 AND PUSH OEMS/ CELL MANUFACTURERS TO SECURE RAW MATERIALS LONG-TERM

A battery maker's competitiveness is hugely influenced by the way it secures raw materials. Material prices, which make up the majority of cell costs, have soared recently and remain volatile. Typically, these prices are passed through to the customer, but availability itself can become an issue and if manufacturers can become an issue. While prices are likely to stabilize again, manufacturers now need to actively control their supply chain. This is especially important when it comes to lithium supplies. To ensure security of supplies and prices below market level, players need to fully integrate with a miner/refiner, for example, by taking a major shareholding.

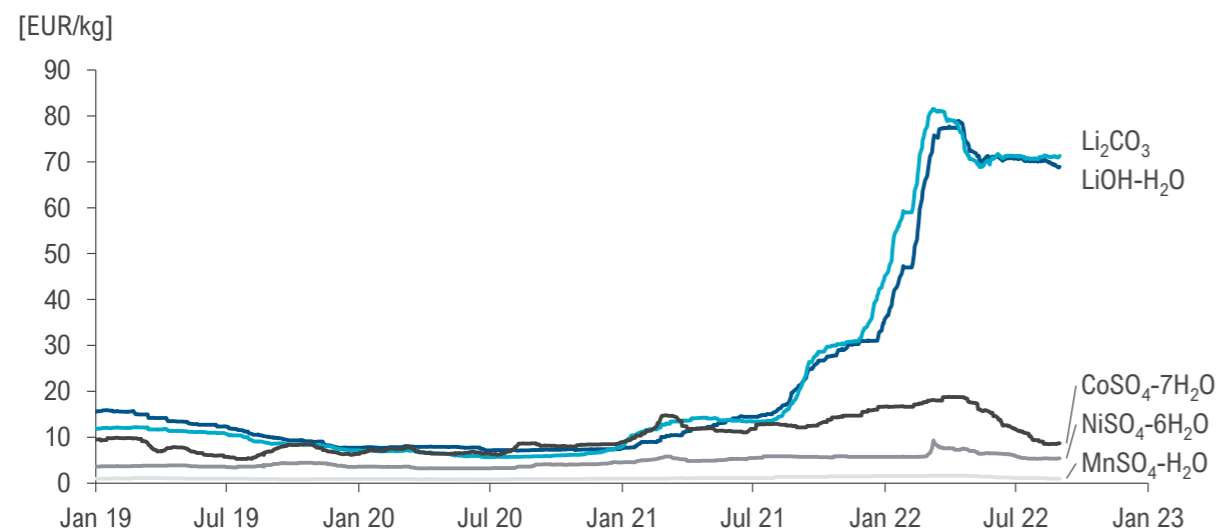
#### MARKET SITUATION AND OUTLOOK: AN OVERHEATED MARKET, SUPPLY DISRUPTIONS, AND COVID HAVE LED TO SOARING PRICES AND GROWING MARKET UNCERTAINTY

Battery material costs climbed steeply throughout 2021. This rise was compounded by

Russia's invasion of Ukraine in February 2022. Between January 2021 and January 2022, LFP cell costs rose by almost 30% and NMC811 cell costs by just over 40% – or roughly 30 US dollars per kilowatt-hour (based on Chinese setups). Prices are now likely to stabilize at levels well above those seen in 2021, although predictions are difficult due to the general market uncertainty.

In the case of lithium, price rises have been driven by strong buyer activity, with many producers over-securing their supplies due to fears of long-term price increases. Supply deficits and Covid-related disruptions have also contributed to rising costs. In the short term, the addition of new supplies are likely to ease the situation and lead to a gradual fall in prices. Longer term, demand for lithium is expected to remain strong, due to the current lack of viable lithium-ion substitutes and the long lead times of new lithium mining projects (up to seven years). This is likely to incentivize suppliers to invest and balance supply and demand, resulting in prices stabilizing at a high level.

The situation with nickel is broadly similar. A price peak in early 2022 was the result of a demand leap after the Covid pandemic and the Russia-Ukraine conflict, during which global stocks had plummeted. Now however,



**Figure 9:** Raw materials prices from Chinese spotmarket in EUR/kg.  
Source: ICCSINO, Roland Berger

”Raw material access will decide over competitiveness of battery manufacturers and OEMs in the next five years.“



Konstantin Knoche

additional supplies are entering the market, and prices are expected to stabilize at a level roughly 30-40% higher compared to 2021. In the long term, new mining projects and increased recycling will balance out the continued strong demand, leading to a stabilization at a high price level.

#### THE BIG CHALLENGE: AS COMPETITION INCREASES, AUTOMOTIVE OEMS, CELL MANUFACTURERS AND CAM PRODUCERS ARE MOVING TO SECURE SUPPLIES OF RAW MATERIALS

Time and materials are running out for battery producers. Taking into account all announced supply contracts, direct investments and around 30% of output is typically reserved for spot-market, less than 30% of global lithium and nickel supplies are available in 2025 for long-term agreements or direct investments. Vertical integration and investment in the value chain are therefore becoming hugely important to secure raw materials and stabilize costs, but are also increasing competition and the need for dedicated strategic investments. Market activity in the area varies by region:

#### Asia/Pacific (incl. China)

M&A activity in Asia is brisk. In particular, China's CATL is pushing forward with major integration efforts. It has, for example, established its own mining company for lithium extraction, which is due to begin operations in 2022. CATL is also buying up access to Indonesia's nickel supplies, investing in several Indonesian nickel projects, including PT Aneka Tambang and PT QMB New Energy Materials. This is notable as Indonesia's government requires domestically mined nickel to be processed in the country (to 60 – 70%). Elsewhere, South Korea's LG is also embarking on very big projects in battery production and recycling in Indonesia.

#### Europe

European players such as Umicore and BASF are moving to co-locate P-CAM and CAM production, but have made no mining investments to date. Electrolyte, separator and other battery material producers are following the cell and CAM industry to co-locate in Europe. It helps that European mineral reserves show a potential independency for lithium, while cobalt and nickel need to be sourced globally. The war in



Ukraine looms large here, especially in relation to supplies of Russian nickel from the company Nor Nickel.

**North America**

Activity in North America is being partly driven by automotive OEMs, such as Ford and GM, moving to secure their own raw materials. Tesla is the clear leader in raw material securitization, while also for example GM secured Lithium from CTR's Hells Kitchen project and Ford secured Nickel from BHP. CAM manufacturers are currently at risk to become contract manufacturers and need to further integrate operations. They are also threatened by recyclers like Redwood Materials who take their raw material from used batteries.

**4.4 INNOVATION POWER  
NEW CAM PRODUCTION METHODS  
ARE BEING INVESTIGATED TO LOWER  
ENVIRONMENTAL FOOTPRINT**

As noted above, sustainability is the key focus area of innovation in battery materials. Developments are largely split into two types: first, processes that can be adapted for use in existing setups and that offer incremental benefits; secondly, completely new production approaches that significantly lower CO<sub>2</sub> emissions. Both mainly target advanced material technology and reducing energy consumption as a way of cutting CO<sub>2</sub> emissions and costs.

**INCREMENTAL PROCESS IMPROVEMENTS: SEVERAL METHODS, FROM NICKEL COATINGS TO RECYCLING WASTE PRODUCTS, ARE BEING EXPLORED**

**Gradient precipitation:** While a high nickel content is desirable in CAM, nickel at the surface of the cathode reacts with other elements to make the battery less efficient. Gradient precipitation aims to overcome this by precipitating sulfates in multiple steps to lower the amount of nickel in the outer shell. The process can potentially remove the need for the second calcination step, thereby significantly lowering energy consumption. Effects on costs however are not decided yet, as the first calcination step is expected to be longer.

**Atomic layer deposition coating:** Adding a layer of nanoparticles to the surface of a cathode can improve its electrochemical characteristics and cycle stability. It also negates the need for the second calcination step. Cost savings could be significant, but scalability is currently thought to be poor.

**Rotary kiln calcination:** Roller hearth kilns have long been the standard reactors used by CAM players for calcination. But their high energy consumption and disposal of the toxic saggars they produce will always be a problem. Rotary kilns are a more energy efficient, cheaper and cleaner alternative, with high sustainability and cost reduction potential. However, the harsh conditions inside the kilns mean their surfaces wear quickly, increasing maintenance requirements.

**NaOH recycling:** Multiple approaches to treat sodium sulfate are currently being investigated. For example, the waste management company SUEZ has developed a salt vaporization technology that recovers sodium hydroxide (NaOH) and sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) from sodium sulfate. This avoids the production of sodium sulfate tailings and allows the recovered NaOH and H<sub>2</sub>SO<sub>4</sub> to be used as cost-efficient input materials. The technology has the highest sustainability potential of the four processes, as sodium sulfate will become critical with EV adaption.

