THE GLOBAL BATTERY VALUE CHAIN

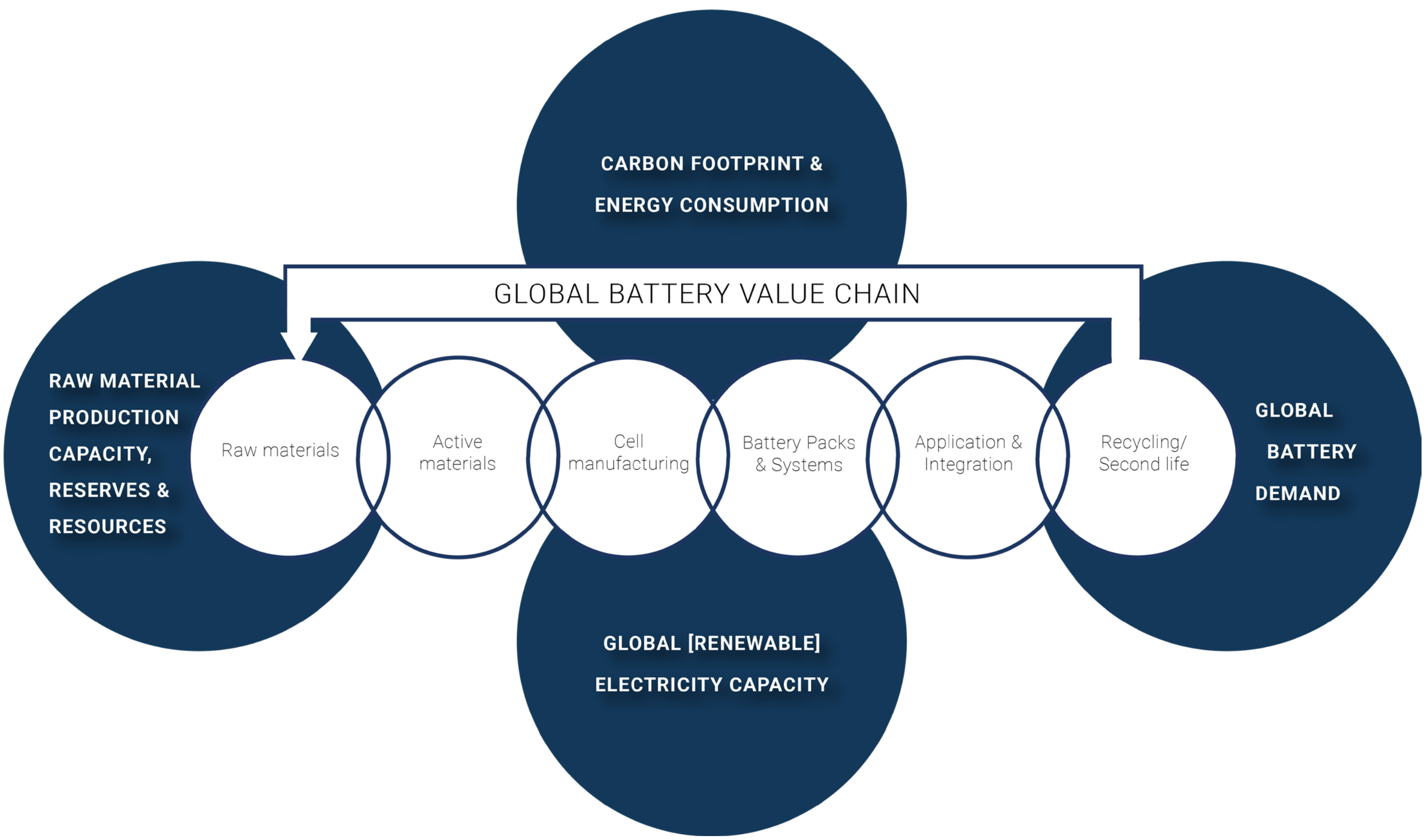
A commissioned report on the landscape, dynamics and future of mobile energy storage solutions

blue institute

FOREWORD

This report was commissioned by the Executive Focus: Battery group, initiated in 2019 within Blue Institute's leadership network. The group includes Volvo Buses, Electrolux, Husqvarna, Polestar, Veoneer, Alstom, Linde and Boliden. The purpose of the group was to build knowledge across businesses, by sharing perspectives and insights concerning the emerging global mobile energy storage ecosystem. The group initiated a parallel research effort, carried out by Blue Institute, in late 2020, which would function as an input to the group's discussions.

The research proceeded in phases with specific topics. Each phase concluded with a group review and further elaborations of the findings. To address specific domains the group has invited leaders and experts such as Mikael Staffas (Boliden), Peter Carlsson (Northvolt), Kristina Edström (Uppsala University) and Staffan Qvist



(Qvist Consulting). The method enabled the group to adapt questions and topics to the rapidly developing battery ecosystem. This report is a synthesis of the research effort as of June 2022.

The interest in mobile energy storage comes from the ongoing transformation of multiple industries towards electrification, which in many cases requires mobile energy storage. Within the area of mobile energy storage, there are various solutions, such as fuel cells and super capacitors, but the dominant solution is electric batteries, which this report focuses on.

The drivers for increasing use of electrical batteries are many and vary across applications. For some applications, such as power tools and household equipment, the main drivers are mobility and convenience. For others, such as cars, climate change and concomitant environmental legislation and climate policy are main drivers. For trains, energy storage enables a solution of the "last mile problem", thereby mitigating investment requirements in infrastructure. In yet other cases, such as trucks and heavy machinery, the large energy requirements are challenging to accommodate by electrical batteries and the above-mentioned electro fuels and fuels cells are tested as an alternative.

Yet it is the transport sector and specifically passenger cars that are the main driver of mobile energy storage demand. Electrical batteries are, for the time being and for the near future, the preferred solution. Producing batteries at the projected scale requires vast amounts of resources such as minerals, energy, active materials, production machinery, and personnel. The size of this market, and the required volumes to fulfill ambitions and targets sets the tone for the whole battery ecosystem. Therefore, the overall dynamics is set by the market for electric vehicles, even though relatively smaller markets such as that for cordless power tools are sizeable and have somewhat different requirements.

The ambition of the report has been to outline the mechanisms that drive the demand for and supply of electric batteries globally. It is meant to facilitate and further discussions concerning the rapidly evolving, complex and interdependent value chain surround mobile energy storage. Blue Institute is solely responsible for all findings, statements and conclusions made in the report. The findings are not necessarily endorsed by the participating companies and experts.

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THE GLOBAL BATTERY VALUE CHAIN – AND ITS DYNAMICS

The lithium-ion battery (LIB) has in many aspects revolutionized the economy. Ever more efficient batteries have driven the mobility revolution, as devices do not need to be tethered to electrical outlets. It is a story of technological advances fueled by innovation, continuous developme-nt and improvement, and investments pushing economies of scale and lowering costs in a virtuous spiral.

Yet the growth in the coming decade will dwarf the development so far. As consumers, regulators, and Original Equipment Manufacturers (OEMs) target climate change, electric vehicles (EVs) are booming. The sheer size of batteries required to enable EVs is such that growth of battery manufacturing capacity has been on an unprecedented scale and will continue to accelerate. In parallel several other applications also transform ending up competing of the same resources. Projections indicate that demand will be ten times as high in 2030 as it was in 2020.

The scale of capacity that is needed to satisfy such demand is in itself a market opportunity. Announced investments in LIB manufacturing capacities comprise more than 280 "gigafactories" (sites capable of producing more than 1 GWh of energy storage per year), from incumbents, start-ups, and automotive OEMs. This represents more than a ten-fold increase in production capacity in the coming decade. Continuous improvement in technology and decreasing costs will also benefit a range of applications, other than vehicles, that use – or could use – batteries.

The speed and scale of demand growth will undoubtedly cause challenges. There are signs of shortages of raw materials, components, people, and equipment. Such shortages have already affected prices and will affect strategic decisions in all parts of the value chain. The price of battery-grade lithium, for example, surged in 2021. The supply of raw materials will be critical, especially as investments downstream rely on securing supply for a considerable amount of time to be economically viable. Yet investments in mineral extraction of battery metals are trailing investments in battery manufacturing, which means that there is a raw material disconnect in the current capacity pipeline.

Companies are therefore scrambling to devise and execute strategies, with considerable movements in the value chain such as up- and downstream integration, joint ventures, and partnerships. In battery production, the scramble to set up ever bigger factories, especially in currently trailing markets such as Europe, has already led to supply constraints on production equipment and personnel. These strains will become more pronounced in the next few years, as regions other than China (which presently dominates battery production) seek to establish regional supply

> The speed and scale of the capacity buildup will undoubtedly also create dynamics that drive the development of new sources of supply, chemistry choice and battery technology, recycling, customer demand and product design.

chains closer to production and end-user markets. Announced investments in battery manufacturing in Europe, for example, imply a twenty-fold increase of capacity to 2030.

Downstream, some OEMs are struggling to meet demand of electric vehicles with long delivery times as a result. The supply of battery cells is only one reason for this, compounding the problem of the semiconductor shortage, longer freight times and higher transportation costs.

Finally, the long-term evolution of the value chain is also dependent on the even larger shifts brought on by climate change. Batteries should be charged with clean electricity, produced without fossil fuels. Charging infrastructure needs to be scaled up massively.

The speed and scale of the capacity buildup will undoubtedly also create dynamics that drive the development of new sources of supply, chemistry choice and battery tech-nology, recycling, customer demand and OEM product design. For example, higher lithium prices and relatively lengthy extraction processes makes novel technologies such as direct lithium extraction more attractive and potentially unlocks new reserves, from other places. Ubiquitous charging infrastructure and high-voltage charging reduces the need of large batteries to combat range anxiety.

As a rapidly growing and evolving market, the value chain is a complex and emerging ecosystem. However, world events have complicated matters further. The study commenced long before the present disruption of supply chains and price volatilities. The effect and duration of the recent upheavals are not known, and not always fully integrated in the analysis, but it is likely that they will further enhance the complexity.

INDEX

ACRONYMS AND COMMON TERMS

Anode: Original Equipment Manufacturer

BEV: Battery Electric Vehicle, a fully electric cehicle, no combustion engine

CAM: Cathode Active Material, the compoud of minerals forming the cathode, such as Lithium, Nickel, Cobalt and Manganese

Cathode: The positive terminal of a battery

CO2: Carbon Dioxide

CO2e: Carbon Dioxide equivalent, a measure to be able to compare different greenhpouse gases

DLE: Direct Lithium Extraction

EES: Electric Energy Storage

ESG — Environmental, Social Governanace

EV: Electrical Vehicle, an acronym related to all vehicles with a traction battery. See also BEV, PHEV.

Gigafactory: A very large battery cell production facility

Gton: Gigaton, one billion tons

ICE: Internal Combustion Engine

LCA: Lifecycle Assement of the total environmental impact of the full lifecycle of a product

LCE: Lithium Carbonate Equivalent

LFP: Battery with a Lithium iron phosphate cathode

LIB: Lithium Ion Battery

Na-ion: Battery with a Sodium based cathode

NCA: Battery with a Lithium Nickel-Cobalt-Aluminum oxide cathode

NMC: Battery with a lithium Nickel Manganese Cobalt oxide cathode

OEM: Original Equipment Manufacturer

PHEV: Plugin Hybrid Electric Vehicle

Second life: A market using products reaching end of life in initial first application

SoH: Battery State of health

Solid state battery: A battery using a solid rather than liquid electrolyte

UPS: Uninterruptible Power Supply

Wh: Watt hour, a measure of energy used with different metric prefixes such as kilo (kWh), Giga (GWh).

