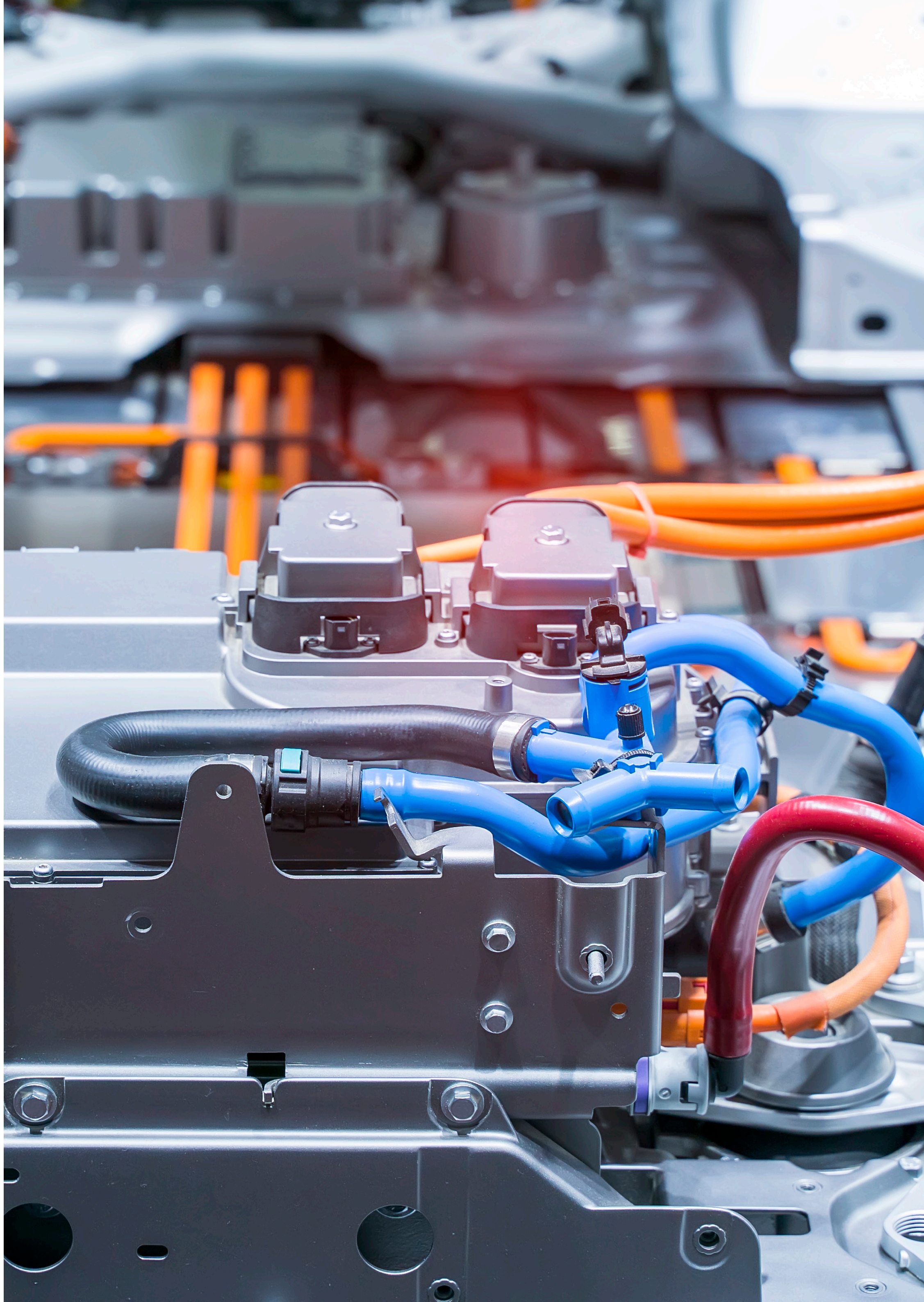
Global Supply Chains of EV Batteries



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Executive summary

As electric car sales continue to break records, supply chain considerations move to the fore

Batteries typically accounts for 30% to 40% of the value of an electric vehicles (EV), and the race to net zero will focus attention on the security of supply of the critical minerals and metals needed to manufacture them.

Electric car sales continued to break records in 2021, testing the resilience of battery supply chains

Few areas in the world of clean energy are as dynamic as EV markets. In 2021, EV sales broke new records, with nearly 10% of global car sales being electric, four times their market share in 2019. Public and private spending on EVs doubled relative to 2020. More and more countries have pledged to phase out ICEs or have ambitious electrification targets. Five times more EV models were available in 2021 relative to 2015, and most major carmakers are announcing plans to further accelerate electrification of their fleets.

China accounted for half of the growth of the EV market in 2021. More vehicles were sold in China in 2021 (3.3 million) than in the entire world in 2020. Sales in Europe continued to grow robustly (up 65% to 2.3 million) after the 2020 boom, and they increased in the United States as well (to 630 000) after two years of decline. The first quarter of 2022 showed similar sales trends.

Today's battery and minerals supply chains revolve around China

China produces three-quarters of all lithium-ion batteries and is home to 70% of production capacity for cathodes and 85% for anodes (both are key components of batteries). Over half of lithium, cobalt and graphite processing and refining capacity is located in China. Europe is responsible for over one-quarter of global EV assembly, but it is home to very little of the supply chain apart from cobalt processing at 20%. The United States has an even smaller role in the global EV battery supply chain, with only 10% of EV production and 7% of battery production capacity. Korea and Japan have considerable shares of the supply chain downstream of raw material processing, particularly in the highly technical production of cathode and anode material. Korea is responsible for 15% of global cathode material production capacity, while Japan accounts for 14% of cathode and 11% of anode material production. Korean and Japanese companies are also involved in the production of other battery components such as separators.

Most key minerals are mined in resource-rich countries such as Australia, Chile and the Democratic Republic of Congo, and handled by a few major companies. Governments in Europe and the United States have bold public sector initiatives to develop domestic battery supply chains, but the majority of the supply chain is likely to remain

Chinese through 2030. For example, 70% of battery production capacity announced for the period to 2030 is in China.

Battery and minerals supply chains will have to expand ten-fold to meet government EV ambitions

The rapid increase in EV sales during the pandemic tested the resilience of battery supply chains, and Russia's war in Ukraine has further exacerbated matters with prices of raw materials such as cobalt, lithium and nickel surging. In May 2022, lithium prices were more than seven times higher than in early 2021 due to unprecedented battery demand and a lack of sufficient investment in new supply capacity. Meanwhile, Russia supplies 20% of global high-purity nickel. Average battery prices fell by 6% to USD 132 per kilowatt-hour in 2021, a slower decline than the 13% drop the previous year. If metal prices in 2022 remain as high as in the first quarter, battery packs would become 15% more expensive than they were in 2021, all else being equal. However, the relative competitiveness of EVs remains unaffected given the current oil price environment.