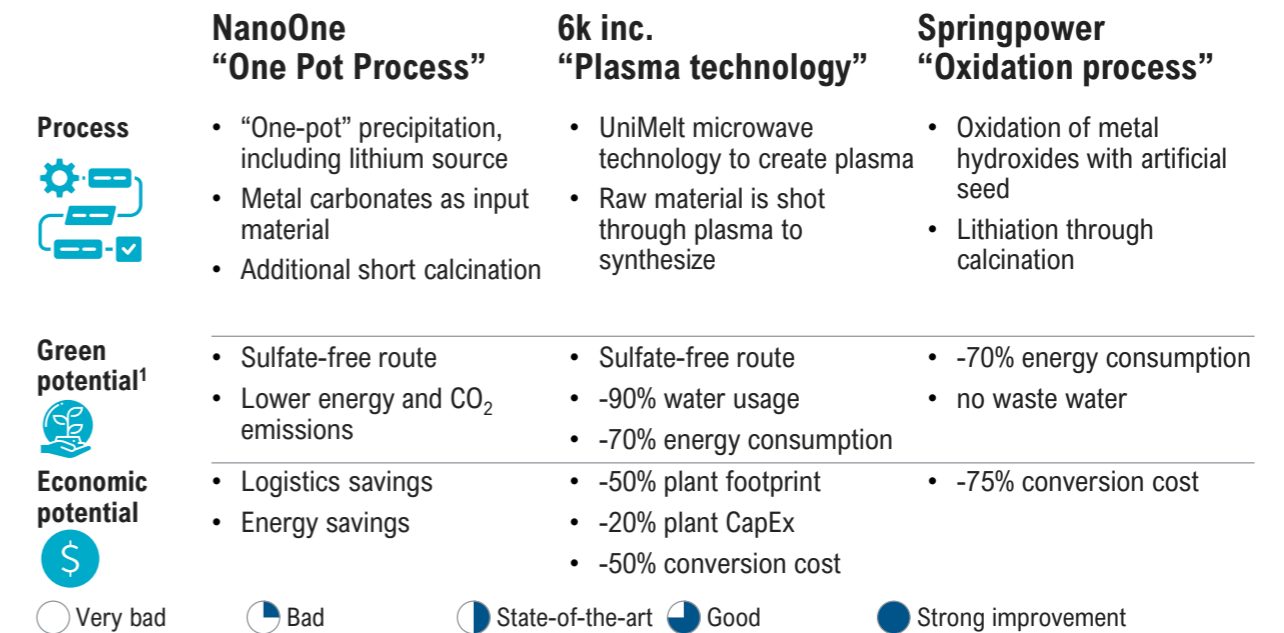
**NOVEL PRODUCTION APPROACHES: 'GAME CHANGER' TECHNOLOGIES PROMISE TO HUGELY REDUCE ENERGY NEEDS AND WASTE, BUT THEY ARE UNPROVEN**

Despite the advances in process adaptations, real sustainability will only be achieved through the introduction of novel process routes. Several CAM players are working on their own technologies, with all claiming to have achieved significant savings in costs and environmental footprint. However, hard information is limited as the industry is secretive and often overhyped. Tesla claims to be leading the way in the field. In 2020, it announced a CAM production process

that produces no waste water and uses 70% less energy. But it is not clear which technology it is using. Tesla bought Springpower International in 2021, a Canadian start-up that has developed a 'clean' process using an oxidant to produce metal hydroxide precursors with little or no effluent. It claimed energy savings and waste savings similar to those from Tesla, but it is not known if this is the technology the EV maker is using.

Some observers believe Tesla's technology may in fact be from NanoOne, another Canadian start-up that is working in partnership with BASF and that acquired Johnson Matthey's Canadian assets. Its "one-pot" precipitation process promises sulfate-free CAM production as well as lower energy consumption and CO<sub>2</sub> emissions. However, details of the process and its benefits have been dialed back since it made its initial claims. 6K, a US plasma specialist, has also developed a novel CAM process. It uses microwave technology, and the company has made similar efficiency and sustainability claims to Springpower.

None of the novel approaches have yet proven industrialization or scalability. But it is clear that CAM players need to explore all possible options and move fast to ensure future sustainability.



**Figure 10:** Comparison of new CAM production technologies (1: As claimed by company).  
Source: Company presentations and announcements

# BATTERY PRODUCTION

## 5.1 SUSTAINABILITY

“The aim of sustainable production is to achieve and maintain certain standards in order to enable a sustainable economy for present and future generations.”<sup>1</sup>

### GHG EMISSION PER KWH PRODUCED

The largest part of the CO<sub>2</sub> emissions in the production of lithium-ion batteries comes from electricity usage for the formation, drying processes and utilization of clean and drying rooms.<sup>2</sup> Therefore, the electricity mix is a critical factor for the GHG emissions. In Asia the emissions are about 600 kilograms CO<sub>2</sub> per kilowatt-hour, for the US about 385 kg CO<sub>2</sub>/kWh and about 300 g CO<sub>2</sub>/kWh for Europe.<sup>3,4,5</sup> Current activities are focusing on the emission reduction through more energy-efficient equipment and the integration of new lower emission technologies.

### OVERALL SCRAP RATE

The high complexity of the production process results in high scrap rates along the entire battery value chain.<sup>6</sup> A production line can have a reject rate of over 30% at the start of production, but with a well-established line the reject rate is reduced to almost five to ten percent.<sup>7,8</sup> For this reason, Asian factories that have been in operation for longer are performing significantly better than European and American factories that are just ramping up. A high degree of digitization should accelerate the process and optimize the overall scrap reduction in the next few years.

### TOTAL HAZARDOUS SUBSTANCE CONSUMPTION PER YEAR

In battery production, some environmentally and humanly harmful components are used, e.g. electrolytes and electrode materials.<sup>9</sup> Currently, there are hardly any differences between the regions in terms of hazardous substance consumption. In a factory, hazardous waste material is about 120 to 130 kg/GW.<sup>10</sup> Efforts across the value chain can lead to a reduced consumption of hazardous materials, e.g. an early conversion from conventional drying to dry coating or the use of water-based LFP instead of NMP-based NMC.



## 5.2 TECHNOLOGY PERFORMANCE

**In order to increase the competitiveness of the battery cell, the used production technology and plant engineering are a decisive factor.**

### CYCLE TIME AND OVERALL EQUIPMENT EFFICIENCY (OEE)

The cycle time and overall equipment efficiency are overall parameters to identify the process stability in the battery production process. The cycle time indicates the speed at which a product can be manufactured. Higher process speed with simultaneously generating high-quality products can only be realized in factories with high process control. The OEE on the other hand divides the equipment performance into three areas: availability, performance, and quality.<sup>11</sup>

The OEE in the battery cell production can be improved among others through process optimization, higher utilization degree, autonomous and scheduled/planned maintenance activities and trainings. Due to the greater experiences on the Asian factory side, cycle time and OEE are evaluated higher compared to Europe and the US.

### FACTORY AUTOMATION

The manufacturing of lithium-ion battery cells has high requirements towards process precision and controlled process environment.<sup>12</sup>

In general, automated processes are less sensitive to errors than manual production steps. Therefore, the automation is an important driver for further optimizing process steps, quality, yield, and throughput. In the area of gigafactories, fully automated individual processes are already dominant, but the interface between process steps differ regarding automation. By reducing the amount of human interference, the quality can be significantly improved. Due to a lower automation degree in their European and US production lines, Asian battery manufacturers have more quality issues with those factories compared to the Asian factories.<sup>13</sup>

” Sustainable battery production requires energy-efficient and resource-efficient power generation. “



Sarah Wennemar



### 5.3 ECONOMY AND COMPETITIVENESS

The market for production of battery cells and production equipment is still dominated by Asian players who excel with their cost leadership. However, many high-quality process technologies “made in Europe” are emerging.

#### PRODUCTION CAPACITIES

In 2022, three Asian companies accounted for 70% of global battery sales. Yet, the electric mobility shift has caused the battery demand to skyrocket in Europe as well.<sup>14, 15</sup> Current projects of cell manufacturers, OEMs and emerging players make Europe the new hotspot for battery cell production. Meanwhile, the European Union’s ambitions will tighten the requirements for “green batteries”, which is going to limit the sales of leading players unless they invest in research and development and focus on optimizing raw materials.<sup>16</sup>

#### PRODUCTION INVESTMENT

An important driver in setting up battery cell production is economies of scale. A study<sup>17</sup> shows that the investment costs of the production equipment have a major impact on cell costs for small production volumes.