AS ELECTROMOBILITY TAKES OFF, THE DEMAND FOR BATTERIES IS SOARING

Electromobility is booming. The demand for applications dependent on batteries have been rising for decades, but the current and projected growth rate is unprecedented, due to the increasing sales of EVs. The demand for EVs in turn is fueled by, and dependent upon, a variety of factors:

- The desire to reduce environmental impact, for example access to renewable energy
- Performance and cost of electric drivetrains
- Viability, such as access to charging infrastructure, local regulations on emissions, tolls, parking

Consequently, demand varies across countries and regions. The overall tendency, however, is that EVs are rapidly increasing the share of passenger car registrations globally. China has been leading the EV market, but to 2030 Europe is considered to have the fastest growth. Other automotive categories, such as light duty commercial vehicles and buses, are also showing significant growth, as are electrified two-wheelers such as e-bikes and e-scooters.

Understanding the future demand for batteries is thus intimately connected to projecting the future demand of electrified transport, and in particular cars. In this study, we have both considered projections that extrapolate forward from actual sales (Type 1 projections) and those that extrapolate backwards from a final or "desired" state, for example, based on emission targets (Type 2 projections). Type 1 projections are constantly evolving with real term data, whereas type 2 projections are more stable. Just a few years ago, Type 2 projections indicated higher demand than Type 1 projections, but as of last year actual EV sales caught up with "desired state" projections. That is, they have converged, and trend extrapolation even generates higher demand figures.

Projections are always uncertain, but they inform the projected demands for batteries, and thus for manufacturing capacity and raw material demand. Thus, they form the planning and investment horizon for companies. Using the demand projections to 2030 from various sources, demand

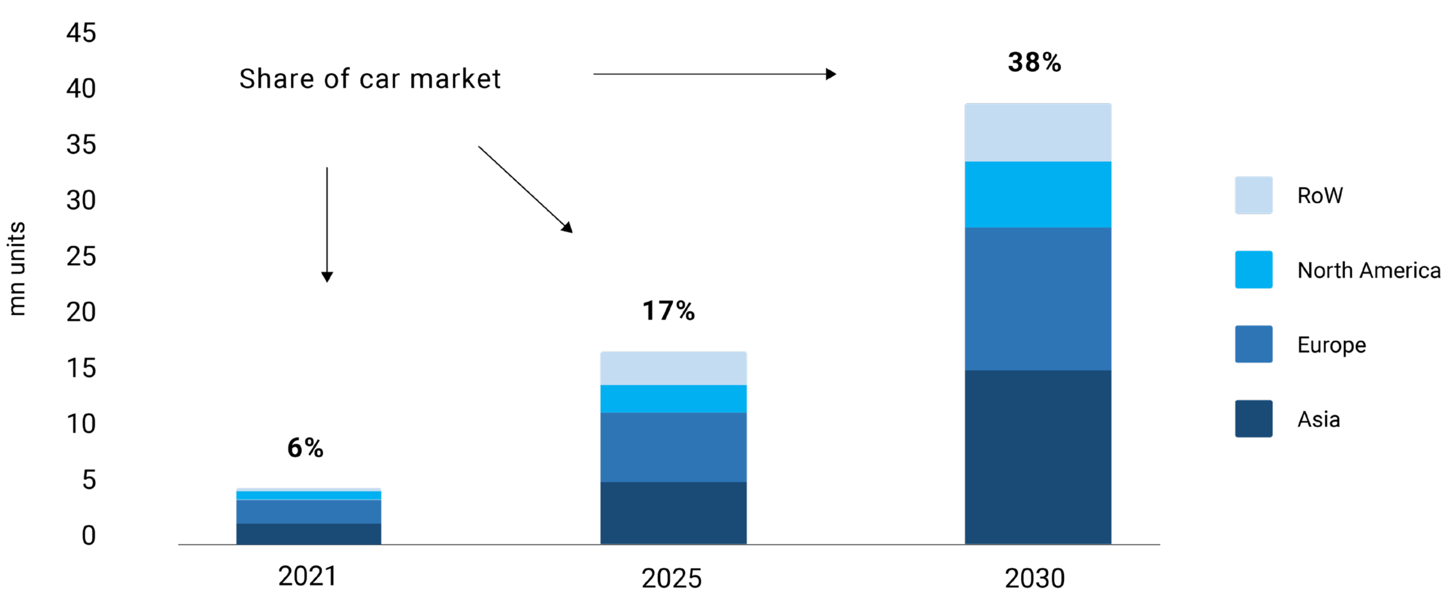

Figure 1. BEV & PHEV sales by region (mn units). Source: Roland Berger

for EVs is growing fast. By 2030, demand could be ten times higher than it is now, with some 30 million EVs sold globally, a third of all cars.

Battery demand will grow in all applications, but automotive ones dominate

Batteries are deployed across a range of applications and sectors. Since the invention and commercialization of LIBs (by Sony in 1991), consumer electronics has been the primary area of application, from personal audio to laptops and mobile phones. Other applications, like hand-held tools, have also largely been electrified and outfitted with LIBs as costs have come down. As recently as 2018, consumer electronics made up 20 percent of demand. In recent years however the primary driver of demand has been in from the automotive sector. In 2021, it is estimated that more than 80 percent of LIBs was destined for automotive applications, while consumer electronics accounted for less than 10 percent, a consequence of the much larger battery capacities required in automotive applications. An EV can easily require a battery capacity one thousand times greater than a laptop.

Battery demand is thus growing rapidly. It is expected that the demand for LIBs will have increased more than ten-fold by the end of this decade, from approximately 240 GWh in 2020 to more than 3 100 GWh in 2030 . The global market for LIBs is already worth more than $50 billion, and McKinsey estimates that it will reach $360 to $410 billion by 2030. This means that lithium-ion chemistries have surpassed more mature battery chemistries, such as lead, by value and energy storage capacity.

Although demand is primarily driven by automotive applications, batteries are and will continue to be important also for other applications. Consumer electronics will continue to be an important market for batteries, but the growth rate has diminished considerably as smart phones and laptops already have a very high market penetration. Other application categories, such as telecom, UPS, household

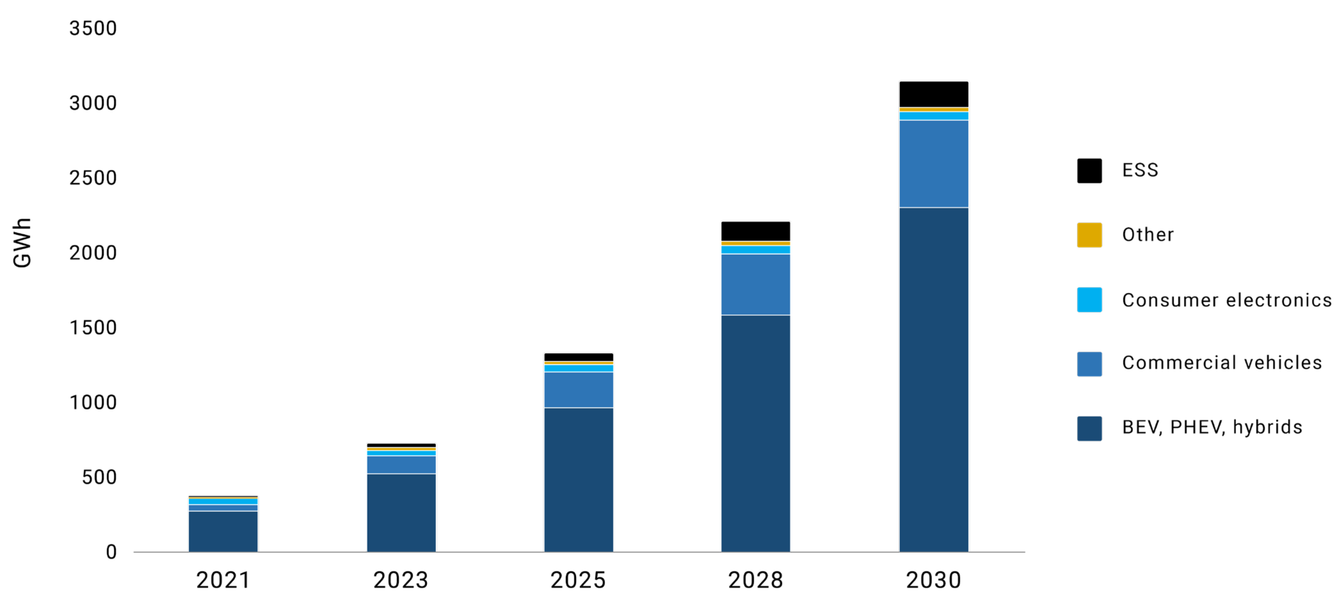

Figure 2. LIB demand by application to 2030 (GWh). Source: Roland Berger, Bloomberg BNEF

appliances, trains, bikes, lawn movers, and power tools, will similarly drive demand for batteries, in many cases with significant growth. In relative numbers, however, these applications require considerably lower volumes. Other applications also drive demand of different types of batteries. Trains and grid electrical storage solutions, for example, might use a different lithium battery chemistry. Power tools and household equipment might use similar chemistry as automotive, but with quite different specifications and properties. All applications have their specific requirements, in a capacity constrained market.

One application category that may drive demand at relatively high volumes is electrical energy storage (EES) applications tied to the power grid. Such solutions partially enable the increase of renewable power sources, particularly small installations. Even though they currently make up a modest part of battery consumption, in the medium and long-term they are often projected to be of considerable importance. For example, a much-quoted calculation by Tesla (which also offers such products) states that 20 TWh of annually produced battery capacity is needed to support the energy transition. In the short term, however, they are not economically viable for large scale energy storage and are not deployed widely as such either. To put it in perspective, currently installed battery EES in Europe is 10 GWh, which is enough for approximately one and a half minute's power consumption.

Mitigating climate change drives electromobility

Battery demand is thus primarily a function of electromobility. The scale of investments required for this global, industrial transition is massive. The pace is high. In the end, whether a third of all cars sold will be fully electric in just a few years depends on customer demand. But what is pushing and enabling such a market are on the one

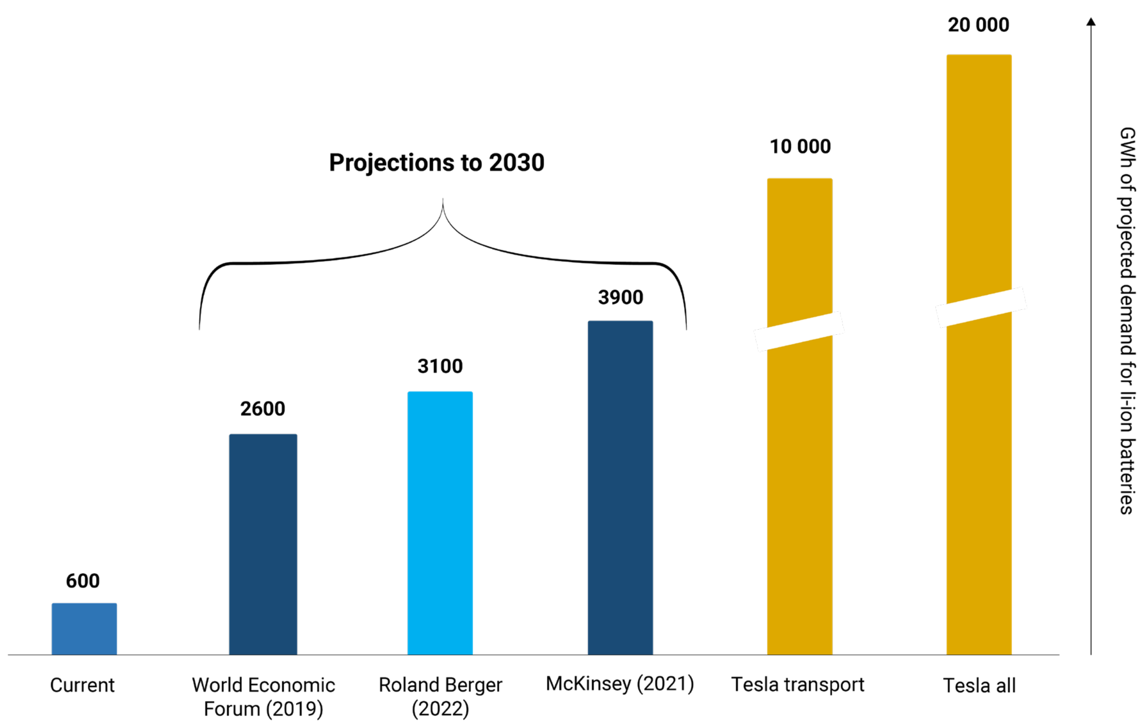

Figure 3. Projected demand for lithium-ion batteries (GWh). Source: Blue Institute, Various

hand climate change policies, and on the other automotive OEMs' successful shift to electric powertrains.