Pressure on the supply of critical materials will continue to mount as road transport electrification expands to meet net zero ambitions. Demand for EV batteries will increase from around 340 GWh today, to over 3500 GWh by 2030 in the Announced Pledges Scenario (APS). Cell components and their supply will also have to expand by the same amount. Additional investments are needed in the short-term, particularly in mining, where lead times are much longer than for other parts of the supply chain – in some cases requiring more than a decade from initial feasibility studies to production, and then several more years to reach nominal production capacity. Projected mineral supply until the end of the 2020s is in line with the demand for EV batteries in the Stated Policies Scenario (STEPS). But the supply of some minerals such as lithium would need to rise by up to one-third by 2030 to satisfy the pledges and announcements for EV bateries in the APS. For example, demand for lithium – the commodity with the largest projected demand-supply gap – is projected to increase sixfold to 500 kilotonnes by 2030 in the APS, requiring the equivalent of 50 new average-sized mines.

There are other variables affecting demand for minerals. If current high commodity prices endure, cathode chemistries could shift towards less mineral-intensive options. For example, lithium iron phosphate cathode chemistry (LFP) does not require nickel nor cobalt, but comes with a lower energy density and is therefore better suited for shorter-range vehicles. LFP share of global EV battery supply has more than doubled since 2020 because of high mineral prices and technology innovation, primarily driven by an increasing uptake in China. Innovation in new chemistries, such as manganese-rich cathodes or even sodium-ion, could further reduce pressure on mining. Recycling can also reduce demand for minerals. Although the impact between now and 2030 is likely to be small, recycling's contribution to moderating mineral demand is critical after 2030. In the Net Zero Emissions by 2050 Scenario (NZE), demand grows even faster, requiring additional demand-side measures and technology innovation. Today’s corporate and consumer preferrence for large car models such as sports utility vehicles (SUVs), which account for half of all electric models available globally and require larger batteries to travel the same distances, is exerting additional pressure.

Ensuring secure, resilient and sustainable EV supply chains will be key to accelerating global uptake

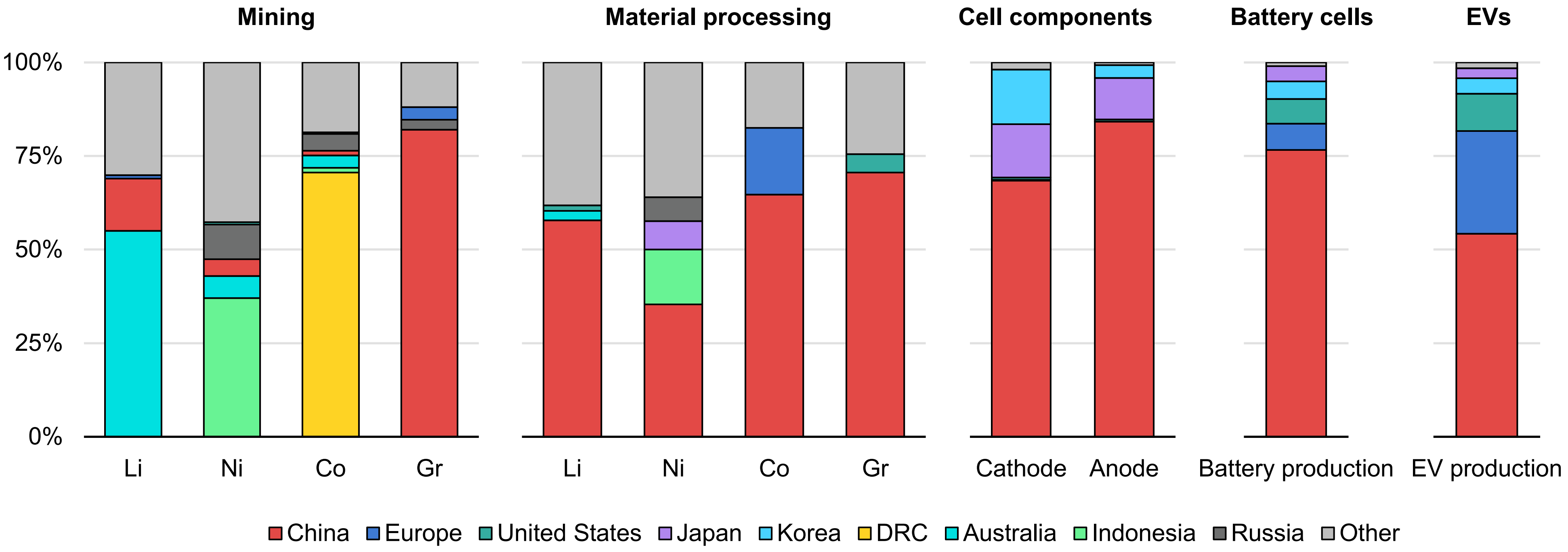
Electrifying road transport requires a wide range of raw materials. While all stages of the supply chain must scale up, extraction and processing are particularly critical due to long lead times. Governments must leverage private investment in sustainable mining and ensure clear and rapid permitting procedures to avoid potential supply bottlenecks.

Innovation and alternative chemistries that require smaller quantities of critical minerals, as well as extensive battery recycling, can ease demand pressure and avoid bottlenecks. Incentivising battery “rightsizing” and the adoption of smaller cars can also decrease demand for critical metals.

Governments should strengthen cooperation between producer and consumer countries to facilitate investment, promote environmentally and socially sustainable practices, and encourage knowledge sharing. Governments should ensure traceability of key EV components and monitor progress of ambitious environmental and social development goals at every stage of battery and EV supply chains.