A meta-study conducted by PEM of RWTH Aachen University (Fig. 11) shows that Asian cell manufacturers currently invest only half as much in production facilities than European players do. Asia continues to assert its price leadership in production equipment and turnkey solutions for battery cell manufacturing.

#### HORIZONTAL PROCESS INTEGRATION

In Europe, there are numerous specialists in plant engineering with extensive know-how in process technologies who have thus become leading suppliers of specialized production equipment in individual processes. From the battery cell manufacturers’ point of view, however, there is a desire for turnkey suppliers. Turnkey solutions can be sourced from companies, but mainly only in Asia. This is driven by the overwhelming size of companies explicitly focused on battery equipment.

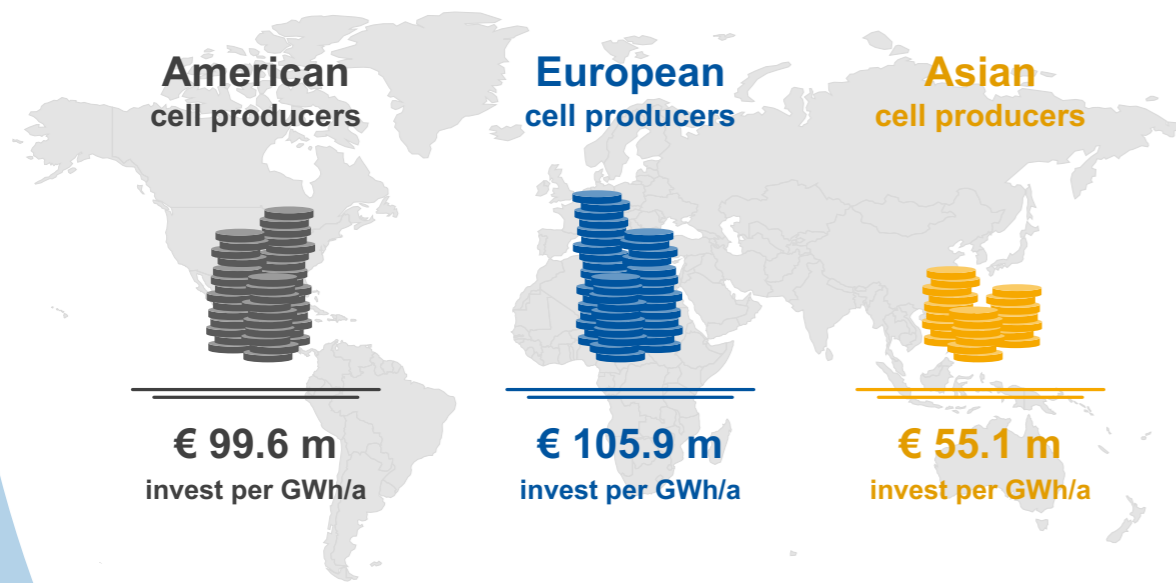


Figure 11: Estimated project costs for the setup of a gigafactory battery cell production by manufacturer origin

### 5.4 INNOVATIVE STRENGTH

Companies from Asia have patented the majority of the manufacturing innovations from the last decades. Recently, however, process innovations from Europe and America emerge which are driven by collaborations.

#### INNOVATIVE PRODUCTION CONCEPTS

In the battery industry, research and development (R&D) is shifting into focus to enable the production of a “green battery”.<sup>18</sup> Essential aspects such as investment costs and energy consumption are addressed by innovative production concepts. Solutions like micro-environments aim to downsize energy-intensive clean and dry rooms to a minimum process volume. Vast investment costs in formation and aging<sup>19</sup> can be reduced by data-based charging and conditioning cycles.

#### PATENTS IN BATTERY CELL PRODUCTION

According to a study, Asia amounts to 70% of all international patent families submitted in the last few years (Fig. 12). However, the number of co-inventions from European and American companies has increased. Since most innova-

tion activities in Asia are carried out by large companies, the contribution of SMEs and universities is much higher in the US and Europe.<sup>20</sup> This underlines the great potential of joint R&D projects for the European market.

#### INNOVATION CYCLE – TIME-TO-MARKET

In order to push new technologies from the first idea to patent application and final integration, various innovation cycles have to be completed. In fast-moving areas such as the battery industry, time-to-market as an indicator for the time that passes until a product idea has reached market maturity is an essential factor. While innovation in Asia is driven by radical investments, the American innovation culture is characterized by agility and a vast network of start-ups. European equipment manufacturers are following this example by focusing more on collaborations.

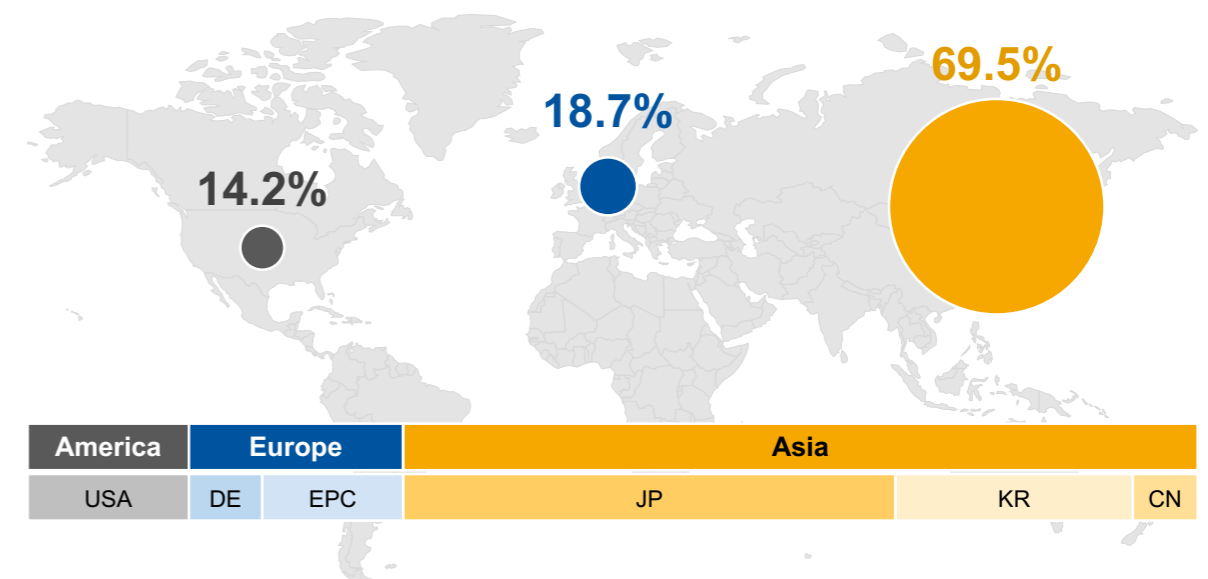


Figure 12: Overview of international patent families covering battery cell manufacturing technology, 2000-2018<sup>3</sup>

Konstantin Sasse

## PRODUCT PERFORMANCE

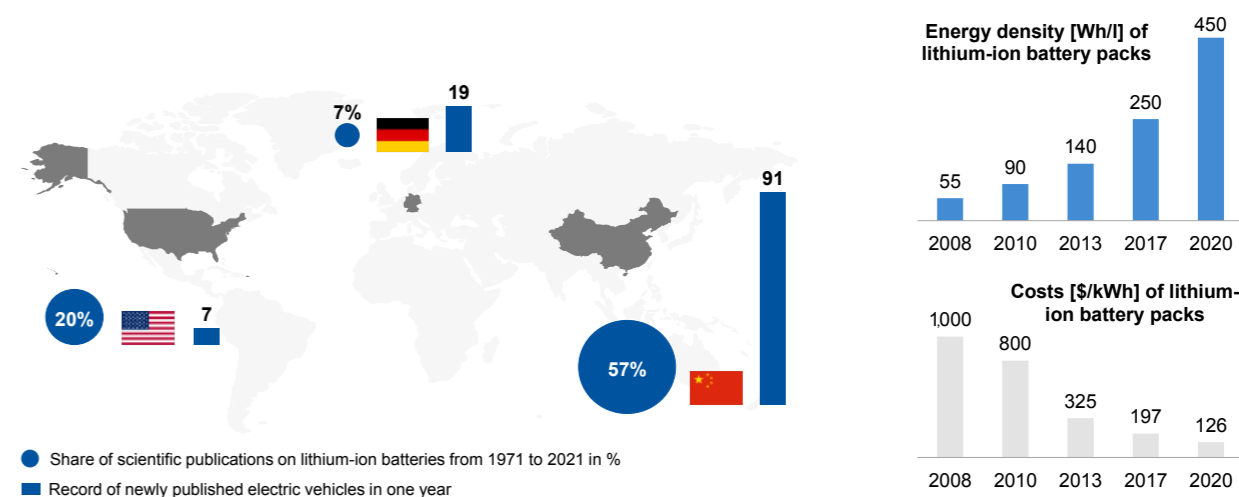
Globally, there has been a strong increase in the technology performance of traction batteries based on the steady increase in energy density at the system level. It can be seen that the energy density of LIBs has increased more than eightfold in the period to 2020, while the cost has fallen to one-eighth. A similar increase can be found in the batterie's warranty performance.