The Paris Agreement, with the goal of limiting global warming to below 2 (preferably to 1,5) degrees Celsius compared to pre-industrial levels, puts special emphasis on the reduction of CO2 emissions. The envisaged reduction of 11-19 Gton of CO2 emissions – between 25 and 40 percent of all emissions - is larger than the entire global transport sector's emissions of 8 Gton. Passenger cars contribute approximately half of transport emissions, and EU transport emissions are roughly one-tenth of the global emissions, at 0,9 Gton. Considering this, the EU targets a reduction of 30 percent by 2030.

Electrification is expected to contribute most of this reduction. To calculate how much CO2 emission reductions EVs contribute, Life Cycle Assessment (LCA) comparisons with internal combustion engines (ICE) are used. LCAs are difficult to do, and exhibit considerable variance: IVL, a research institute, found that each kWh of battery capacity produced resulted in carbon footprints ranging from 59 to 119 kg CO2e.

In essence, EVs generate a significantly larger carbon footprint in manufacturing compared to ICE cars, but less in usage. This is primarily because the production of batteries is energy intense. According to IVL, the production of an NMC111 cell and pack requires 313 kWh of energy per kWh of storage capacity.

Thus, a "carbon debt" is incurred when the battery is produced, which can be mitigated over time by using clean energy. The larger the battery, the larger the debt. After the

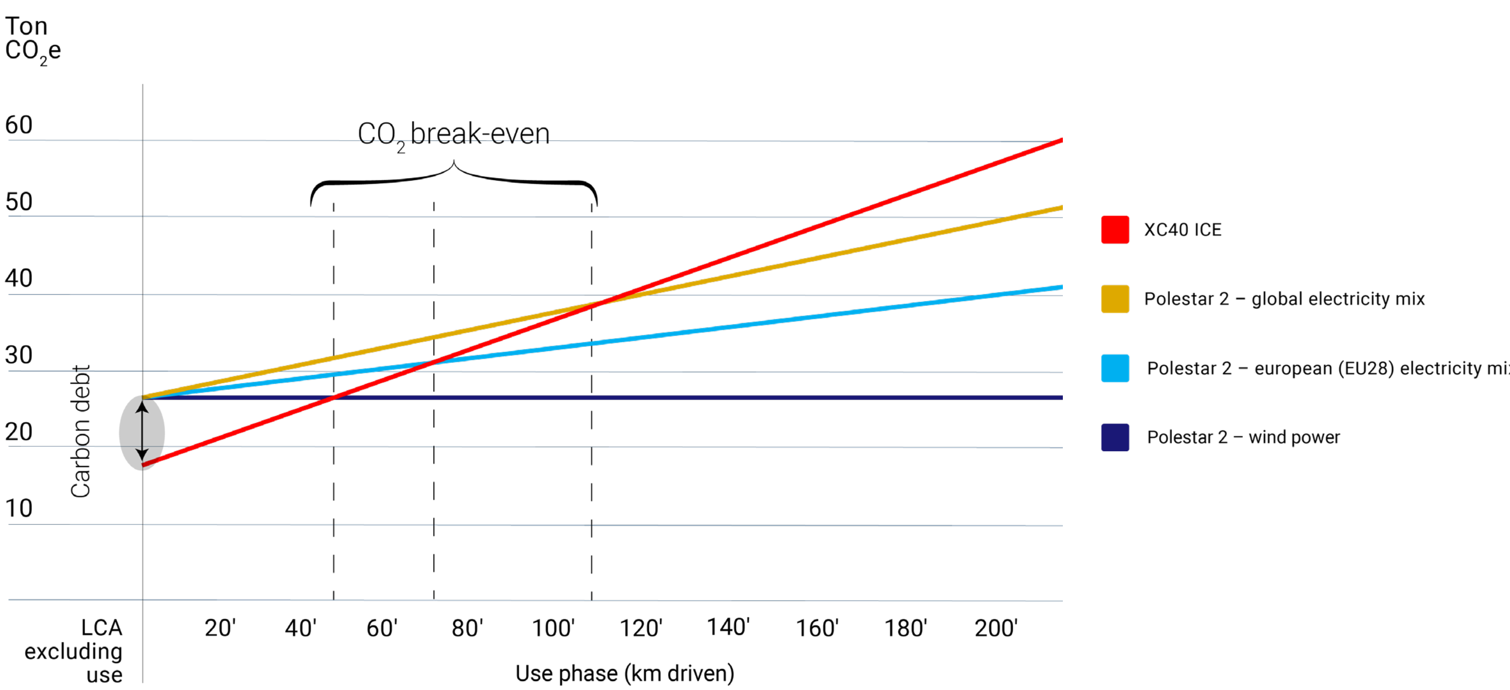

Figure 4. Total amount of CO_2e emissions from Polestar 2 (with different electricity mixes), and XC40 ICE (ton CO_2e). Source: Polestar

debt has been compensated for, the "CO2 break-even", EVs contribute to decrease emissions. How much, and when the break-even occurs, depends on several factors.

First, it depends on how the battery is produced, which materials are used and the energy supply in production (described further in the next section). To highlight this and other lifecycle information, a new EU regulatory framework for batteries proposes several requirements driving focus on emissions, second life and recycling. From July 1, 2024, all EV and rechargeable industrial batteries will require a carbon footprint declaration. Based on this, batteries will on January 1, 2026, be subject to classification into carbon footprint performance classes, a battery passport. From July 1, 2027, batteries will have to comply with maximum life cycle carbon footprint thresholds. The aim is to provide information for customers when purchasing battery powered products, and an opportunity for European manufacturers to differentiate their batteries through environmental and social parameters.

Secondly, it depends on how the electricity that charges the battery is generated (the "electricity mix"), as well as the overall life of the vehicle. Emissions from electricity generation varies greatly between countries and even locally. In Sweden the average CO2 emissions per kWh is in the rage

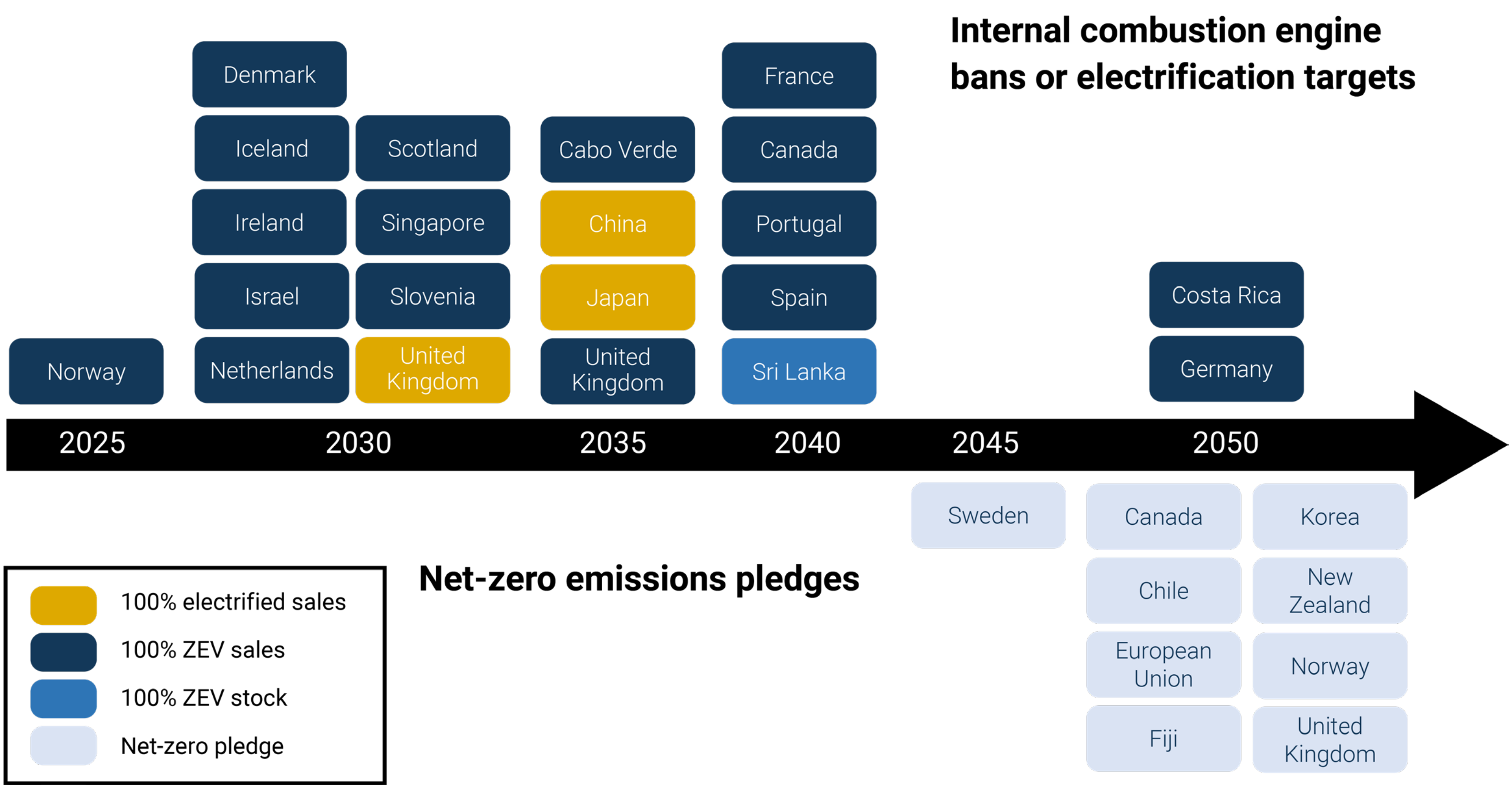

Figure 5. Timeline with policies/stated targets. Source: S&P Global

of 40 grams, while it is 360 grams in Germany, and 550 grams in China. The actual LCA of an application, such as an EV, can thus be estimated – illustrated here by the Polestar model 2 under various use conditions.

Finally, a battery that is then used in another application ("second life"), such as energy storage, or recycled, of course contributes positively to the LCA of that subsequent, application.

The key takeaway is that EVs are more or less climate negative when produced but have the potential in the longer term to reduce emissions compared to ICE vehicles. Therefore, promoting EVS are a preferred policy avenue for mitigating climate change.
Among common policies used to promote EVs are:

- Taxation and tax incentives for vehicles
- Taxation of fossil fuels
- Subsidies for charging infrastructure, private and public
- Electrified fleets in public transportation, utilities, etc.

While climate change is by far the most common objective of policies, other considerations are also important for driving regulative action. In China, mitigating local emissions, especially in urban environments, has been a key driver for the growth of EVs. Even though subsidies for EVs in China are being phased out, it remains the biggest market for EVs. Another consideration is reducing dependency on imported fuels. Championing local supply chains and job growth is also a common objective of regulative action.