China dominates the entire downstream EV battery supply chain

Geographical distribution of the global EV battery supply chain



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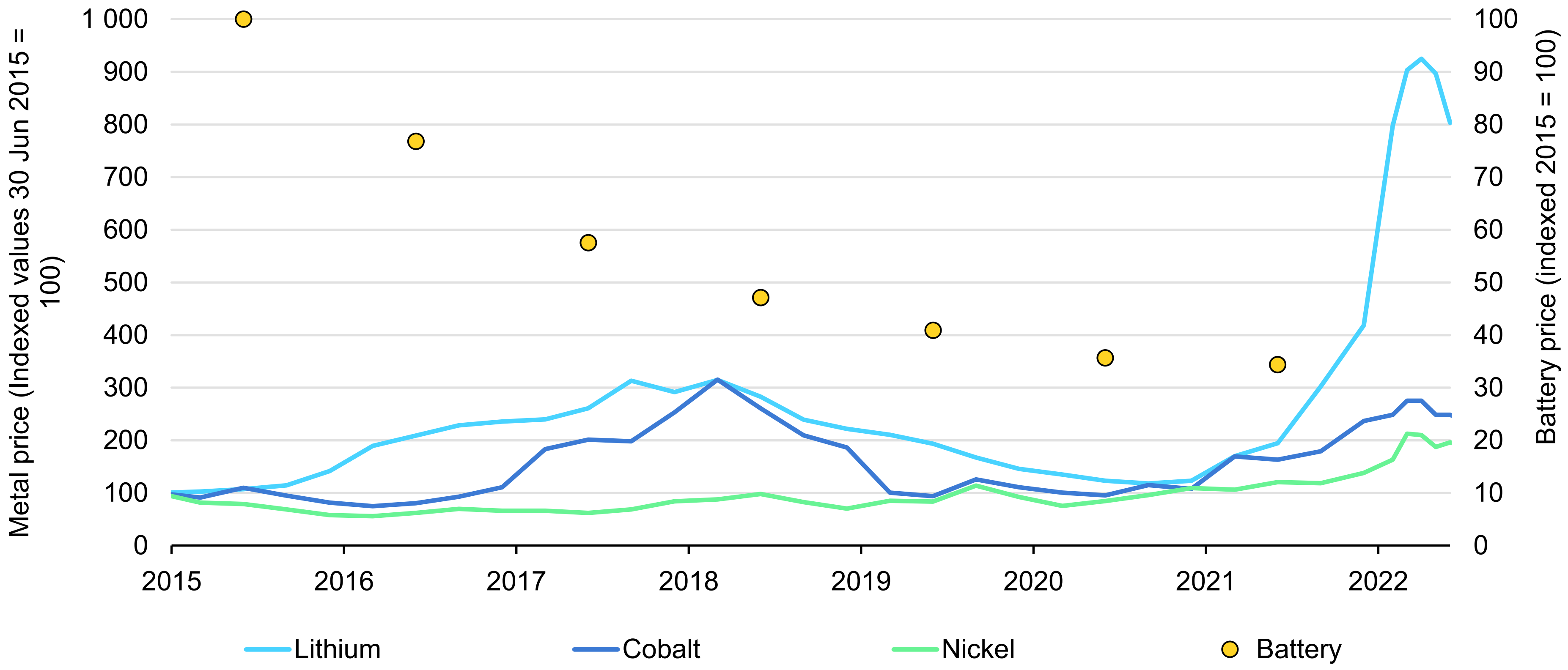
Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of Congo. Geographical breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production capacity data. Cell component production is based on cathode and anode material production capacity data. Battery cell production is based on battery cell production capacity data. EV production is based on EV production data. Although Indonesia produces around 40% of total nickel, little of this is currently used in the EV battery supply chain. The largest Class 1 battery-grade nickel producers are Russia, Canada and Australia.

Sources: IEA analysis based on: EV Volumes; US Geological Survey (2022); Benchmark Mineral Intelligence; Bloomberg NEF.

Battery metal prices increased dramatically in early 2022, posing a significant challenge to the EV industry

Battery metals prices, 2015 – July 2022



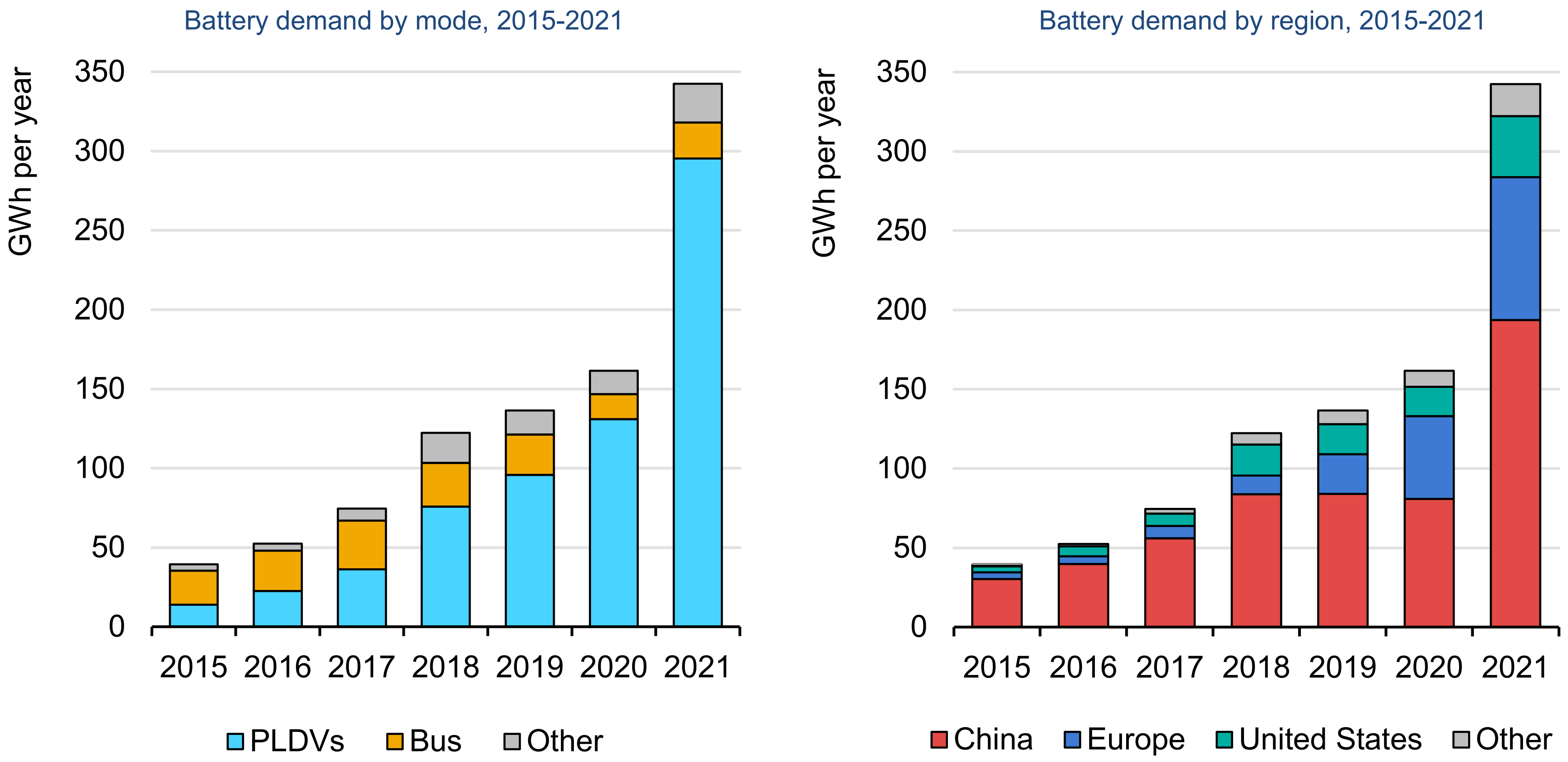
Sources: IEA analysis based on S&P Global