### INCREASING WARRANTY SERVICES CONVINCING CUSTOMERS

In China, Germany and the USA, the warranty period and the guaranteed kilometers of electric vehicles are increasing. Warranty periods of eight years are common practice for the various vehicle classes. A differentiated study shows that there are differences for the guaranteed mileage, however. Upper-class vehicles in the USA were covered up to an average of 216,000 kilometers in 2021. In China and Germany, this figure was only 160,000 kilometers. It can be assumed that the guaranteed performance will continue to rise in the coming years as the field data of the battery systems increase. Even today, the technically possible cycle life is longer than the vehicle service life.

### NEW VEHICLE MODELS PROVIDE THE MARKET WITH INNOVATION

The presentation of new electric vehicles shows clear patterns. Chinese manufacturers produce by far the most new models. The highest level to date was reached in 2019 with 91 vehicles. Manufacturers in other countries are a long way from such figures. The effort put into research and development is also reflected in a steady increase in publications in the field of lithium-ion batteries. Here, too, China dominates. Over the period under review from 1971 to 2021, scientists from China published 57% of all publications, followed the USA with a quota of 20%. Germany contributes 7% to the publications.



**Figure 13:** Overview of product performance indicators.

Source: Muralidharan et al.; *Adv. Energy Mater.* 2022, p. 13; <https://doi.org/10.1002/aenm.202103050>; Web of Science (as of September 2022); PEM RWTH Aachen University



Jan-Philipp Hasenberg, Konstantin Knoche

## BATTERY USAGE

### BATTERIES IN THE FIELD ARE ONLY AS SUSTAINABLE AND COMPETITIVE AS ENVIRONMENT AND OUTER INFLUENCES ALLOW THEM TO BE

In this chapter, we look at battery usage in relation to EVs (both private and commercial). They represent the key market for batteries and are one of the main drivers for improvements in battery sustainability and technologies. Among the subchapters, sustainability is shown to be mainly influenced by electricity mix, while the focus in technology and competitiveness is on charging technology and infrastructure. Innovation power looks mainly at developments in charging and battery swapping.

### 7.1 SUSTAINABILITY ENERGY TRANSITION IN LEADING EV MARKETS WILL INCREASE THE SUSTAINABILITY OF BATTERIES AND EVS MORE AND MORE – NORWAY LEADING IN THE MARKET

With the UN's Paris Agreement of 2015 aiming to limit global warming to well below 2°C compared to pre-industrial levels, all countries are moving to increase their share of renewable energy sources and lower CO<sub>2</sub> emissions. Many have set ambitious targets. The European Union's 2022 RePowerEU plan, for example, aims for member states to achieve a 45% renewable energies share by 2030. Germany's plans go even further, with an 80% target by 2030, while Sweden is targeting a 100% share by 2040. The US Inflation Reduction Act of 2022 sets the goal of achieving net-zero carbon emissions by 2050. China, meanwhile, is forcing companies to buy at least 40% of their power from non-fossil fuel sources by 2030. As battery usage is linked to the CO<sub>2</sub> intensity of electricity grids, these shifts in renewables shares will have a major impact on the EV market.

### ELECTRICITY MIX AND SUSTAINABILITY: SHARE OF RENEWABLES DETERMINES THE EMISSIONS OF

### ELECTRIC VEHICLES PER KILOMETER AND LIFETIME

A country's electricity mix is a major factor in the sustainability of its EV fleet. An increased share of renewables means a lower carbon footprint of electricity, lowering the CO<sub>2</sub> emissions of an EV per kilometer and thereby its overall lifetime emissions. For example, in the largely fossil fuel-powered Chinese grid, an 18 kilowatt-hour per 100 kilometers EV would emit 97 grams of CO<sub>2</sub> per kilometer, while the same car in Sweden, which is heavily reliant on hydropower, would emit just two grams of CO<sub>2</sub> per kilometer. To put these figures in perspective, the average CO<sub>2</sub> emission for new cars (both conventional and electric) in Germany in 2021 was 118.7 grams of CO<sub>2</sub> per kilometer. As countries transition to renewable energy sources, EVs will emit less and less CO<sub>2</sub> over their lifetimes.

Norway has the highest penetration of EV vehicles, with all-electric or plug-in hybrid vehicles making up around 96% of new car registrations in the second half of 2021. This is largely due to government schemes that incentivized the purchase of EVs up until 2022. Sweden, another big EV player, spent 280 million US dollars on similar schemes. As both countries have a very high share of non-fossil fuel power generation

and therefore low carbon intensity, their large EV fleets are the most sustainable in the world.

**7.2 TECHNOLOGY PERFORMANCE**  
**THE FOCUS IN ELECTRIC MOBILITY IS SHIFTING FROM BATTERIES TO CHARGING AND EFFICIENCIES, WHILE ENERGY STORAGE SYSTEMS PROMISE TO HASTEN THE ENERGY TRANSITION**

With EV ranges now generally considered to be sufficient, producers are looking beyond batteries to maximize the potential of their technology. Elsewhere, stationary energy storage systems (ESS) are taking off as new sodium-ion technologies promise efficient bulk storage.

**THE CHARGING CAPABILITIES OF BATTERIES AND INFRASTRUCTURE, AS WELL AS E-DRIVE AND AERODYNAMIC EFFICIENCIES, ARE BECOMING MORE AND MORE IMPORTANT FOR EVS**

For a long time, EV range was considered the most important factor in EV battery manufacturing. This led to bigger and better pack sizes and energy density innovations. For example, the BMW i3's 60Ah battery, found in versions from 2013, offered around 80 watt-hours per kilogram and 98.5 watt-hours per liter on a pack

level. The same figures for the 2018 Tesla Model 3 battery were 166 Wh/kg and 240 Wh/l. It has also led to significant advances in aerodynamics. For example, the best-in-class Mercedes Vision EQXX has a drag coefficient of 0.17, beating that of the series production leaders Mercedes-Benz EQS (0.208), and Tesla Model S (0.208) and Hyundai Ioniq 6 (0.21). It can achieve 8.7 kWh/100km, beating that of the previous best-in-class, the Hyundai Ioniq Electric, at 16.3 kWh/100km, according to ADAC Ecotest.

**CHARGED UP: FAST CHARGING IS NOW THE PRIMARY FOCUS OF BATTERY USAGE TECHNOLOGY, BUT DRIVERS ARE CONCERNED ABOUT LACK OF INFRASTRUCTURE**

With energy densities now believed to have reached a sufficient level, attention turns towards fast charging capabilities and infrastructure. These are as important as pack size because "range anxiety" will fall if drivers have access to sufficient charging infrastructure.

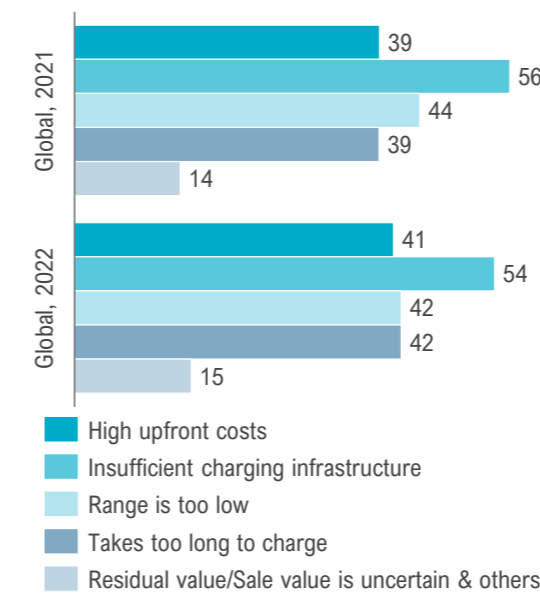
The recent (April 2022) Roland Berger EV Charging Index survey revealed that insufficient charging infrastructure was the primary overall concern about owning an EV. However, it also found that fears over range anxiety have indeed decreased as access to charging infrastructure improves. Specific concerns varied according to the situation in different countries, however.