At all political levels, ambitions/targets around the world have been set to limit or phase-out fossil fuels in transportation. European countries and the EU have set the most ambitious targets. Also states, such as California in the US, and cities have phase-out targets.

Ambitions and targets are one thing – actual policies are another. Many ambitions are many years (electoral cycles) away, so the resilience of ambitions will be an important indicator to follow.

	REVENUE (LATEST)	ANNOUNCED INVESTMENT	TARGETS (SHARES OF EV SALES)	ANNOUNCED PHASE-OUT OF ICE
Volkswagen	263	101 by 2026	50% by 2030	2035 (Europe)
Toyota	258	70 by 2030	3,5 mn by 2030	
Mercedes-Benz	182	60 by 2026	50% by 2030	
Ford	127	50 by 2026	50% by 2030	2040 (2035 in Europe)
Honda	125	40 by 2032	0,5 mn by 2030	2040
GM	122	35 by 2025		2035
BMW	117	30 by 2025	50% by 2030	
SAIC	107	No data	No data	No new investments in ICE
Stellantis	104		70% by 2030	2045 (some brands 2030)
Hyundai	93	16 by 2030		

Figure 6. Electromobility targets of largest automotive OEMs. (Based on company announcements; revenue and investments in bn USD.)

The automotive sector is transforming

These policies as well as competitive pressures in the transport sector has led most OEMs to adopt strategies and goals, backed up by investments, to shift from combustion engines to electric powertrains. For these strategies to prove viable, the sustainability of the policies is important: especially that electrification leads to lower climate impact. This entails ensuring that dependencies in the supply chain – from materials to the production of the electricity charging the batteries – are also adequate.

Regulatory pressure and consumer demand for EVs varies by region. Europe is mainly regulation-driven, with high subsidies and ambitious targets. One example is heavy duty vehicles that will need to comply with CO2 reduction targets of 15 percent in 2025, and 30 percent in 2030, with significant penalties for non-compliance. In China, the largest market for EVs, has seen a sustained consumer pull despite reduced subsidies. In the US, both regulation and demand has been lower, but on the other hand the market success of Tesla has driven competitive developments of electrical offerings. As EV sales accelerated while the car market slowed down in 2020 and 2021, the shift to electrification is well under way.

Therefore, virtually all major OEMs are investing heavily in electrification and launching EV product ranges. Many have defined targets in the short- and mid-term, and some, like Volvo Car Group, have announced the total phase-out of ICE within a decade. In many cases, such phase-out is differentiated based on market/region and brand, with more premium brands having more aggressive timelines.

These strategies and investments by OEMs will profoundly transform the automotive supply chain. Coupled with other investments (in sensors and software for example), components that are exclusive to ICE powertrains (for example, conventional transmission and combustion engines) will drastically decrease in value and importance. For countries with large automotive industries, such as Germany and the US, the shift towards electrical powertrains makes a lot of jobs obsolete. Only in Germany, IFO, a research institute, calculates 100,000 jobs in the automotive sector will change by 2030. Not only components and the organization of production and supply chains are affected, but also business models, which is beyond the scope of this study to examine in-depth. Re-training and investment in the battery supply chain can reduce the effects on labor markets. For example, studies by McKinsey estimate that on average 80 jobs are created for every 1 GWh of battery production capacity. That number should increase significantly if other parts of the supply chain are also located in a country.

OEMs are therefore engaged in sourcing and developing new capabilities, especially pertaining to batteries. They also face strategic choices in sourcing supply and how to organize the supply chain. Whereas most OEMs just a few years ago simply bought batteries from the large battery producers (mainly in China, South Korea, and Japan), increasing demand has driven a more active involvement in battery production. Strategies vary between OEMs, but a combination of joint ventures, partnerships and wholly owned factories are common.

Tesla, the pioneers of the modern EV, exemplifies this well with their role both as a battery producer themselves, as well as maintaining deep partnerships and joint ventures with multiple battery producers. Volkswagen is another example, with plans to establish six gigafactories in Europe, as well as long-term supply agreements with Northvolt (in which it has a 20 percent stake) and material suppliers such as Umicore.

This is indicative of how OEMs are integrating all the way upstream with mining companies, as raw material supply has tightened. Volkswagen describes this as "the new focus" (mining to refining to cathode production), where the geographies are South America, Australia, Africa, China, as opposed to the "classical procurement focus" (cathode production to cell production to module assembly to OEM).

Forward integration is also taking place. An enabling factor for battery applications is charging availability. This can be part of the supplied product offer, directly or indirectly. Tesla offers charging infrastructure as an integrated – and exclusive – offer, while others are partnering to provide charging capacity. Charging coverage and charging speed are important factors for future sizing of batteries. Higher coverage and faster charging could enable smaller batteries and thus lower costs and CO2 footprint.

Another aspect of forward integration are partnerships around second life, where battery producers, OEMs and second life actors collaborate around the battery lifecycle.

Another example is power distribution grid integration, where OEMs and utilities collaborate around electrical power storage, where vehicle batteries become an integral part of the grid.

Regardless of how production is organized, OEMs will be the dominant interest in driving battery demand and technology development. It is the requirements of automotive OEMs that matter most for battery manufacturing, perhaps to the detriment of other applications. For example, in the automotive industry energy density is crucial, since it determines the effective range of a vehicle. For power tools, power density is more important in order to release high amounts of energy quickly.

OEMs must balance several requirements which influences battery manufacture along important dimensions such as choice of chemistry, localization, which in turn also influences raw material needs. These trade-offs will be addressed further in the following sections.

Regardless of how production is organized, OEMs will be the dominant interest in driving battery demand and technology development.

THE RAMP-UP OF BATTERY PRODUCTION CAPACITY IS CRUCIAL TO THE ELECTROMOBILITY TRANSITION

As the world and the automotive industry transitions to drastically reduce emissions, the buildup of battery production capacity becomes crucial. Mobile energy storage is what is required for the transition, and LIBs are the dominant solution. But the necessary scale-up is huge and unprecedented and comes with significant uncertainty.

Battery production capacity has more than doubled in the last three years, and now stands at approximately 600 GWh/year globally. Last year, the top 15 producers added more capacity than was available globally in 2019. The capacity pipeline – announced investments and targets by battery producers – has been growing even more rapidly. In 2020, the capacity pipeline to 2030 rose from 850 GWh to 3 TWh, as new investments were announced. Currently, the capacity pipeline, as tracked by Benchmark Minerals, exceeds 4 TWh to 2030, and 6 TWh ten years into the future, ten times the size of current capacity.

At this rate, production capacity will more than match projected demand. However, a pipeline is not actual operational production capacity but rather announcements, targets, and work in various stages of progress. Nonetheless, only in 2021 a total of $150 bn was committed to investments in battery manufacturing.

What we are seeing is not merely a scaling of a supply chain: it is the establishment of entirely new supply chains – in plural – across the globe. Manufacturing a battery is a complex process involving multiple steps and tiers of producers. Battery-grade raw materials (such as lithium and nickel) are finished into active materials, which in turn are made into cells, then packed together to achieve the required battery capacity, and finally assembled into the application. The whole process is in turn supplied by chemical suppliers, component suppliers and equipment suppliers.

Incumbent battery manufacturers, such as CATL, LG and Panasonic, are scaling production and establishing new sites, but so are new entrants, such as Northvolt, as well as incumbents upstream (such as Rio Tinto, a mining company) and downstream (automotive OEMs) in the value chain. A multitude of actors combined with various strategies means that this supply chain is still emerging. The

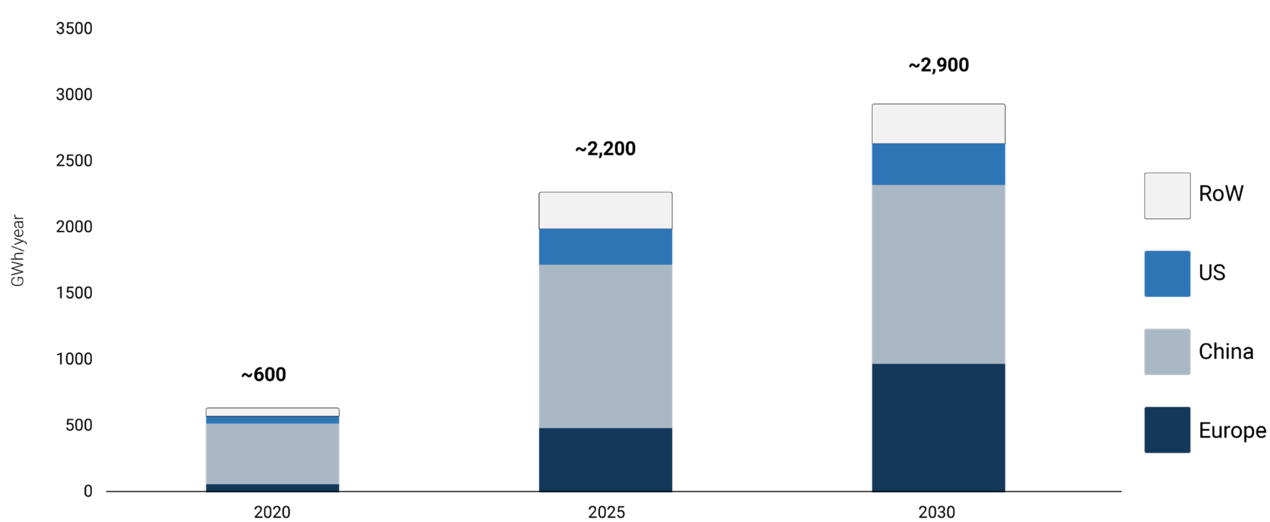

Figure 7. Projected battery production capacity per region (GWh). Source: McKinsey & Co

investment choices made depend on many factors, and in turn will have repercussions both on the demand for raw materials and the localization of production.

China dominates battery production, but other regions will grow faster

Since the first commercial LIB, Asia has been the leader in battery manufacture. Initially tied to consumer electronics, Japanese and South Korean companies, increasingly with production in China, dominated the sector. Chinese companies became increasingly important, growing with a pioneering market for electromobility. In 2021, 90 percent of LIBs were produced in Asia. China dominates battery production, the preceding value chain, and is the largest end-user market. This will likely continue in the short- and mid-term future.

But battery production is also important in the US and in Europe, even though they lag China. The US has deemed LIBs to be critical to competitiveness and has established a vision to build a robust supply-chain by 2030. As the home of Tesla and some real experience of scaled up battery production, it is primarily a market-led development. So far, the US "only" has 20 gigafactories in the pipeline, despite the size of their car market. These planned investments are predominantly by Asian big, first-tier battery producers with both capital and experience.

The EU has also established a vision and strategy for a European supply chain. Aggregate announced capacity investments in the EU outpace the US, but they have fewer operational gigafactories and there are more start-ups and government-funded ventures.

The market is fairly concentrated (the top 5 companies account for 70 percent of global output) but moving rapidly, with many new entrants as well as involvement from large incumbents up- and downstream in the value chain. The market will therefore continue to be extremely competitive.