Notes: Lithium prices are from June 2022. Cobalt and Nickel from July 2022

EV batteries and supply chains

Recent developments in batteries and critical materials

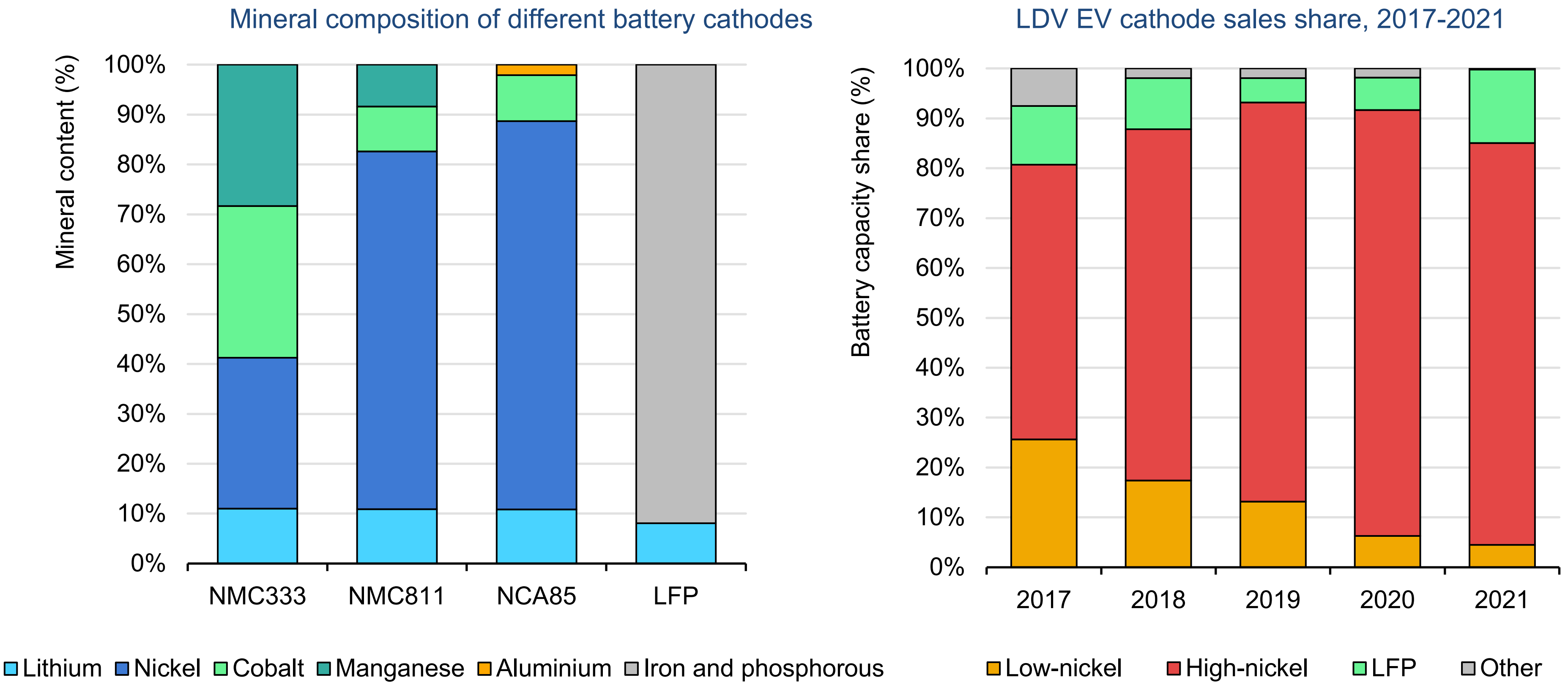
Global battery demand doubled in 2021, driven by electric car sales in China



Notes: GWh = gigawatt-hours; PLDVs = passenger light-duty vehicles; other includes medium- and heavy-duty trucks and two/three-wheelers. This analysis does not include conventional hybrid vehicles.

Sources: IEA analysis based on EV Volumes.

High-nickel cathode battery chemistries remain dominant though lithium iron phosphate is making a comeback



Mineral composition of different battery cathodes

LDV EV cathode sales share, 2017-2021

Notes: LDV = light-duty vehicle; LFP = lithium iron phosphate; NMC = lithium nickel manganese cobalt oxide; NCA = lithium nickel cobalt aluminium oxide. Low-nickel includes: NMC333. High-nickel includes: NMC532, NMC622, NMC721, NMC811, NCA and NMCA. Cathode sales share is based on capacity.
Sources: IEA analysis based on EV Volumes.

Battery demand for EVs doubled in 2021

Automotive lithium-ion (Li-ion) battery demand was 340 gigawatt-hours (GWh) in 2021, more than twice the level of 2020. This increase is driven by the increase in electric passenger cars (registrations increased by 120%). The average battery capacity of battery electric vehicles (BEVs) was 55 kilowatt-hours (kWh) in 2021, down from 56 kWh in 2020, whereas the average capacity increased for plug-in hybrid electric vehicles to 14 kWh in 2021, up from 13 kWh in 2020. Battery demand for other transport modes, including medium- and heavy-duty trucks and two/three-wheelers, increased by 65%. Average battery capacities for BEV light-duty vehicles changed regionally, with increases of more than 10% occurring in Korea and several European countries. [1]

China experienced unprecedented growth and accounted for the largest share of automotive battery demand, with almost 200 GWh of battery demand in 2021, up 140% from 2020. Growth was also impressive in the United States where demand more than doubled in 2021, albeit from a lower base. Europe's demand growth was slightly lower than last year, yet it still increased more than 70%.

The surge in battery demand was met in 2021 due to sufficient battery factory capacity. The nameplate capacity of a factory is the intended full-load sustained output of a facility. Calculated as total demand of EVs, consumer electronics, and stationary storage batteries over the nameplate capacities of all battery plants, the global average utilisation rate for battery factories was 43% of nameplate capacity in 2021, up from 33% in 2020. The low global average utilisation rate is explained by two primary factors. First, there was strategic early investment in battery plant capacity to prepare for projected demand growth. Second, some factories are still ramping up production capacity to reach nameplate capacity, a process that can take from three to six years.

Nickel-based battery chemistries remain dominant

A key defining feature of batteries is their cathode chemistry, which determines both the battery performance and its material demand. For the automotive sector, three broad categories of cathode chemistry are most relevant today: lithium nickel manganese cobalt oxide (NMC); lithium nickel cobalt aluminium oxide (NCA); and lithium iron phosphate (LFP). NMC and NCA cathodes have become increasingly dominant as they offer high energy density based on higher nickel content in the cathode. Higher nickel content, however, requires more complex and controlled production processes. LFP is a lower cost and more stable chemistry, with lower risk of catching fire and a longer cycle life. It typically only has 65 - 75% of the energy

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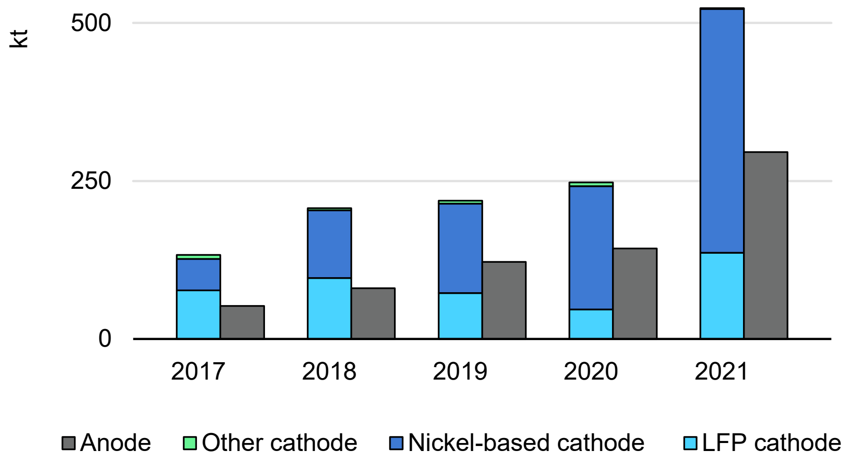
[1] This report is an excerpt from the Global Electric Vehicle Outlook 2022

density compared with a high-nickel NMC such as NMC811, although recent technology innovations have significantly improved their energy density. NCA is used exclusively by Tesla.