In under-developed EV markets, such as Turkey and Indonesia, for example, charging infrastructure is not sufficient to support the use of EVs, while in more developed markets, such as Japan, people were more sensitive about charging times. Range anxiety was most pronounced in countries with limited battery R&D and there-

fore poor EV performance. And respondents in developing countries, such as Thailand and Brazil, were more concerned about their ability to pay the high upfront costs of EVs. Where charging was the major concern, respondents were most worried about access to fast DC chargers.

**ULTRA-FAST CHARGING: ONLY DC CHARGING NETWORKS CAN REDUCE CHARGING TIMES AND SUPPORT THE NEW GENERATION OF HIGH POWER-RATED EVS**

Most EVs currently have a 400V electrical architecture and a maximum charging rate of 50kW. This is sufficient for charging at today's Level 1 and 2 AC stations, and even faster Level 3 DC stations, which offer up to 150kW. But as EV batteries evolve, requirements are changing. Some new EVs, such as the Porsche Taycan, Audi e-Tron GT and Kia EV6, have peak power ratings of 220 to 270 kilowatts, requiring faster charging speeds to reduce charging times. New 800V architectures are an enabler for ultra-fast charging on system level, easily accommodating charging rates of up to 350kW as they remove heat spots from the charging socket to the battery. Currently, they are expensive to engineer and feature on only a handful of EV

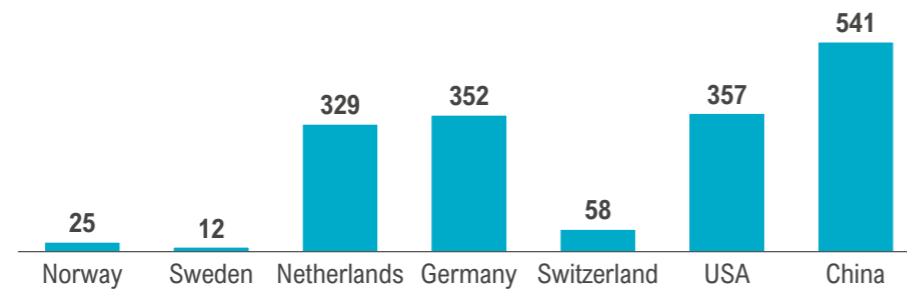


**Figure 15:** Respondent concerns about owning an EV. Source: Roland Berger EV Charging Index online survey

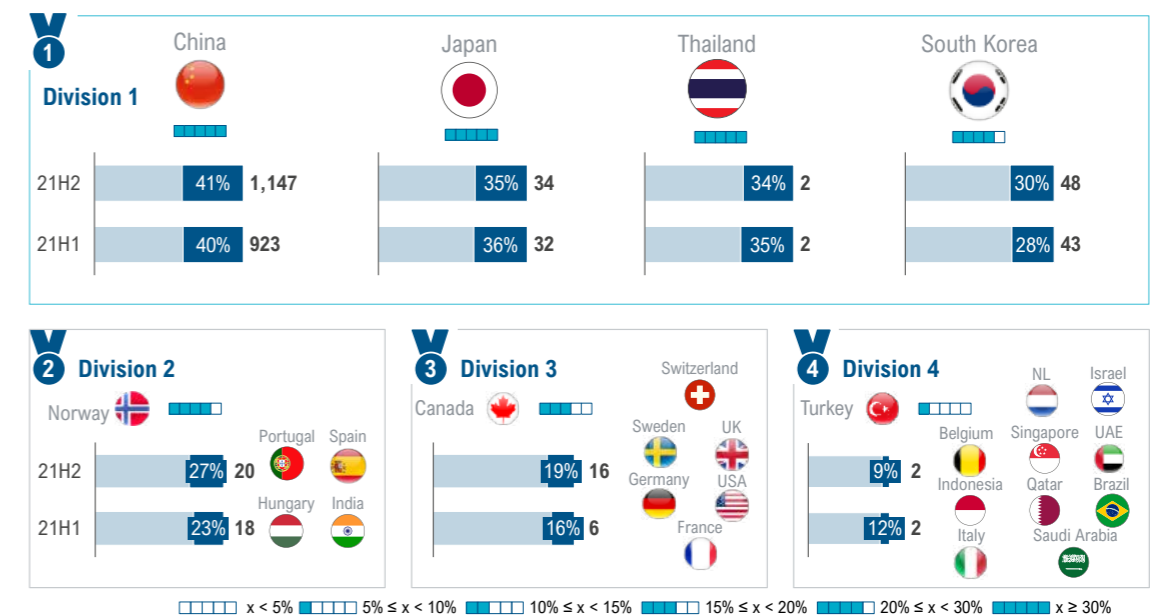
**EV (PV) sales penetration rate H2-2021 [%]**



**Carbon intensity in electricity mix [g CO<sub>2</sub>/kWh]**



**Figure 14:** Carbon intensity of electricity mix in leading EV markets in 2021. Source: ourworldindata.org, Roland Berger EV Charging Index



**Figure 16:** Percentage split of AC and DC charging points and total number of charging points by selected countries. Source: National Govt./Statistics Bureau, Secondary research; Roland Berger EV Charging Index



models, but along with other innovations, such as silicon usage and tabless designs that lower internal resistance, they are likely to further improve charging times in the future.

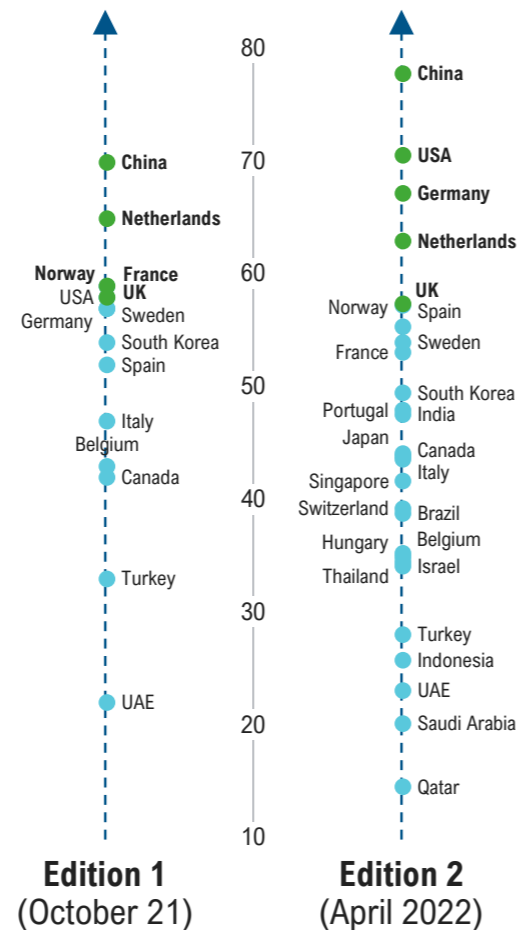
But it is DC charging stations that will be the key to ultra-fast charging. While cheap-to-install AC stations still dominate charging networks, ultra-fast DC chargers offer significantly higher power ratings, usually a minimum of 100kW. They are not yet as widespread as AC chargers but are catching up. In several countries with large charging networks, including China, Japan, and South Korea, DC chargers now have a significant share. In China, for example, they had a 41% share by the end of 2021. Drivers of public DC charging networks in these countries could include a lack of suitable conditions for home charging, a faster-pace of life making EV owners more sensitive to charging times and charging policies and incentives.

### STATIONARY ENERGY STORAGE SYSTEMS ARE NECESSARY FOR A STABLE ENERGY TRANSITION

ESS has multiple applications, from home energy storage to soaking up excess renewable energy. Global demand is expected to reach 160 gigawatt-hours in 2022, with cumulative installed capacity set to hit around 730 gigawatt-hours in 2030. Decentralized storage at renewable sites already accounts for a major share of ESS and will be critical to the global transition to renewable energy. For example, the Kapolei Energy Storage projects by Longroad Development at solar parks in Hawaii provide 185 megawatts of power and 565 megawatt-hours of energy. Another increasingly popular ESS trend is in so-called uninterruptable power supplies (UPS) for energy-intensive business applications, such as data centers. These can be used not only as backup power sources to fill the gap between loss of power and generators kicking in, but also to provide energy for longer periods. As the latter application becomes more popular, technological requirements will switch from the high power for a few minutes to a larger amount of sustained energy provision. First example of

this trend can be observed in the 2.75 megawatt grid-supporting battery system in St. Ghislain, Belgium, which comes with a storage capacity of 5.5 megawatt-hours.

Due to its lower costs and energy density requirements, the current ESS market is dominated by LFP technology. But, as mentioned previously, sodium-ion technology is now a viable option, while hydrogen storage is also making inroads. It offers the possibility of industrial use, but has the major drawback of huge efficiency losses as the renewable energy is converted into hydrogen via electrolysis and then back into electricity in a fuel cell. However, because much more energy can be stored using hydrogen, it offers the best prospect of managing power peaks from renewable generation.