With such a growth rate and many companies competing for market share, bottlenecks are becoming apparent. With almost 300 gigafactories announced and planned,

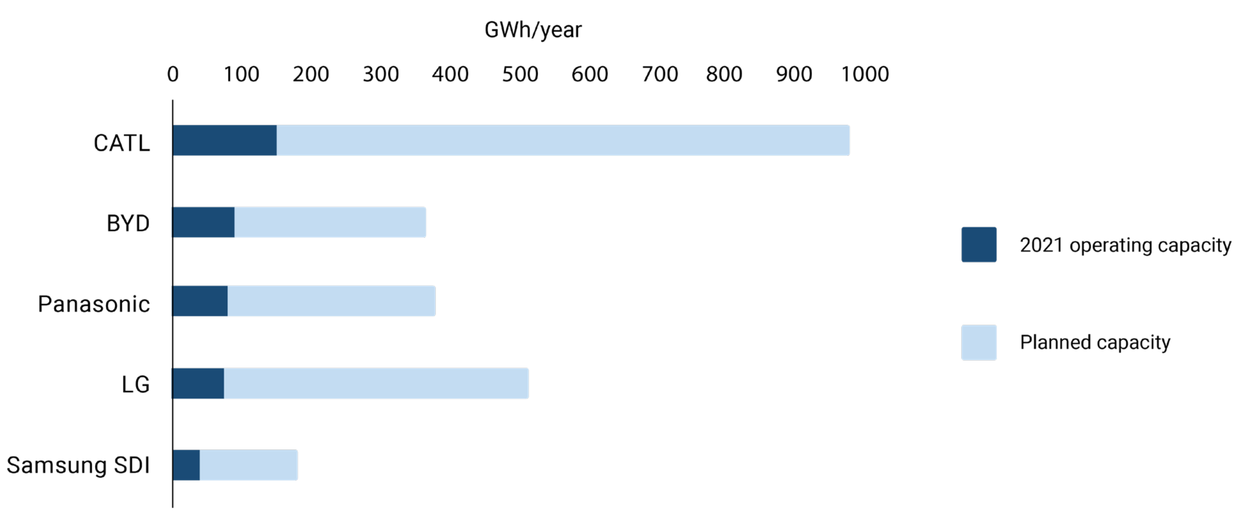

Figure 8. Top battery manufacturers. Source: Wood Mackenzie, Blue Institute

the supply of production equipment to populate massive production lines is strained. Personnel to staff the sites are another bottleneck. Supply of raw materials, components and chemicals need to be secured. All these bottlenecks are especially challenging in the US and in Europe, as the supply chain is less developed there and must be built from scratch. An advantage, however, is access to clean energy supply for production and closeness to the market.

Navigating these bottlenecks will determine the time to full operation of planned capacity, and different producers' ultimate success. Not all planned sites will succeed, and delays are expected.

In many cases this navigation entails integrating across the value chain, through acquisitions, joint ventures, and partnerships. For example, Northvolt's investment in a facility to produce active materials in Sweden and the joint venture with Galp in Portugal for mineral processing (lithium), as well as partnerships with OEMs to supply batteries for a long period of time, is indicative of such moves.

Such examples and the capacity pipeline as a whole indicate a significant regionalization of battery manufacture, as more capacity is planned in Europe and the US. China will maintain a leading position even by 2030, but the gap will narrow, and the volumes planned outside China are – compared to the present situation – massive.

Building regional supply chains is, as noted previously, a strategic priority by both the US and the EU. However, there are also clear business benefits which have prompted OEMs to pursue such strategies. Regional supply chains minimize political risks and resource dependency, creates jobs locally, and simplifies logistics. In fact, one source of the Chinese price advantage is that the entire supply chain is concentrated in a relatively small region around Shenzhen.

Other important factors are environmental, social and governance (ESG) concerns. As LCA profiles of batteries are critical, especially for automotive OEMs, clean energy in production is a source of differentiation. Northvolt, for example, states that its first factory will produce cells with the lowest carbon footprint in the world. The difference between the smallest and largest carbon footprint of LIB production is more than three times, significantly affecting the carbon footprint of an EV. In this sense, not only region but country and even locality can make a difference.

> ”
> In 2021, 90 percent of LIBs were produced in Asia. China dominates battery production, the preceding value chain, and is the largest end-user market.

The introduction of "battery passports" will be of importance as they show the provenance of each cell. Also, stricter labor laws can mitigate corporate governance risks.

However, localizing supply chains entails more than just investment in battery manufacturing. What China dominates even more than LIB production are cathode, anode, and precursor refining stages. In these areas, US and EU investments have to date been much lower than those in battery production. In Europe alone, consultancy Roland Berger estimates that an additional €15-20 bn of investment in precursor stages is needed to localize supply chains. And even more to develop domestic sources of raw materials.

Can price reductions continue?

As with most technologies, cost in relation to performance is everything. Batteries are far from commodities, and as such prices depend on specific configurations and interplay with other processes. Nevertheless, "average" prices are published and indicate the main trend. The cost of cells has fallen spectacularly over the last decade. Bloomberg surveys average offered prices, with the latest figure (Nov 2021) at $ 132/kWh at the pack level and $97/kWh at the cell level, a decline of six percent compared to the previous year. Batteries were cheapest in China, and approximately 40 percent more costly in the US and Europe. However, there is a large price span for different batteries according to specifications and quality. High performance power tool batteries can be more than twice the price of the high-volume high-capacity batteries. The price differences come from both a different technical specification with for example smaller particles, thicker copper foil, different electrolyte, and the relatively smaller volumes. For this type of batteries, the price development has not had the same decline.

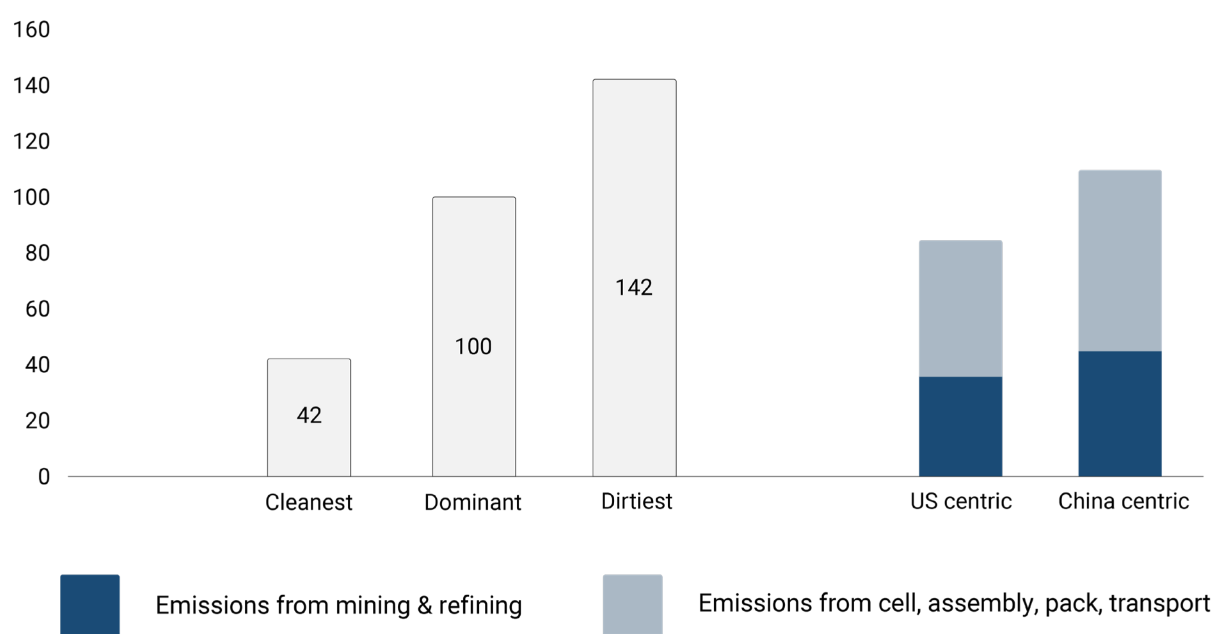

Figure 9: Battery production carbon footprint. Source: Argonne National Lab, Roland Berger

It has long been said that competitive price/price parity with ICE at is at $100/kWh, though that is a complex equation, especially with volatile energy prices and the desired size of battery. Nevertheless, further price decreases of batteries are both expected and necessary to achieve the kind of market share envisaged for EVs.

The rapid decline in cost per kWh has been a function of economies of scale (and learning) on the one hand, and higher energy densities through chemistry choice on the other. Economies of scale and learning has succeeded in lowering production-related costs, to just over 20 percent of total costs. This presents a challenge, as further cost decline at the same pace become harder to achieve. Nevertheless, according to Roland Berger, a consultancy firm, even larger sites and improved processes can lower costs by 15 to 20 percent further until 2025.

That scale economies are a key driver for the decrease in costs has added to the speed of capacity growth. Gigafactories are now the norm. Average plant size was 2,5 GWh in 2016, and 7 GWh in 2019, according to McKinsey. More than 280 gigafactories are expected to be operational by 2030.

Improvements in cell performance have also contributed to the rapid cost decline per kWh. Cell configuration is expected to further lower costs, and advances in how cells are integrated into the application can also drive down costs. For high volume cells, Roland Berger estimates that improved cell chemistry can contribute to a further 20 percent cost reduction to 2025.

A challenge to continuing price decreases is that the cost of materials is now a much larger share of the cost,

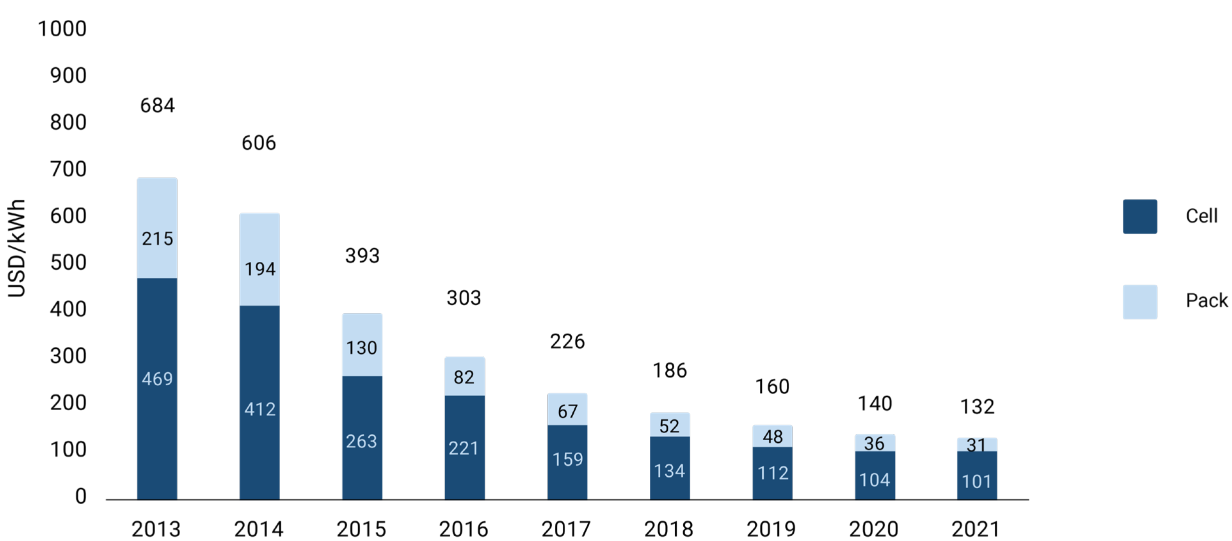

Figure 10. Volume-weighted average pack and cell price split. Source: Bloomberg NEF, Avicenne, Roland Berger

compared to a decade ago. This is more difficult to alter with higher volumes: indeed, as supplies become tighter, material costs are rising.

In summary, there are factors that indicate further price reductions, but current bottlenecks that in the short term may reverse the trend. Moreover, batteries come in many different forms and for different application markets, resulting in large price spans.

Application requirements drive chemistry choice

The choice and improvement of chemistries have vast importance for the dynamics of the value chain, both downstream (cost/performance and characteristics) and upstream (raw material demand).

Chemistries are defined by the composition of minerals that are used. They produce different characteristics: for example, high energy density to enable high transport range; or high-power density to release large amount of energy quickly. The choice of chemistry is to a large extent determined by the application end markets. For EVs, cost and energy density are most important, but other concerns are also important, such as availability of supply, safety, c-rate, and so on. The main lithium chemistries (thus targeting automotive requirements) are nickel based with cobalt (NMC, NCA) and iron phosphate (LFP). Graphite is mainly used for the anode.