Nickel-based chemistries, such as NMC and NCA, were dominant in the electric car battery market in 2021 with 75% of cathode material demand share due to their advantages for driving range. However, there has been a major resurgence of LFP over the last two years, reaching an EV cathode material demand share of 25%, mainly driven by the increased uptake of electric cars in China. LFP is still used for most medium- and heavy-duty vehicle applications due to its superior cycle life, which suits intensive usage and frequent charging, and the fact that most electric medium- and heavy-duty vehicles are in China, where LFP is mainly used. The cost advantages for LFP in China became more apparent recently as subsidies that favoured high-nickel chemistries were phased out.

Cathode and anode demand surged alongside battery demand in 2021. Demand for cathode material reached 520 kilotonnes (kt), more than doubling from 2020. Demand for anode material also doubled to reach 300 kt. The significantly higher material requirement for cathode material is due to the much higher energy densities of the graphite anodes in comparison to leading cathodes, thus requiring less anode material per cell.

Battery cathode and anode material demand



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Notes: kt = kilotonnes; LFP = lithium iron phosphate. Nickel-based cathode includes: lithium nickel manganese cobalt oxide NMC333, NMC532, NMC622, NMC721, NMC811; lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt aluminium oxide (NMCA).
Sources: IEA analysis based on EV Volumes.

Resurgence of LFP

Nickel-based chemistries retained dominance of the market in 2021 with 85% of EV battery demand. However, there has been a major resurgence of LFP battery chemistries over the last two years with 15% of EV battery demand in 2021, doubling from 7% in 2020, primarily driven by increasing uptake of LFP in electric cars in China. LFP demand share in LDVs in China more than doubled from 11% in 2020 to 25% in 2021, despite the lower energy density of LFP than high-nickel chemistries. Given high battery metal prices, LFP has become more attractive as it contains no cobalt or nickel, instead using low cost iron and phosphorous (though remaining exposed to rising lithium prices). LFP relies on lithium carbonate rather than hydroxide used for nickel-rich chemistries.

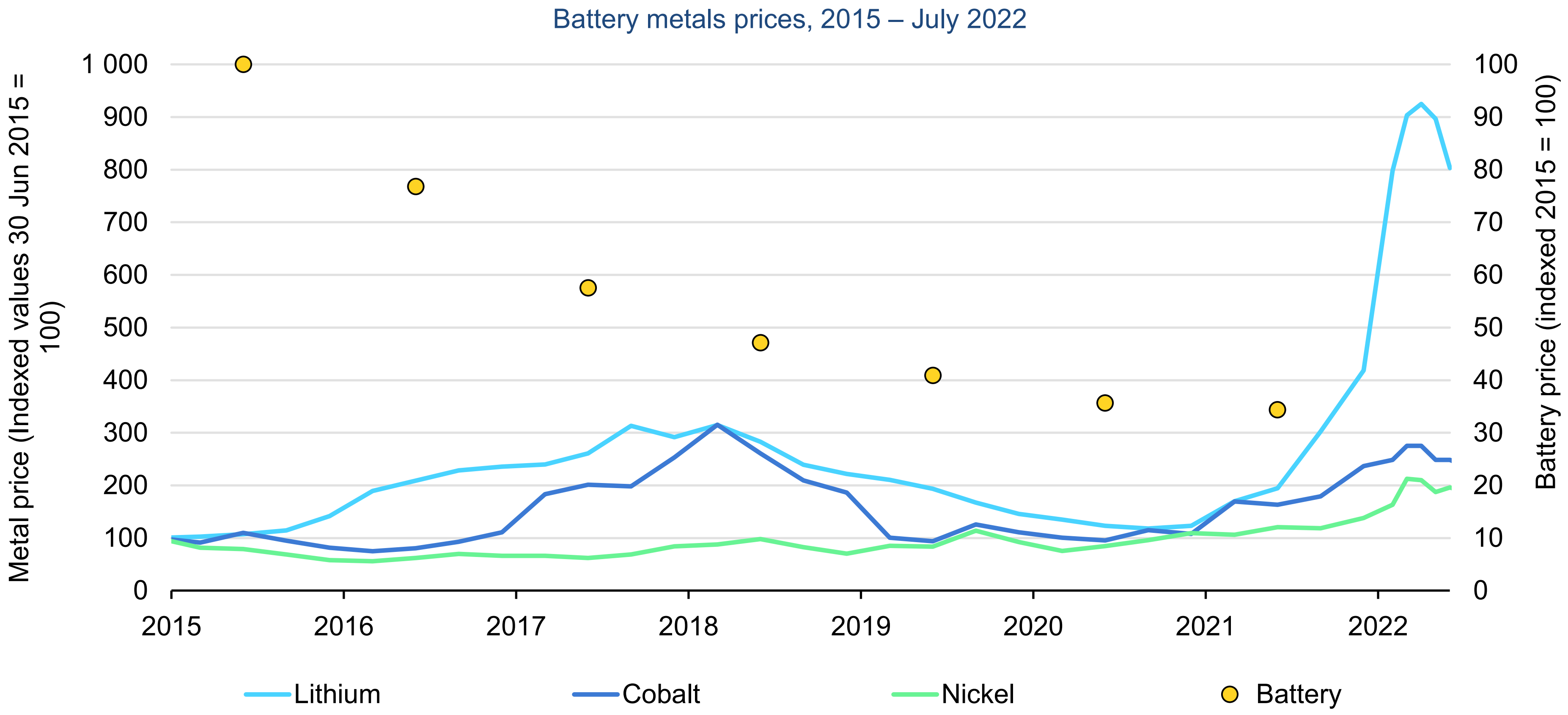
The cost advantages of LFP in a high commodity price market are one reason for the resurgence. Another is the recent innovation of cell-to-pack (CTP) technology, eliminating the need for modules to house cells in the battery pack, thereby reducing the dead weight in the pack and improving the energy density of LFP batteries. CTP technology was pioneered by BYD with the Blade battery and it continues to be improved. CATL released their third-generation CTP battery increasing the LFP pack energy density to around 85% of a conventional NMC811 battery. CTP is also being applied to high-nickel chemistries to further improve their energy density.

LFP production is mostly limited to China – the traditional main hub – for the LFP battery chemistry. One reason for this is LFP patents; the research consortium owning the patents formed an agreement with battery makers in China in which they would not be charged a licence fee for using LFP if only used in China. These patents and licence fees are set to expire in 2022 making production and sales abroad more attractive. Another key reason is the early subsidies in the LFP supply chain in China.

LFP is now set to surge globally. Recently, major non-Chinese EV manufacturers, such as Tesla and Volkswagen, announced moves to LFP chemistries for entry-level high volume EV models. Almost half of all Tesla EVs produced in the first-quarter of 2022 used LFP. LFP battery production is now planned in Europe and the United States to meet anticipated LFP demand for EVs in these regions.