**Figure 17:** Overall score evolution through the two Roland Berger EV Charging Index editions (points out of 100). Source: *EV Volume, Roland Berger EV Charging Index*

### 7.3 COMPETITIVENESS THE MOST COMPETITIVE MARKETS FOR BATTERIES AND EVS WILL BE THE ONES WITH BEST CHARGING PERFORMANCE

The competitiveness of an EV battery in the usage phase is largely predetermined by its components and quality. But competitiveness also needs to take into account the environment the battery is used in. Therefore, the markets with highest competitive attractiveness in the usage phase will be those that offer the best supporting network. The Roland Berger EV Charging Index from April 2022 is a great indicator of competitiveness in the global EV and EV charging space. In this subchapter, we outline results from the survey to highlight the status and growth in key markets.

### THE RB EV CHARGING INDEX: THE LATEST EDITION OF THE SIX-MONTHLY SURVEY REVEALED STARTLING GROWTH IN CHARGING MARKETS ACROSS THE GLOBE

Roland Berger publishes the Index on a six-monthly basis. The April 2022 edition was the second in the series and was based on more than 10,000 customer surveys in 27 key global markets (representing more than 96% of global EV sales), dozens of expert interviews and comprehensive industry research. Results were used to rank the markets in 28 leading indicators, as well as to award an overall score and ranking.

The second edition revealed significant growth in EV markets. For example, EV sales increased by 55% compared to the first edition, and in the same period, the total number of available charging stations grew by 58%. While China, the Netherlands and the UK still lead the world in charging infrastructure, countries such as the US and Germany are catching up fast.

**MARKET LEADERS: ROLAND BERGER IDENTIFIED 'CHAMPION' MARKETS THAT ARE MATURE WITH ADVANCED INFRASTRUCTURE AND HIGH**

### GROWTH POTENTIAL

The second edition also introduced new market analysis. Based on an evaluation of maturity and future potential, Roland Berger identified four charging market categories: Champion; NextGen; Emerging; and Early. The Champion cluster comprised seven countries, with China and the USA leading the way.

What makes these markets stand out? The key attributes are a high maturity of EV adoption and advanced charging infrastructure, even though customer satisfaction was not necessarily higher than in other markets. In terms of market maturity, Champion countries significantly outperform NextGen, Emerging and Early countries across all indicators. For example, more than 364,000 EVs were sold in Germany, a Champion market, in the six months leading up to the survey. This was much higher than Italy's 70,000 sales during the same period (Italy is an emerging market country). Sales in China were more than 2.1 million.

In terms of public charging infrastructure, Champion countries demonstrate clear leadership in network size and growth. For example, China has 2.6 million charging points in total (1.1 million of them public), while India, a typical NextGen market, has only 20,000 charging points. As noted in the previous subchapter, China is also leading when it comes to the installation of DC chargers, with 41% of public charging points being DC. The potential for growth is another Champion attribute.

The Index also highlighted regional variations. For example, East Asia is positioned as an infrastructure and device production center, while the United States and China are leaders in high-tech OEMs, being home to the likes of Tesla and NIO. Europe appears to be the front runner in EV penetration and EV infrastructure.

**GROWTH DRIVERS: RISING EV SALES, INCENTIVES AND BETTER TECHNOLOGY ARE LEADING TO A RAPID EXPANSION OF CHARGING**

**INFRASTRUCTURE**

The RB Index found that there are four key drivers behind the startling growth in EV charging:

- 1. Volume of EVs:** With the help of regulation and increasing practicability, the adoption of passenger and commercial EVs is rapidly increasing, driving demand for charging infrastructure.
- 2. Clear policy guidance:** Driven by targets to reduce CO<sub>2</sub> emissions and ban sales of diesel and petrol cars, most countries have ambitious plans to install charging stations. To facilitate the process, many offer subsidy programs for both vehicle sales and charging infrastructure development.
- 3. Unmet customer demand:** Demand for charging is not fully met. Leading concerns include insufficient charging infrastructure and low charging efficiency. Over half (57%) of survey respondents believe that current charging times are too long, and 54% have doubts about the number of available charging stations.
- 4. Maturing technology:** As the capacity of battery technology increases so does the demand for fast-charging stations. And as new technologies improve the efficiency of both batteries and charging stations, costs will fall and alternative solutions will grow.

**7.4 INNOVATION POWER**  
**BATTERY SWAPPING IS GETTING MORE ATTENTION RECENTLY WITH THE EUROPEAN MARKET BEING INVESTIGATED AFTER SUCCESS IN ASIA**

Due to its increasing importance to the EV market, the battery charging industry is awash with new developments. For example, vehicle-to-everything (V2X) and vehicle-to-grid (V2G) technologies are receiving particular attention. They enable EVs to charge other devices and storage units, as well as sell power back to the grid. Both are seen as enablers of the energy transition, as with millions of EVs on the road, a massive amount of storage of renewable energy is possible – potentially enough to stabilize grids in times of need. Smart charging, where EVs automatically charge themselves when power prices are lowest, induction charging, which removes the need for charging cables, and high-power charging are among other promising technologies. Such innovations are covered and monitored in the Roland Berger EV Charging Index. Here we look in detail at a relatively new and growing sector in EV charging – the battery swapping market.

**BATTERY SWAPPING: NEW TECHNOLOGIES OFFER SWAP TIMES COMPARABLE TO CONVENTIONAL REFUELING, AS WELL AS POWER STORAGE OPTIONS**

Battery swapping, where an EV drives into a swapping station and autonomously has its entire battery replaced with a fully charged one, is not a new idea. Mercedes-Benz experimented with the idea in the 1970s and the start-up Better Place ran a battery switching business until its bankruptcy in 2013. But now, with EV sales rocketing, new business models are coming on line. The benefits of these battery swap modes are many – for example: replacement times are about the same length as conventional refueling times; batteries can be charged at times of lowest cost power; and not-in-use batteries can be used to store power at times of grid overload. However, there are also challenges to overcome. Most EV models do not support swapping, for example, and there is a lack of compatibility between the systems used by current players. An additional point to consider is the customer acceptance, as various batteries and potentially different state-of-health batteries will be used. Customers thus need to detach from ownership thinking.

grew from around 300 in early 2021 to more than 1,300 by June 2022. NIO’s second-generation swapping stations launched during this period, offering a park & one-click service, a swapping time of just three minutes, and a simultaneous check-up of the EV’s powertrain.

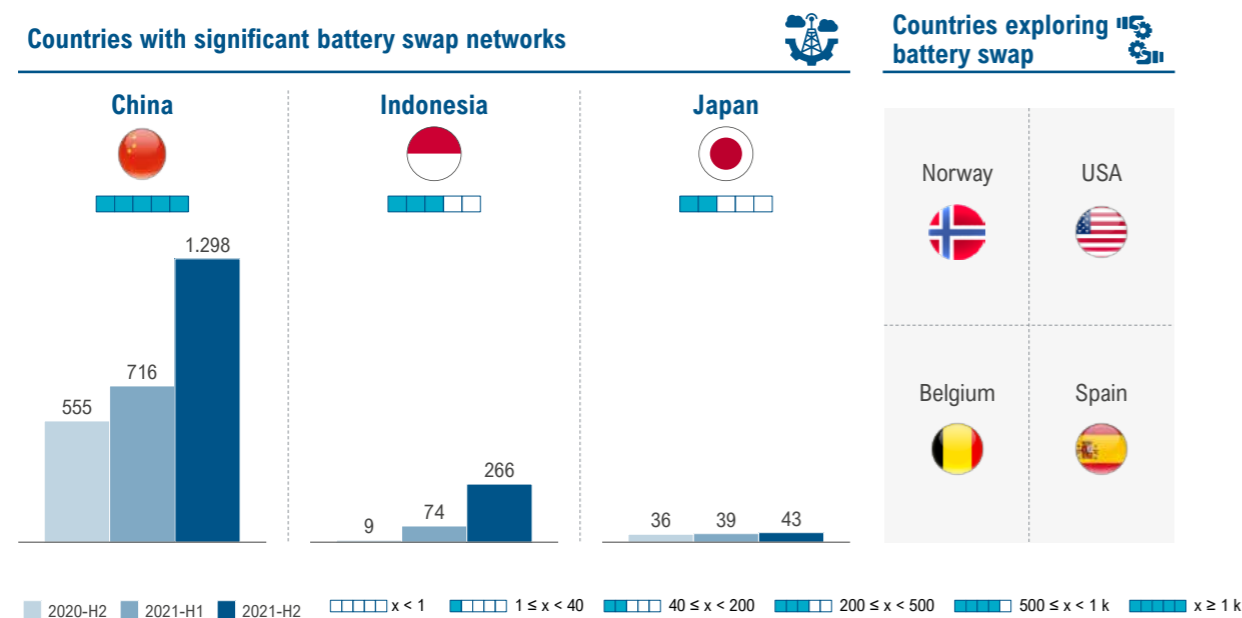
NIO’s business model shows that it has learned several lessons from the likes of Better Place. For example, it has alleviated the high costs of swapping stations by integrating them into existing infrastructure such as gas stations and shopping malls. It has also timed its push to coincide with the rapid increase in EV sales. The company has also used battery swapping as a platform for a battery-as-a-service model, in which the EV driver owns the car but leases the battery for a monthly payment. As the battery is the most expensive part of an EV, this reduces upfront costs for buyers and ensures they always have access to the most advanced batteries, while maximizing revenue for NIO. The leasing service is operated in partnership with CATL and Wuhan Weineng, which owns the batteries. CATL has also entered the swapping market, under the brand EVOGO.