Different chemistries come with different trade-offs. Somewhat simplified, NMC has been the dominant chemistry used in cars, as it delivers high energy density. However, LFP is cheaper, safer (on cell level), does not degenerate as quickly, and contains no cobalt – advantages that have prompted many OEMs and battery manufacturers to choose it instead. In recent years, LFP has rapidly

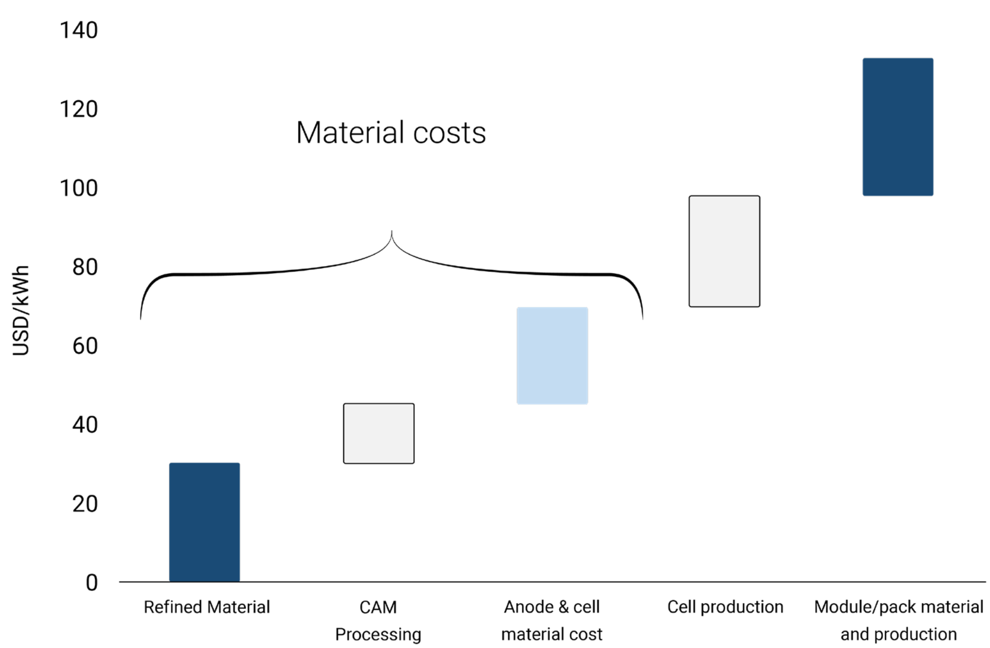

Figure 11. Cost breakdown of NMC811 battery cost. Source: Avicenne, Roland Berger

gained ground and is catching up with NMC. For other applications, other chemistries may be more suitable. The characteristics on cell level are or can however be enhanced, mitigated, compensated for on pack level, BMS or in the product system. As an example, NMC cells has in general better energy efficiency, but are worse in a safety perspective. Here OEMs compensate for this with safety systems on pack and system level.

As noted previously, regulators and OEMs, especially in Europe, are focusing on the sustainability of supply chains (LCA, but also ethical and labor rights concerns). The new EU regulatory framework proposes several requirements focusing on emissions. In the framework targets and ambitions for collection rates, recycling efficiency, material recovery, replaceability and second life are proposed, discussed later in the report. As far as different chemistries have higher or lower carbon footprints, or are more or less costly to recycle, this will probably affect chemistry choice.

In the short and medium run, we expect chemistries to continue to improve incrementally along familiar compositions, dependent on customer demand and sourcing. Existing production lines can adjust and shift chemistries relatively straightforward (securing supply is another matter). However, looking further afield to different types of batteries, such as solid-state batteries, would require new capacity investments.

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> In the short and medium run, we expect chemistries to continue to improve incrementally along familiar compositions... In a longer perspective, there are very promising avenues of research and development ongoing that could potentially disrupt the LIB value chain in a longer perspective.

Future batteries promise higher performance, but will take time to reach the market

There are very promising avenues of research and development ongoing that could potentially disrupt the LIB value chain in a longer perspective. Among those are solid-state lithium-ion batteries, which have the potential to drastically improve energy density, reduce cost, improve life and safety, and enable very high charge rates. Samsung is currently building a solid-state pilot line, with prototype cells expected in 2025 and possible start of mass production in 2027.

Another avenue is using other sodium rather than lithium as the cathode material. Sodium has the advantage of being cheap and abundant. CATL has the intention to introduce Sodium-ion batteries in the short term on an industrial scale, with the relatively low energy density (300 Wh/l) offset by low cost and rapid charge rate. Batteries Europe roadmap on new and emerging battery technologies expect to gain adequate understanding of sodium characteristics by 2025 to evaluate commercial introduction.

Another interesting development is to replace/merge the anode graphite with silicon. If successful, the silicon can provide up to 10 times higher storage capacity and provide a higher energy density. As with many of these emerging technologies there are obstacles to address, here one thing is the extreme volumetric change during molecule intercalation and deintercalation in the anode material – a problem to overcome before it can be utilized in lithium batteries.

Most patents are filed in Japan and Korea, as Samsung, Panasonic, LG, and Toyota together account for 75 percent of all battery related patents since 2000. Battery research primarily relates to various lithium-based combinations, as well as other sodium- and zinc-based technologies – all with different pros and cons. A lot of focus is on solid state lithium-ion, where patent activity has increased significantly the last 10 years.

According to some qualified judgements, the energy density potential can more than double in 10 years. Technology development can over time significantly change the dynamics in supply chains and potential sourcing constraints – but in the short term there are no shortcuts, and commercialization will also take time.

In parallel to battery technology development alternative energy storage technologies are developed. For some applications, such as long-haul trucks and off-road machinery, fuel cells are a clear alternative. Currently this technology has a much lower efficiency but enable better operational range due to the lower weight of stored energy. Despite advancements and interest in this field, large-scale commercialization on the scale that is now transforming the automotive sector, is clearly trailing the development of the LIB value chain.

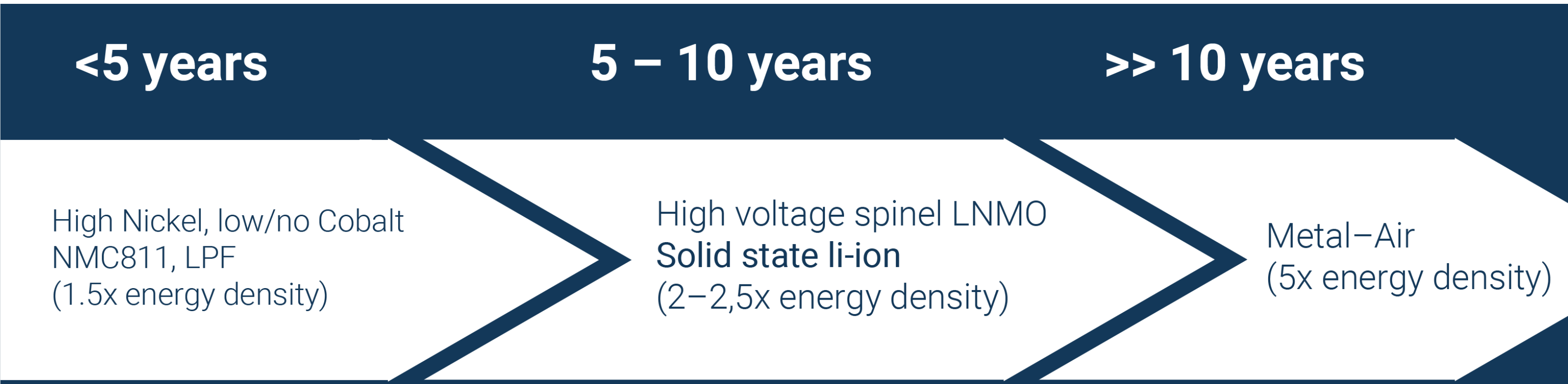


Figure 12. Energy density potential technology development. Source: Blue Institute

BATTERY TYPE	APPLICATIONS	PROS	CONS	TRENDS
Lithium Nickel Manganese Cobalt Oxide – NMC	EV, power tools, e-bikes	Specific energy, C-rate, life span, configurability (power vs energy)	Cost, stability	Stable
Lithium Iron Phosphate – LFP	EV, phones, power tools, computers solar	Cost, C-rate, cycle life, thermal stability, safety	Specific energy, self-discharge	Increasing
Lithium Nickel Cobalt Aluminium Oxide – NCA	EV (Tesla)	Specific ener-gy, OK specific power, life span	Cost, stability	
Lithium Titanate – LTO	Electric powertra-ins, uninteruptible power supply, military, wind/solar	C-rate, security, thermal stability, life span, ”green”	Cost, specific energy	Niche
Lithium Manganese Oxide – LMO	E-bikes, power tools, EV	C-rate, thermal stability, cost	Specific energy, life span, specific power	Niche
Lithium Cobalt Oxide – LCO	Mobile phones, computers, cameras	Specific energy	Life span, thermal stability, specific power, C-rate	Niche

Figure 13. Energy density potential technology development. Source: Blue Institute

CAN RAW MATERIAL SUPPLY KEEP UP WITH DEMAND?

> The uncertainty inherent in developing battery production capacity has to a large extent to do with the ability to secure supplies... A surge in demand for battery minerals will put strains on supply chains.

A battery in an electric car can weigh more than half a ton. While components like foil and structural materials such as aluminum, copper and steel all contribute to the weight, a large share comes from the anode and cathode minerals. Scaled to tens of millions of vehicles, the supply of minerals needs to expand exponentially. That is especially so for lithium that up until now has provided laptops, mobile phones and power tools with relatively small batteries.

Thus, the uncertainty inherent in developing battery production capacity has to a large extent to do with the ability to secure supplies of the required materials. And this is further complicated by the fact that electromobility is the major driver of an even larger, metal intensive global energy transition. This transition will also drive demand for metals that are required for renewable energy sources and power infrastructure. A recent report from KU Leuven estimates that 50 to 60 percent of future increased demand for clean energy metals is attributable to the growing EV market.

Such a surge in demand for minerals such as lithium, nickel, cobalt, copper, and graphite will put strains on supply chains. In the short term, demand seems to outpace supply. However, it is not straightforward to project how supply will evolve. With global markets and emerging supply chains, price signals and supply restrictions will affect investments in new supply and technological development in various ways. This creates a complex and dynamic interplay where strategic choices today will determine future value chains.

In this section, we examine how batteries affect and are affected by raw material supply. We begin with an overview of how chemistry choice impacts the demand for various minerals. We then look at the ramifications for the supply of battery metals. We address issues such as whether supplies will be sufficient to meet demand, where supplies may come from, how secondary supply (recycling) can impact the value chain, and how the supply chain will be organized.

The choice of battery technology drives mineral demand

As stated, a major driver for metal demand is the rise of electromobility. That in turn makes the current energy transition, to a large extent, a LIB economy, and that in turn makes it a commodity economy. If raw materials in 2015 made up 30 to 40 percent of the cost of a LIB, they now account for 70 to 80 percent.

Battery minerals include lithium (used in all chemistries today), nickel, manganese, cobalt[1] and graphite. The demand for these minerals, for battery production, is dependent on chemistry choice. For example, NMC811 requires higher volumes of nickel than NMC111, which in turn requires more cobalt. LFP contains neither nickel nor cobalt.

Chemistry choice, as outlined in the previous section, is related to performance and various characteristics suitable for different applications, in turn driving different sourcing needs. But other supply considerations also matter to battery producers and their customers, such as ESG concerns and security of supply. Due to ethics and supply risk inherent in Cobalt, which is primarily mined in the Democratic Republic of the Congo, DRC, there has been a trend to move from cobalt into high nickel chemistries or into LFP, which is less efficient, but cheaper and more stable. For example, Tesla's current batteries now contain on average only 5 percent Cobalt, down from one third a few years ago. Likewise, the Eurasian Resources Group (ERG) and Glencore has initiated the development of a block chain solution "Re|Source" to track responsibly produced cobalt.