A surge in LFP poses a challenge for battery recycling as it is difficult to make a profit recovering iron and phosphorous. Without valuable metals such as nickel and cobalt, the value that can be recovered from LFP batteries drops considerably from conventional recycling methods and its economic viability is a concern. LFP appears to require direct recycling to be profitable or will require regulatory intervention, frameworks or alternative business models.

Battery metal prices increased dramatically in early 2022, posing a significant challenge to the EV industry



Notes: Lithium prices are from June 2022. Cobalt and Nickel from July 2022

Sources: IEA analysis based on S&P Global

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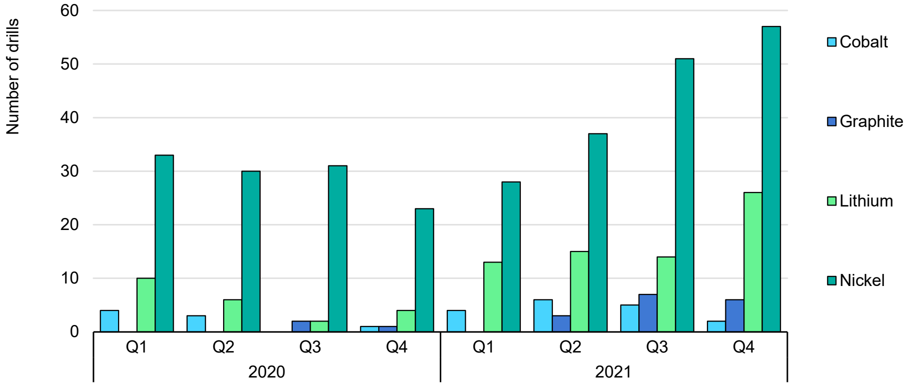
Significant battery metal price increases in 2022 reflect concerns of tightening supply and underinvestment

High battery demand has spurred significant increases in demand for key metals used in their production. Between the start of 2021 and May 2022 lithium prices increased more than sevenfold and cobalt prices more than doubled. Nickel prices almost doubled over the same period reaching levels not seen for almost a decade.

The unprecedented battery metal price rises have been caused by a combination of surging battery demand, increasing pressure on supply chains and concerns around tightening supply. The supply constraints have been driven by three trends: first, production challenges caused by the pandemic; second, concerns around Class 1 nickel supply from Russia; and third, structural underinvestment in new supply capacity during the three years preceding 2021 when metal prices were low. Some producers delayed or even curtailed planned projects and expansions due to low lithium prices. For example, the Australian mining company Galaxy Resources reduced lithium mine production at its most important mine by about 40% in 2019 as did other Australian lithium mining companies. The last time there was a price surge in battery metal prices was for lithium and cobalt in 2017 due to optimistic expectations for growth in battery demand, before prices collapsed in 2018. Lithium has reached unprecedented price levels today being almost 200% higher than its previous peak.

Cobalt prices are also up sharply in recent months, although they are not yet at at the level experienced at its peak. This likely reflects lower demand expectations due to low cobalt chemistries gaining battery market share. Supply issues, such as disruptions in port operations in South Africa caused by the pandemic and civil unrest also contributed to the cobalt price increases.

Quarterly drilling activity by commodity type, 2020-2021



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Sources: IEA analysis based on S&P Global.

In March 2022 the price of nickel reached record levels and experienced highly volatile movement, causing the London Metal Exchange to temporarily close trade for the commodity. This was primarily driven by a short squeeze by market players, but recent concerns about the supply of nickel from Russia due to its invasion of Ukraine has also fuelled price rises. Russia is the world's largest producer of battery-grade (Class 1) nickel.

Price increases are usually followed by expansion in supply with new mines or life extension of existing ones. Drilling activity is an indicator of exploration in the mining sector. Since battery metal commodity prices have begun to rise, so have drill counts (from 2020 to 2021, +50% for nickel and a threefold increase for lithium). High prices may therefore be a long-term benefit for future battery metals supply, stimulating significant supply investment to compensate for the underinvestment during the years of low commodity prices.

Batteries have yet to experience the full impact of commodity price surges

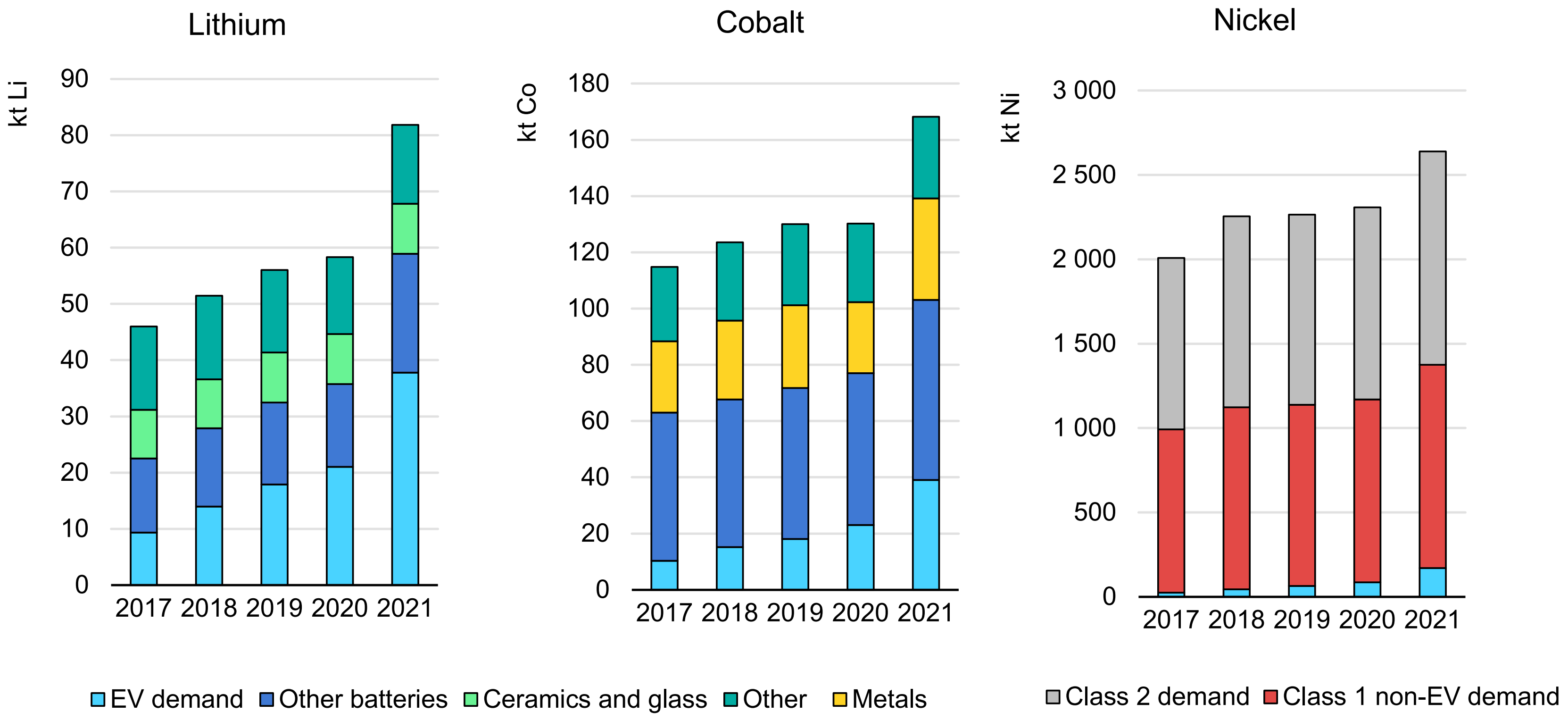
Despite the recent commodity price surge, battery prices still declined in 2021 with BNEF's annual battery price survey recording a sales-weighted average price of USD 132/kWh, a 6% decrease from 2020. Although this represents a significant reduction from the 13% decrease from 2019 to 2020, there are several factors that partially insulated the average battery price from the commodity price rises last year. First, the rising prices incentivised chemistry substitutions. Many automakers switched to lower cost cathode chemistries with less commodity price exposure, such as LFP, which saw a significant increase in adoption, over nickel-rich chemistries. Second, commodity prices were relatively low for the first half of 2021 which helped the average price decline. Third, the use of higher nickel chemistries such as NMC811 reduced the use of cobalt, the most expensive metal constituent in batteries per kilogramme (kg) (cobalt is around 5% of NMC811 cell price based on 2021 average price), also offsetting some costs, particularly in the first half of 2021.