These developments, as well players like NIO making first forays into Europe (the company opened its first European swapping station in Norway in May 2022), the acceptance of battery swapping is likely to increase. As the industry grows, consolidation is expected.

China developed the current technology and is leading the way in its rollout. The technology is now penetrating countries like Indonesia and Japan, which share China’s preference for public charging rather than charging at home. The carmaker NIO is particularly advanced, with swapping stations across Asia. As the advantages of swapping become clear, interest is also rising in the US and Europe.

**FOCUS ON NIO: THE CHINESE BATTERY SWAP MARKET LEADER IS RAPIDLY EXPANDING AND DEVELOPING NEW BATTERY-AS-A-SERVICE MODELS**

Under the brand NIO Power, NIO aims to offer a range of charging options in different settings, from shopping malls to parking lots and service stations. This includes a rapidly expanding battery swapping network. Its number of stations



**Figure 18:** Number of battery swap stations by country. Source: National Govt./Statistics Bureau, Secondary research; Roland Berger EV Charging Index



## 2<sup>ND</sup> USE AND RECYCLING

When considering sustainable cell production, recycling is seen as the most important process step to reduce the CO<sub>2</sub> footprint of the cells produced. If a battery is unusable for electric mobility applications due to aging, it does not necessarily have to be irretrievably destroyed. In addition to conventional recycling, there are other ways to achieve a second phase of use for the packs, modules, or cells. Stationary storage systems are a prominent solution here.

### 8.1 SUSTAINABILITY

#### LCA BATTERIES IN STATIONARY APPLICATIONS

The use of 2nd-life batteries in stationary applications leads to advantages in terms of the Levelized Cost of Energy (LCOE) and CO<sub>2</sub> emissions of batteries. Compared to 1st-life batteries in the same applications, 2nd-life batteries showed 12 to 57% less LCOE and 7 to 31% less CO<sub>2</sub> emissions than 1st-life batteries.<sup>21</sup>

For the same application, 2nd-life batteries have the lowest CO<sub>2</sub> emissions per delivered energy compared to other energy storage systems. Typical applications for 2nd-life batteries as stationary storage are, for example, in photovoltaic systems, as power buffers for fast charging stations or as emergency power supplies for households.<sup>22</sup>

#### RECYCLING EFFICIENCIES AND/OR RECOVERY RATES IN THE RECYCLING PROCESS OF DIFFERENT SUPPLIERS

Currently, European companies have recycling efficiencies of 60 to 95%. American companies report efficiencies of 65 to 80% depending on cell type, while Asian companies report recovery rates of 80%. In 2018, the Chinese government held automakers responsible for recycling the batteries in their vehicles and set guidelines for vehicle manufacturers to take a more active role in battery recycling. The EU has set a similar guideline,

requiring at least 65% of spent batteries to be recycled by 2025, or 70% from 2030. North America currently has no such regulations.<sup>23, 24, 25, 26, 27</sup>

### 8.2 TECHNOLOGY PERFORMANCE

#### ACHIEVABLE RECOVERY RATES IN THE RECYCLING PROCESS OF BATTERIES WITH CURRENT PROCESSES

Currently, two main process groups are used for battery recycling: pyrometallurgical and hydrometallurgical approaches. Pyrometallurgical processes use high temperatures for LIB treatment and melt materials for their subsequent recovery. Advantages are the lack of necessary pretreatment of battery components, a short process chain, easy scalability, and possible treatment of different battery types. Disadvantages are that the process is particularly energy-intensive and associated with the generation of waste that cannot be recycled or is difficult to recycle. The achievable recovery rates with pyrometallurgical approaches are 40 to 60% for nickel and cobalt and very low values for lithium.

Hydrometallurgical processes dissolve metals from pretreated battery waste by a process known as "leaching". The resulting aqueous solution containing metal ions and impurities is concentrated and purified by



Nikolaus Lackner

” In the current decade, strong market growth in battery recycling can be expected, following the growth of battery production with several years distance.“

further post-treatment. In a final step, the metal ions are extracted stepwise from the aqueous solution to recover pure metals from it. Hydrometallurgical approaches require pretreatment of the components to be recycled, for example mechanical shredding, but use lower temperatures than pyrometallurgical approaches and are therefore less energy-intensive. With hydrometallurgical approaches, recovery rates of more than 90% can be achieved for the active materials of the batteries.<sup>28,29,30</sup>

A combination of both approaches is possible, and high recovery rates can be reached as well. In order to select a suitable process for battery recycling, an analysis of the metals contained in the battery is essential.

### 8.3 PROFITABILITY

#### COMPETITIVENESS

#### CAPITAL EXPENDITURE OF A RECYCLING PLANT (CAPEX)

The capital expenditure (CapEx) of a recycling plant for LIB varies depending on the recycling process used. The company Neometals has published an estimate of the capital expenditure for a hydrometallurgical recycling plant (throughput: 18.25 kilotons per year). According to this, the total capital expenditure is estimated to be approximately 165 million US

dollars, which includes a safety margin of 15 million dollars. Direct capital expenditures (e.g. hydromet, land and buildings) will require 96 million dollars, while indirect capital expenditures (e.g. engineering, project management, owner's costs) will be 54 million dollars.<sup>31</sup>

#### OPERATING EXPENSES OF A RECYCLING PLANT (OPEX)

Operating expenses (OpEx) also depend on the recycling process used. Neometals estimates that the operating expenditure for the hydrometallurgical recycling plant is 1,560 US dollars per ton. Of this, reagents and consumables account for the largest share (33.4%). In addition, 26.4% is required for operating supplies, 22.9% for labor, and 12.8% for general and administration. The smallest share, 4.5%, is for maintenance of the recycling plant.<sup>31</sup>

#### ANNOUNCED RECYCLING CAPACITIES PER YEAR IN EUROPE

Numerous companies have already announced that they will enter the market for LIB recycling and intend to build up corresponding capacities in several European countries. Currently, recycling plants with a capacity of approximately 116 kilotons per year are already installed in Europe (as of 07/2022). It is predicted that the total