The carbon footprint of raw material extraction and refining is also an important concern, as it represents a large part of the LCA of the final application. Different minerals and even mineral sources can therefore also affect chemistry choice and source of supply. For example, lithium hydroxide from spodumene has twice the carbon footprint compared to that from brine. Producing it from brine, on the other hand, consumes much more water. Similarly, Class 1 nickel from sulphides has only a fifth of the carbon footprint of Class 2 nickel from laterites. Mineral prices and availability of supply is therefore influenced by chemistry choice, but it can also be expected to influence innovation efforts and strategic choices that over time influences mineral demand.

The dynamic interplay between demand, battery characteristics and mineral supply makes it hard to predict exactly how will this play out. On the one hand, minerals are not distributed evenly in the earth. Therefore, some countries are particularly important for the supply of battery minerals and are benefiting from the surge in demand. On the other, tight supply chains can spur efforts to develop new resources and extraction technologies, and high prices changes the economic viability of lower resources with lower mineral concentrations. In the next section, we consider how increased battery demand can be met with increased supply of the main minerals.

[1]Copper is also central to the energy transition, both for use in vehicles and in infrastructure. This will drive demand for copper, but producers are well placed to provide additional supply without anticipated shortages globally.

Will there be enough supply?

None of the main battery metals are scarce in the earth's crust; what is scarce is high-grade reserves that can be extracted cheaply, conversion facilities, and investments upstream in the value chain. Compared to the announced investments in battery production, investments in in mineral extraction is scant.

The differences in timescales between developing new mineral resources and setting up factories also matter. Investors have been hesitant to commit to new mines due to doubts over the duration of the boom in lithium demand. If new battery technologies begin to supplant lithium-ion in a decade, the business case for a mine that will have a lifetime of several decades is affected. The time it takes to secure permits and establish new mining operations is in many cases also an important factor.

Lithium

As lithium is the one mineral which is used extensively in all currently used major battery chemistries and used almost exclusively for batteries – more than 95 percent of all lithium produced is destined for batteries (other usages include glass and ceramics) – it is at the heart of the battery value chain.

Most of the world's lithium (99 percent) is extracted in just a few places. Four spodumene mines in Australia account for more than half of world production. The rest comes from two brine operations each in Argentina and Chile, and three operations (two brine, one rock) in China.

Global lithium production in 2021 was approximately 530 kt LCE (lithium carbonate equivalents), an increase of 21 percent from 2020. Consumption was almost a third

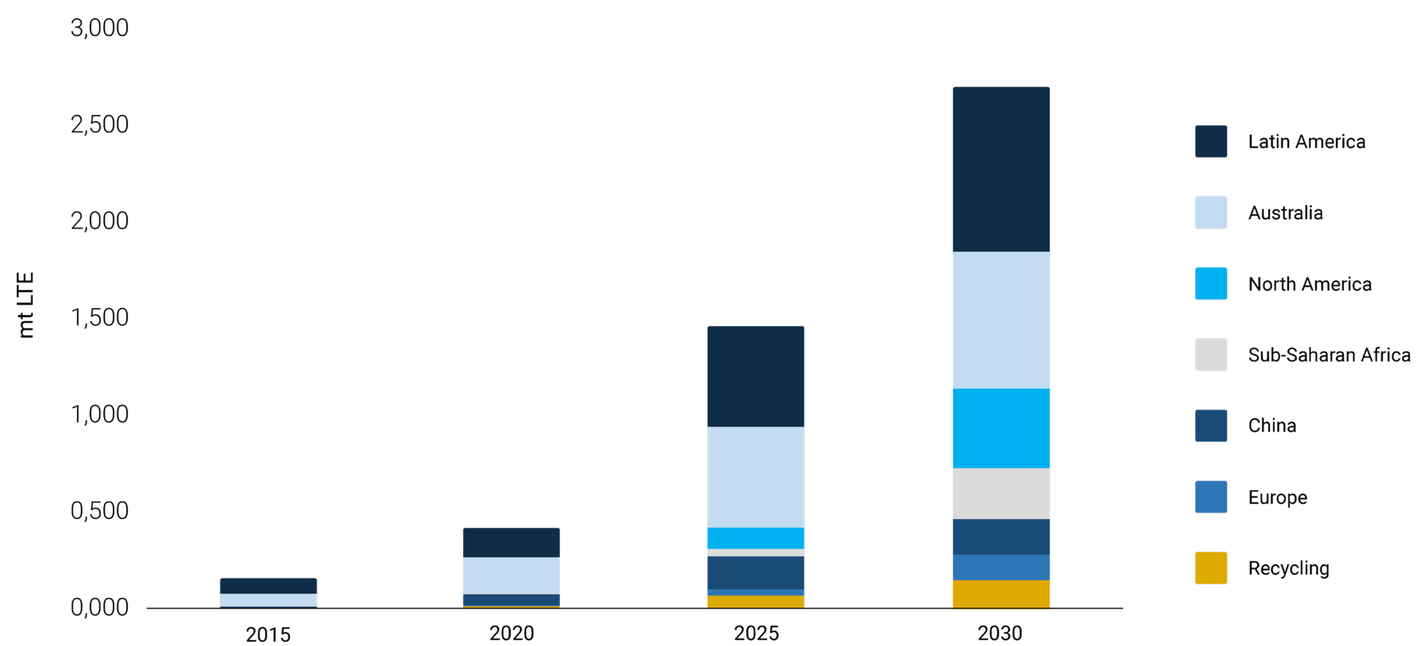


Figure 14. Projected lithium supply by region (mt LTE). Source: Benchmark minerals, Roland Berger

higher than in 2020. However, lithium production and prices have fluctuated in the recent past. Prices declined in 2019 after earlier anticipation of EV take-offs failed to materialize, and some production was closed. Last year, as demand surged and expected future demand even more so, spot prices increased rapidly, by seven times in 2021.

Lithium is not a commodity however, being both relatively low volume and in need of considerable refinement to be used in batteries. Thus, most of the trade in lithium is handled in long term contracts. Nevertheless, the price increase will slowly filter through into contracts. Expectations are that 2022 will see a reversal of the long trend of price decline, and that batteries at the cell level will increase in price by 10 to 20 percent this year.

As consumption outpaces demand, production is increasing new resources are being developed. Projections indicate that production could increase by a factor of 5 to 2030. Lithium thus has a strong global pipeline, according to KU Leuven, but capital investment in lithium extraction is still trailing investment in battery production. With the LIB demand projections outlined previously, and the announced capacity pipeline in battery production, there may be supply shortages especially in the short term. In fact, global capacity of more than 1 TWh will not be possible until 2025, according to Benchmark Minerals.

The scramble for lithium may alter and diversify the supply of raw materials. While Australia and South America will continue to be the largest suppliers, other regions may become increasingly important. Exploration stage activities are taking place in North America and in Europe, in particular. However, exploration and development of resources is inherently uncertain and volatile. There is also the element of time, with anything from 3 to 7 years (or more) to become a fully operational site.

New technologies may unlock supply in Europe, North America

Many of the potential new resources in the North America and Europe are found in brine and clay, and may be extracted using a novel technology, direct lithium extraction. DLE has several advantages over both mineral extraction (as in Australia) and evaporative extraction from brine (as in South America). DLE produces very high-grade lithium, which means that the need for subsequent refining is reduced and drastically reduces the carbon footprint. If combined with geothermal energy, it is carbon neutral. It is also much faster than evaporative processes.

DLE is not yet proven at scale but could unlock vast quantities of lithium in Europe and in the North America. The technology is also used by Rio Tinto, a mining giant, for extraction of lithium as a byproduct from their Boron mine site in California, with a capacity of 10 ktons per year. There is also the potential to extract lithium from the 90 years of waste rock that has already been accumulated at that site. Rio Tinto has also invested in Serbia, although the project is halted for now by local concerns.

Will conversion capacity be localized to end-markets?

When it comes to the organization of the supply chain, the extraction of minerals such as lithium from rock or brine is only the first step in supplying battery manufacturers with raw materials. Battery minerals, and particularly lithium, needs to be extensively refined to be of a grade suitable for the performance and safety requirements of batteries.

China is said to dominate lithium-ion, but that is only partially true. What China dominates currently is battery production as well as spodumene conversion capacity, that is, producing battery-grade lithium hydroxide or lithium carbonate. But when it comes to raw materials, China is more dependent on resource imports than any other country. However, Chinese companies such as Tianqi Lithium have large stakes in mineral operations and conversions outside China.

Conversion capacity, thus, is also increasing rapidly as gigafactories are being built, although it is trailing investments in battery production. This capacity is faster to build and has also carried higher margins than the extraction phase historically. As in other parts of the value-chain, long-term partnerships and joint ventures are being established to secure supply. A recent example is the Northvolt-Galp joint venture in Portugal, to build Europe's largest conversion plant for lithium hydroxide, that will be able to supply material for 50 GWh of battery production. However, new entrants far from mining operations may have challenges in securing the raw ore needed in the coming decade.

Nickel and cobalt

Other important battery minerals include nickel and cobalt, as well as the anode material graphite. Nickel is much more of a commodity than lithium, being mainly used in steel production. However, nickel supply is currently uncertain. One reason is because Russia is a major supplier, especially of battery-grade nickel. Furthermore, flaws in LME trading have been resulted in highly volatile prices. Another major Nickel supplier, Indonesia, is eying the more profitable subsequent steps in the value chain – refining and even battery manufacture – and are ramping

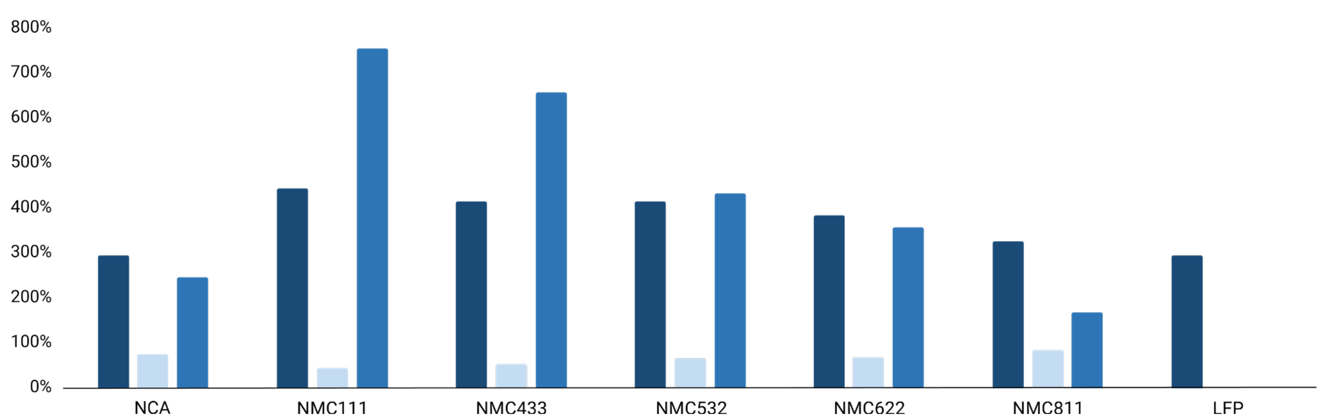


Figure 16. Required increase in global mineral production to 2030 by chemistry. Source: Blue Institute

up production based in part on localization requirements of such operations in the country.

Cobalt is a critical mineral in common battery chemistries such as NMC and NCA. The production of Cobalt is predominantly in Congo, which supplies almost three quarters of global consumption. If battery chemistries remain stable at the projected demand of 2030, production would have to ramp up more than sevenfold. However, the ESG footprint of cobalt from Congo, as well as security of supply, has rather prompted efforts to tweak chemistries or switch to LFP to reduce the reliance on Cobalt in batteries.