However, a key reason is the impact of rising commodity prices has yet to fully materialise. Automakers increasingly use contracts in which material costs are linked with commodity prices for high volume battery orders, though, there is a time lag. Therefore, these automakers did not feel the result of the exceptional commodity price rises from the last three months of 2021 until the first-quarter of 2022.

If metal prices were to remain at levels experienced in the first three months of 2022 throughout the rest of the year, then we estimate that battery pack prices might increase by up to 15% from the 2021 weighted average price, all else being equal. The impact is likely to be mitigated by OEMs substituting other more cost-effective chemistries, but these price increases nonetheless will pose major challenges for automakers, increasing battery costs, decreasing manufacturer margins and raising costs for consumers.

EV batteries are the main demand driver for lithium demand, but their importance is also rapidly rising for cobalt and nickel

Battery metals demand, 2017 - 2021



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Notes: Class 1 nickel (>99.8%) is suitable for use in batteries and Class 2 nickel (<99.8%) is not applicable for use in batteries without significant further processing. Other batteries includes: batteries for stationary storage and consumer electronics.

Sources: IEA analysis based on EV Volumes and S&P Global.

Critical metal demand and prices are increasingly driven by batteries

The three most critical metals for Li-ion batteries are lithium, cobalt and nickel. All three metals are abundant in the earth's crust, however, supply depends on mine production capacity. The exceptional rise in demand for batteries is now outstripping supply, with new mines not being built fast enough.

Lithium

Lithium demand has almost doubled since 2017 to 80 kt in 2021, of which demand for EV batteries accounts for 47%, up from 36% in 2020 and only 20% in 2017. Lithium is also used in the production of ceramics, glass and lubricants. Batteries are now the dominant driver of demand for lithium and therefore set the price. The availability of lithium supply is of particular concern because it is irreplaceable for Li-ion batteries and there are no commercial alternative battery chemistries available at scale today that meet the performance of Li-ion batteries. Alternative lithium-free chemistries, however, are making progress, for instance, with Na-ion being commercially introduced by CATL in 2021.

Cobalt

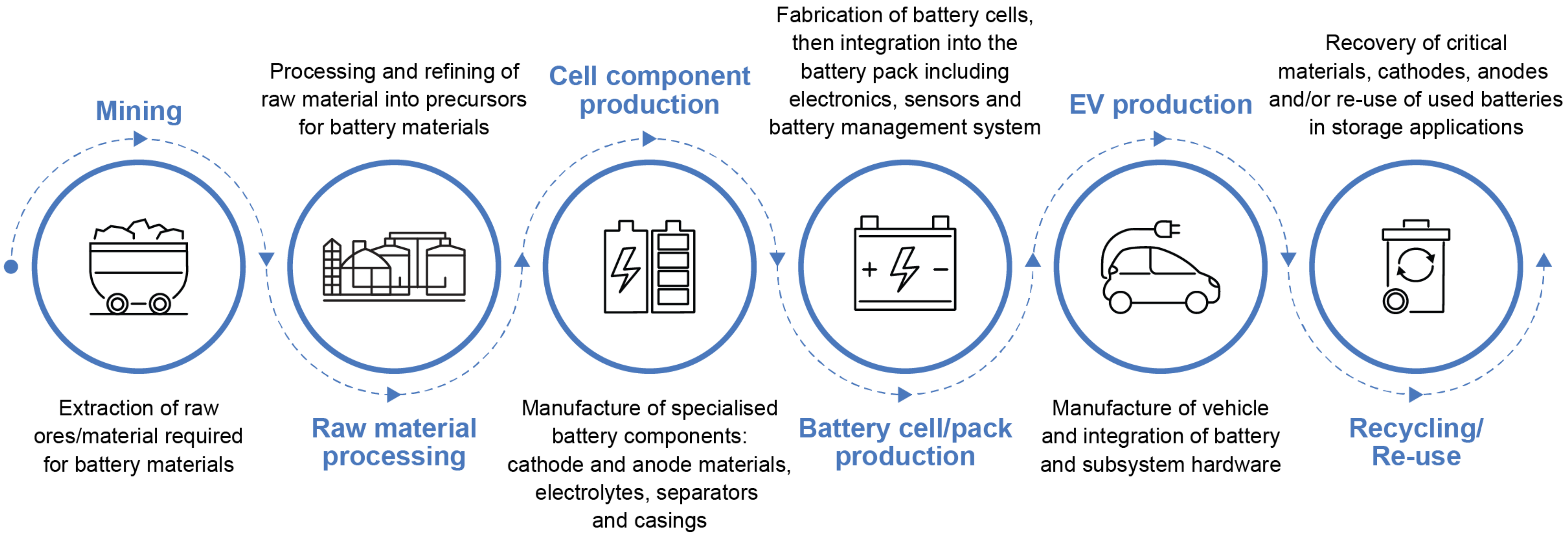
Cobalt demand was 170 kt in 2021, of which the EV battery share was 24%, up from 18% in 2020. Cobalt is also used in superalloys, hard metals and catalysts. The cobalt intensity of Li-ion batteries has decreased significantly over recent years as battery makers moved to higher nickel content chemistries to achieve higher energy densities and lower costs (cobalt is the most expensive constituent per kg of Li-ion battery metal). The additional concerns of human rights abuses and child labour related to cobalt mining in the Democratic Republic of Congo (DRC) have also motivated battery makers to move away from cobalt-intensive chemistries.