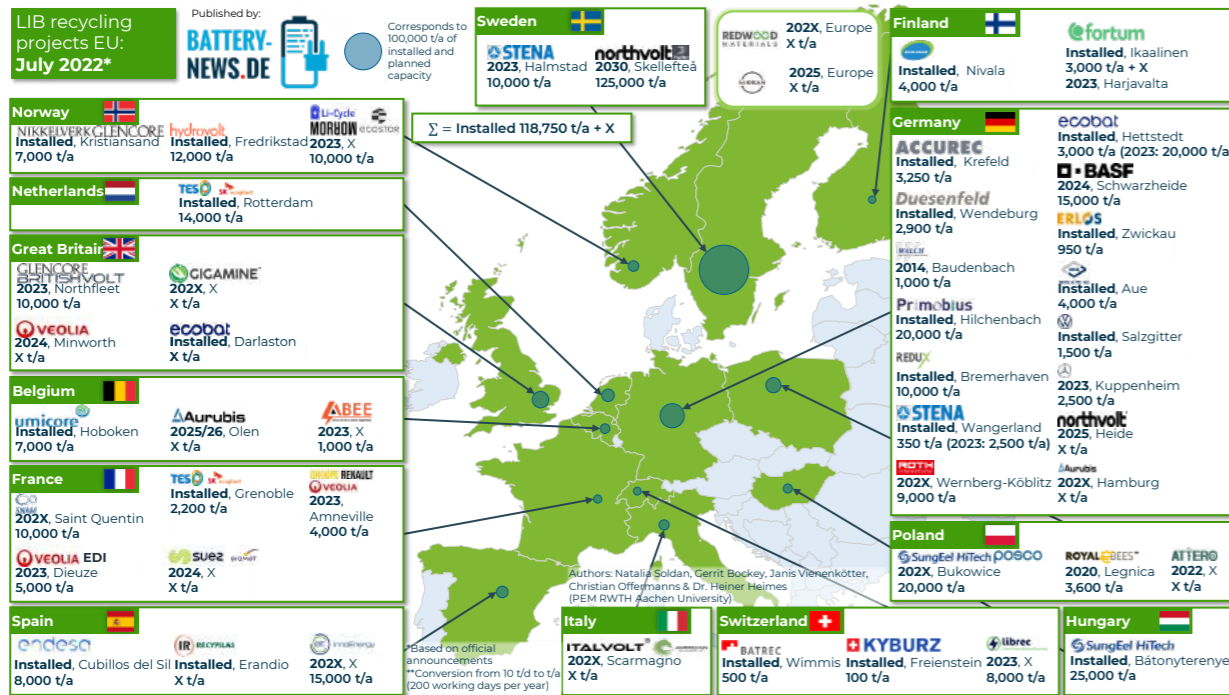


Figure 19: Battery Atlas – Recycling Companies<sup>32</sup>  
Source: Battery Atlas

capacity of recycling plants in Europe will increase to approximately 400 kilotons per year by 2030. In addition, while some companies have announced capacity additions, they have not yet published exact figures on this. This could lead to an even higher total capacity.

### 8.4 PROFITABILITY COMPETITIVENESS LIB RECYCLING IN CHINA, USA, AND EUROPE

China has by far the largest capacity for LIB recycling. More than half of the world’s recycling capacity is located in China, which is also where most of the investment in this area has been made to date. However, plans for new recycling facilities in Europe and North America have now also been revealed, indicating a strong increase in capacity in these markets.<sup>33</sup> Policies and regulations in the respective countries play an important role in the expansion of recycling capacities. In

China, some regulations already exist in this regard. In Europe, too, a comprehensive set of regulations is expected, including the introduction of a battery passport. In the USA, there are currently hardly any regulations, but LIB recycling is increasingly being promoted by the government.<sup>34</sup>

### PUBLICATIONS ON THE SUBJECT OF LIB RECYCLING

The growing interest in LIB recycling is also reflected in the development of publications in this field. As a quantitative evaluation of more than 3,500 chemistry-related publications shows, the annual growth rate of the publication volume for LIB recycling was 32%. At the same time, the volume of scientific publications as a whole has grown at an annual rate of only 4% over the past decade.<sup>35</sup> The data also underscore China’s role in this area, as by far the largest share of publications originated in China.

### PATENT APPLICATIONS IN THE FIELD OF LIB RECYCLING

Patent applications play an important role in the currently still early market phase of LIB recycling. An analysis of the available literature on LIB recycling showed that patent applications make up a large part of this literature, at 74%. Among these, the organizations with the largest volume of patent applications are mainly located in China, Japan and France. China also plays the most important role in the patent applications, as by far the most patent applications on LIB recycling come from China.<sup>36</sup>



116 KILOTONS  
INSTALLED LIB RECYCLING  
CAPACITY IN EUROPE





Wolfgang Bernhart, Tim Hotz, Konstantin Knoche

## SUMMARY

### BATTERY MONITOR 2022: KEY TAKEAWAYS

To summarize the findings in this second edition of the Battery Monitor: sustainability, availability of raw materials, the EV market and the push for ever-more powerful batteries are driving the battery market. Regulation and new policy are playing key parts, targeting CO<sub>2</sub> emissions and battery material recycling. But future installed over capacity presents risks to players in the form of a lack of demand and scarcity of resources. So where does this leave the key stakeholders in the value chain? In this section, we outline the key takeaways for each:

#### **CAM/AMM manufacturers**

Downstream customers start to secure their own raw materials and CAM manufacturers must secure independent supplies of raw materials or risk becoming build-to-print companies. Innovation is required for cost-effective CAM such as high-manganese or advanced LFP, and in sodium-sulfate-free production routes.

#### **OEMs and cell manufacturers**

Not only to get access to critical raw materials, but also to establish responsible value chains, OEMs need to investigate downstream value chains. The carbon footprint of nickel can vary drastically depending on selected production route. To achieve a 30 kg CO<sub>2</sub> eq/kWh battery, additionally recycling is inevitable.

Next to securing raw materials, new cell makers need to secure sales volume in order to survive in an overheated market. European and American cell makers need to leverage a technological advantage through digitization and automation, to decrease costs in their high-labour cost environment.

#### **Equipment providers**

As CapEx in EU/NAR is nearly double of Asia, European and American equipment providers need to either catch up in CapEx-effective

solutions or need to offer advancements in digitization to justify price premium. The current supply/demand balance of equipment is much in favour of equipment vendors, but e.g. announcements from VW to build six gigafactories with equipment from Wuxi Lead show the cost pressure of the industry.

#### **System assemblers**

Energy density at pack level is increasing almost linearly. Further improvements need to be considered to simultaneously increase energy density and decrease costs, such as cell-to-pack technology.

#### **Recyclers**

The recycling market is still building up, and there is room for players to define the ecosystem. France, China, and Japan are the driving countries in the further development of LIB recycling, whereby China has a significantly larger share. Europe has a total recycling capacity of up to 400 kilotons in 2030 and shows the highest recycling efficiency of all markets.

#### **Policy makers**

Regulation is playing the key role in success and sustainability of the battery market. While the US Inflation Reduction Act is expected to have a huge impact on economics, the European incentives are comparatively low. The financial attractiveness for the battery industry to co-locate to Europe is lower than in the US, especially with energy prices increasing.

#### **Investors**

Announced overcapacity in cell manufacturing will likely lead to market consolidation, and new investments need to be carefully considered. The general focus for investments now is on the upstream value chain: while we already had quite a lot of movement in the European market, the US will be in focus for the next phase of major investments.

Konstantin Knoche, Wolfgang Bernhart

## CLOSING WORDS

As we have seen in this report, the battery industry is taking more and more shape in Europe and North America. While the whole value chain is currently still relying on China, European and North American initiatives to co-locate the value chain are beginning to bear fruit and the upstream value chain is following the cell manufacturers to these regions. New focus topics have been identified in the Battery Monitor 2022. In this report, we looked at the whole value chain, starting from an overarching perspective, coming over materials, cell and pack production to the battery usage phase and recycling in the end. To close this report, we here want to provide brief highlights of each chapter.

Future installed overcapacity in battery production presents risks to players in the form of a lack of demand and scarcity of resources. This results in more and more raw material hedging and vertical integration chain under aid of the respective governments. From a political perspective, the recently released Inflation Reduction Act will significantly increase attractiveness for investments along the battery value chain in the USA, while European incentives focus more on sustainability increases. CO<sub>2</sub> target of OEMs for batteries and battery materials can only be achieved by recycling. Highest criticality here is the CAM production process, emitting significant amounts of CO<sub>2</sub> and producing loads of sodium sulfate, which is not a problem with the current state of the industry, but will become one with the industry ramping-up. Within the battery production, digitization and automatization have been identified as major trends and drivers of the industry. With their help, European and American companies can generate short innovation cycles due to collaborations and

joint developments between cell manufacturers and equipment providers. In terms of battery system technology and performance, Asian players are leading the industry with being cell-to-pack pioneers, while European and American players are more reserved on this – with the exception of a single American OEM. The Recycling chapter of the Battery Monitor 2022 has shown the evolving industry and the massive CO<sub>2</sub>- saving of a closed loop and a very strong co-location approach in the market. As the ecosystems around recycling are currently evolving, there is still room to shape the industry. Finally, the Battery Usage chapter has identified the surroundings of EVs as being the major driver of not only customer acceptance, but also sustainability of electric mobility. The ongoing energy transmission in all major markets, as well as the increasing charging infrastructure together with innovative concepts such as battery swapping, will further increase acceptance of the new mobility. Having addressed all these topics, it will be very interesting to see how they evolve for the next edition of the battery monitor. While production technology trends will take longer to be adopted across the industry, for example sulfate-free CAM production, we might see the first implementation and some pioneer work from newcomers during the industrialization progress. What might be much faster paced is the ongoing vertical integration of the value chain. The number of investments and long-term agreements for material supply have skyrocketed in 2021 and 2022 and is expected to continue to do so. All in all, we think 2023 will be full of highlights and breakthroughs, and thus are looking forward to the next edition of the Battery Monitor.

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# IMPRINT



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