Graphite

Anode materials make up the largest single component of high-capacity batteries by volume – an EV requires 10 to 15 times more graphite than lithium in its battery. The growth of LIB demand means that approximately half of the world's graphite supply ends up in batteries. According to Benchmark Minerals, there will be a deficit of graphite in the short term. Production will thus need to ramp up, but a challenge is that both natural and synthetic graphite is carbon intensive to produce. China mines two-thirds of the global graphite supply and produces virtually all battery-grade anode material today. That exacerbates the challenge since the Chinese electricity mix is coal-based and particularly carbon intensive.

Secondary supply: potentially a significant source in the mid- and long term

Another potential source of raw material comes from recycled products, which is significant for minerals such as copper and aluminum. When it comes to battery minerals, currently available volumes for recycling are low in comparison to demand. The main reason for this is the delay of material availability for recycling. As an example, if the lifespan for a car is 17 years, battery minerals enter the raw material market again 17 years from now.

This may even be prolonged, as a large portion of batteries (30 percent) are reused in other applications in less developed markets. Batteries are remanufactured or repurposed to new applications since there's still a significant capacity left in the battery, a second life. For vehicles this happens when the battery has 80 percent capacity left. Due to their size, second life EV batteries are commonly seen as usable in EES applications – although the chemistries and characteristics may not be the best suited for such applications. In this case, batteries can enable sustainable energy production, as the prolonged battery life might lower the total CO2 footprint of the battery lifecycle. That is if the batteries are still competitively efficient after first use, otherwise the minerals might be better off recycled into a new battery.

The estimated battery availability for recycling in 2030 is 315GWh, of which 145 GWh will be available for second life. Estimated battery demand at that time is 3100GWh. This would mean that recycled batteries could theoretically supply 10 percent of new production with recycled material, assuming a 100 percent recycling grade.

The three main technologies used for recycling are pyrometallurgical, hydrometallurgical and mechanical, where a combination of mechanical and hydrometallurgical is most

> The dynamic interplay between demand, battery chemistries and mineral supply makes it hard to predict exactly how the market will play out.

common for LIBs. With current technologies the recycling efficiency is in average about 50 percent. Profitability, however, is low. This implies that only 5 percent of supply could come from recycling in 2030 – if demanded chemistries are the same.

In the new proposed regulatory framework for batteries, the EU member states should achieve a minimum collection rate of 70 percent by end of 2030, and specific recovery rates will be specified för lithium, nickel, copper, cobalt and other valuable materials in the range of 95 percent. This requires significant improvements in recycling efficiency compared to what is available today.

New research shows promising ways to recycle cathode black mass. The process does not rely on breaking down the battery into constituent chemical elements, but rather on extracting the cathode compound, removing impurities, and adding fresh elements to 'renovate' the powder. The process called Hydro to Cathode and is used by Ascend Elements.

How second life and recycling will impact the battery ecosystem dynamics is uncertain. There are several factors such as recycling efficiency, battery design, Battery State of Health (SoH), closeness to recycling plants, mineral prices, energy mix, and second life application values that will impact outcomes.

CONCLUSIONS

WHAT WILL THE FUTURE SUPPLY CHAINS LOOK LIKE?

This study has followed and outlined the emerging supply chain of lithium-ion batteries. In a relatively short period of time, there have been rapid changes in terms of actual operations as well as future projections. It is obvious that the world is in the beginning of a massive industrial transformation, centered on climate change, with huge impact on multiple sectors.

At the center of this transformation is electromobility, which in turns depends on energy storage solutions. The dominant technology right now – and for the foreseeable future – is the lithium-ion battery. The rapid price to performance development of batteries has in turn affected other sectors where they enable new categories of applications, such as power tools, robotics and micromobility.

The transformation necessitates a rapid scale up of battery production capacity, and of all that is needed to produce those batteries. Large investments are needed, and many have already been committed or announced. However, in some parts of the value chain, investments are still lagging. More investments upstream are needed. If they are not forthcoming, the supply chain and therefore also the market will continue to be tight. Prices have already increased and may continue to rise for a period, until bottlenecks have been cleared.

The situation creates opportunities, and a dynamic interplay where choices and investments in one part of the value chain greatly effects conditions in other parts. To deal with this, market actors are increasingly pursuing strategies for integration across the value chain. Automotive OEMs are sourcing supply from not yet existing mines, and mining companies are acquiring battery producers. Vertical integration will be name of the game in the coming decade.

The outcomes are uncertain, and the ecosystem is evolving rapidly. One thing that is certain, is that when demand and supply are not in balance, not everyone will succeed, and many plans and strategies will fail. As a forward-looking summary we provide an expanding horizon of possibilities, where different issues and factors become critical at different timescales. However, the value chain is still emerging, and the horizon should be seen as indicators to follow and questions to ask as the ecosystem unfolds.

Despite these caveats, it is obvious that a tipping point has been reached. Especially the automotive sector has gone far in a transition with investments and irreversible strategic decisions. The sale of electrified vehicles is the main indicator to track. Furthermore, LIBs are the most cost competitive and therefore dominant energy storage for most volume applications and will remain so in the short- and mid-term outlook. Investment will center on LIB rather than on other energy storage solutions for mobility in the short- and mid-term. However, for applications requiring substantially more capacity, such as heavy-duty trucks, trains, EES, supply constraints of LIBs may make alternative solutions, such as fuel cells, more attractive.

The most challenging (and uncertain) industrial factor is the ability to grow battery production capacity to keep up with demand, across all types of applications. The evolving actual production capacity is the main indicator to track. Production capacity at cell level in turn requires the buildup of supporting supply chains.

For production capacity to increase as planned, the supply of materials, components and machinery needs to keep pace. Especially the supply of raw materials (particularly of lithium and graphite) is a main uncertainty. Here, indicators to track include:

- In the short-term, scaling existing production rapidly in lithium
- In the mid- and long-term, developing new supply of lithium and nickel
- In the mid- and long-term, developing new extraction methods such as DLE, which if proven viable can unlock new resources at lower cost and with drastically lower carbon footprint
- In addition, localizing supply chains for conversion, precursor, and CAM production

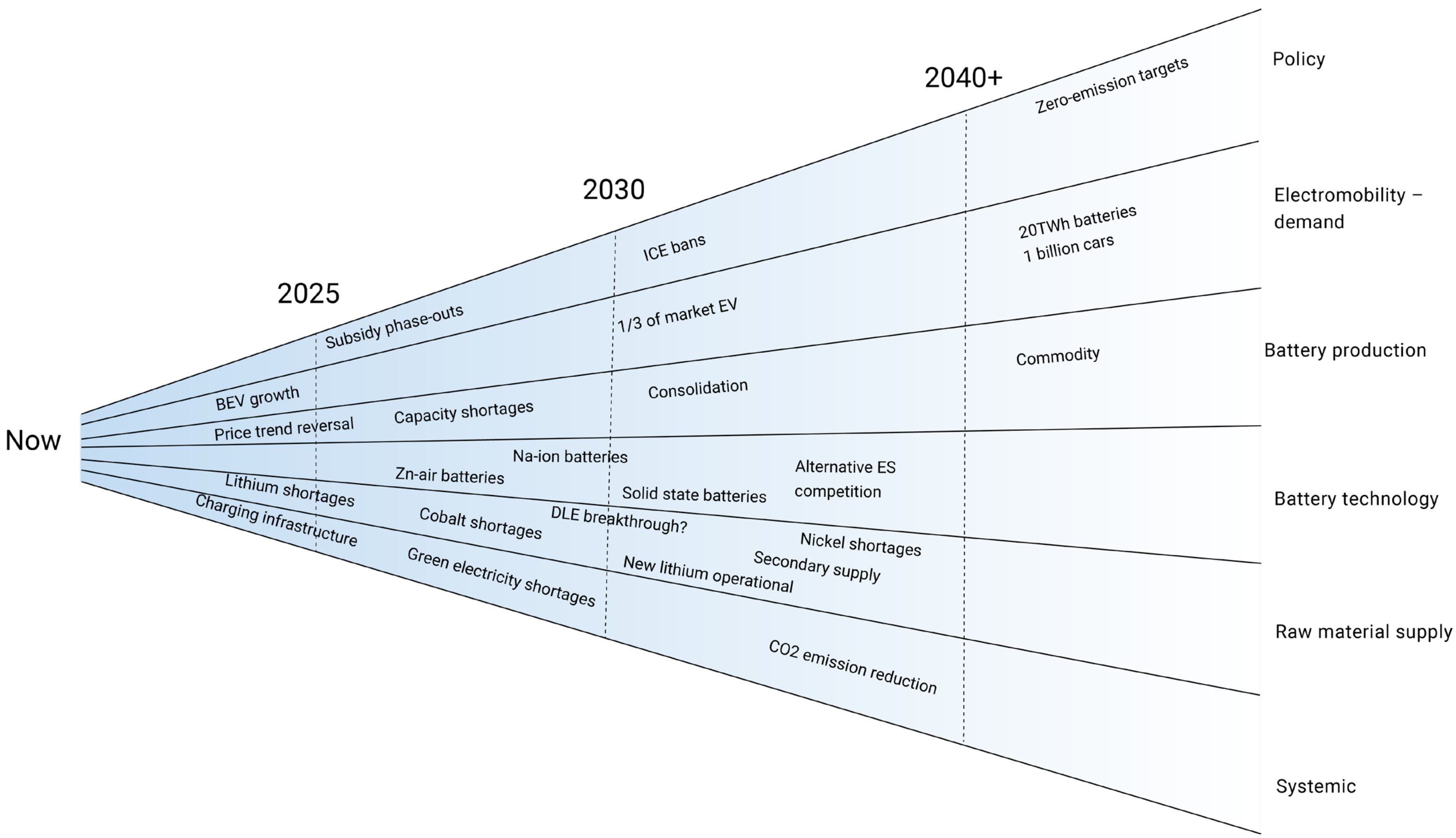
Bottlenecks in the supply of materials and components, coupled with the increasing focus on reducing batteries' carbon footprint, will undoubtedly influence technological development and chemistry choice. In the short term, continued incremental development along the dominant chemistries, along with scale and learning effects, will continue to improve performance. Efforts to decrease the environmental impact of material extraction, refining and cell production will continue. The more potentially radical shifts, such as sodium batteries and solid electrolytes, remain uncertain and probably will not be commercially feasible at scale until beyond 2030. Nevertheless, the size and growth of demand will ensure investment and efforts along more disruptive lines. For the same reason, developments in hydrogen fuel cells will also continue.

The evolution of prices therefore remains uncertain, but with demand outpacing supply, it is likely that the last decade's track record of drastically improved price/performance ratios will be paused or even reversed for some time. It is also evident that batteries are far from commodities, where specific requirements and smaller volume application markets have faced a much less favorable price evolution.

In the longer term, the demand and supply of mobile energy storage is likely to be significantly larger than we can even forecast today, but it will be more uncertain as to which solutions and technologies will provide them. Demand can be severely altered by behavioral change and/or in the face of societal investment in public transportation, for example. New technology breakthroughs may alter the ecosystem dynamics. Finally, since the main driver behind the rapid growth in demand comes from mitigating climate change, ultimately the ability of electrical batteries to contribute lies in the successful transition of energy production and infrastructure to support reduced CO2 emissions.

HORIZONS

Indicators to watch, bottlenecks to overcome



The value chain is rapidly evolving and still emerging. There is an expanding horizon of possibilities and challenges where interdependent indicators, policies, technologies and supply sources come in to play at different timescales. The only thing that is certain, is that not everyone will succeed, and many plans and strategies will fail.

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