Nickel

Nickel demand is dominated by stainless steel production. Total demand was 2 640 kt in 2021, of which the share of EV-related demand was 7%, up from 4% in 2020. Batteries require Class 1 nickel (>99.8% purity), while Class 2 nickel (<99.8% purity) cannot be used without further significant processing. Nickel-based cathodes are the dominant EV battery chemistries today and are expected to remain so in the future due to the demand for longer driving range EVs particularly in Europe and the United States. There is almost seven times more nickel than lithium by weight in an NMC811 battery, therefore, EV Li-ion battery prices are most sensitive to nickel prices. This is of significant current concern given the war in Ukraine because Russia is the world's largest supplier of Class 1 battery-grade nickel, producing around 20% of global supply.

Making batteries for EVs requires several stages

EV battery supply chain



Mining

Extraction of raw ores/material required for battery materials

Raw material processing

Processing and refining of raw material into precursors for battery materials

Cell component production

Manufacture of specialised battery components: cathode and anode materials, electrolytes, separators and casings

Battery cell/pack production

Fabrication of battery cells, then integration into the battery pack including electronics, sensors and battery management system

EV production

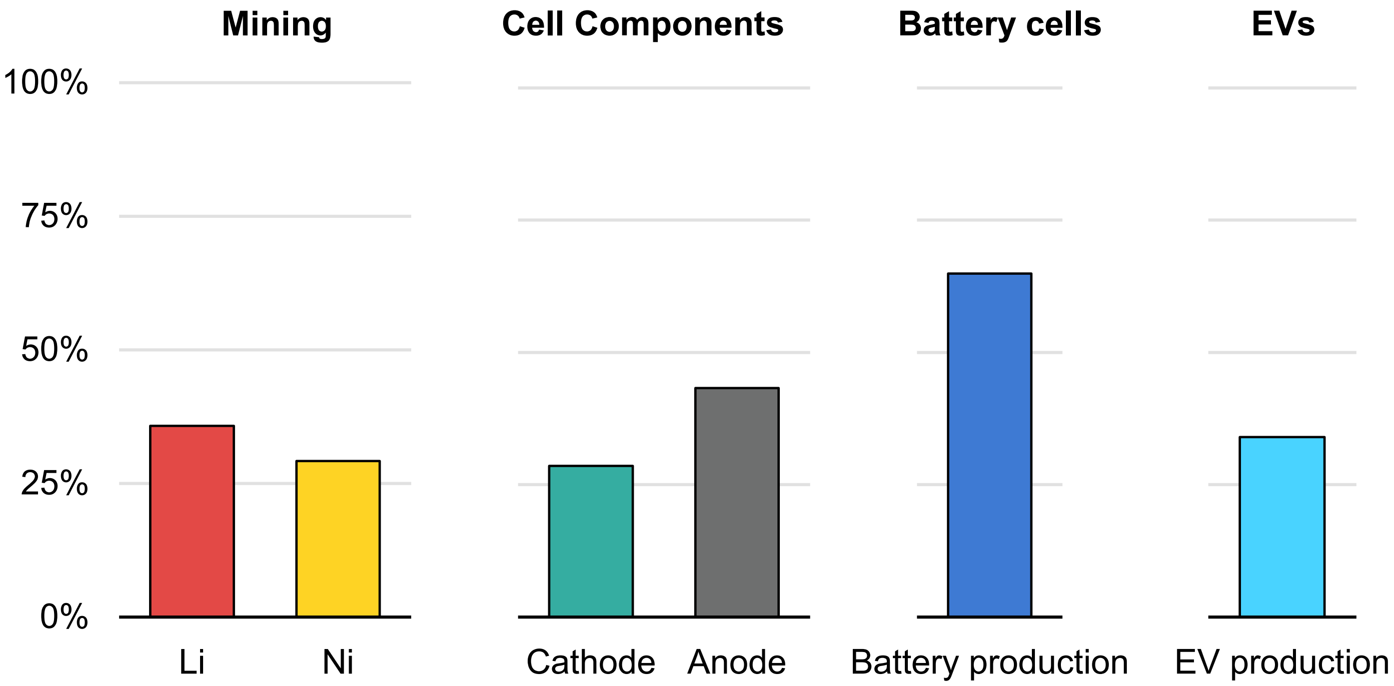
Manufacture of vehicle and integration of battery and subsystem hardware

Recycling/ Re-use

Recovery of critical materials, cathodes, anodes and/or re-use of used batteries in storage applications

Production in all stages of the EV battery supply chain is concentrated in few companies

Share of total production of top-three companies at each stage of the EV battery supply chain, 2021



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Notes: The figure shows production percentages of top-three companies for 2021: EV production by sales; battery production by MWh produced; cathode and anode by production capacity; mining by production capacity. Top-three companies by production (country where headquartered): *lithium* - Sociedad Química y Minera de Chile (Chile); Pilbara Minerals (Australia); Allkem (Australia); *nickel* - Jinchuan Group (China); BHP Group (Australia); Vale SA (Brazil); *cathode* - Sumitomo (Japan); Tianjin B&M Science and Technology (China); Shenzhen Dynanonic (China); *anode* - Ningbo Shanshan (China); BTR New Energy Materials (China); Shanghai Putailai New Energy Technology (China); *battery production* - CATL (China); LG Energy Solution (Korea); Panasonic (Japan); *EV production* - Tesla (United States); VW Group (Germany); and BYD (China).

Sources: IEA analysis based on Benchmark Mineral Intelligence; Bloomberg NEF; S&P Global.

EV battery supply chains

EV battery supply chains consist of multiple complex stages that are spread around the world. From extracting the necessary mineral ores, refining to form sufficient purity chemicals, then advanced materials synthesis to form cathode and anode materials. Similar complex supply chains characterise other battery components such as electrolytes and separators. Cells are then fabricated and housed in modules within a battery pack which is integrated into the EV. To understand current trends and future prospects of EVs, it is critical to understand all of the stages in this complex supply chain.

Mining

The five key battery materials are lithium, nickel, cobalt, graphite and manganese.[2] Lithium is extracted from two very different sources: brine or hard rock. Lithium brines are concentrated salt water containing high lithium contents and are typically located in the high elevation areas of Bolivia, Argentina and Chile in South America with Chile being the largest producer. Brine deposits often contain large quantities of other useful elements such as sodium, potassium, magnesium and boron which offsets some of the cost of pumping and processing brine. Lithium hard rock (spodumene) is primarily mined in Australia. Novel processes are being developed to extract lithium from unconventional resources such as geothermal brine. Currently, the top-five lithium suppliers account for about half of global lithium production. Major lithium suppliers include a mixture of large chemical and mining companies including: Sociedad Química y Minera de Chile SA (Chile); Pilbara Minerals (Australia); Allkem (Australia); Livent Corporation (United States); and Ganfeng Lithium Co. (China). Unlike for other battery metals, lithium extraction companies tend to be specialised in lithium mining and chemical companies.

Nickel is found primarily in two types of deposit – sulphide and laterite. Sulphide deposits are mainly located in Russia, Canada and Australia and tend to contain higher grade nickel. It is more easily processed into Class 1 battery-grade nickel. Laterite, however, tends to contain lower grade nickel and is mainly found in Indonesia, Philippines and New Caledonia. Laterite requires additional energy intensive processing to become battery-grade nickel. Nickel production is less concentrated than lithium with about nine companies supplying half of global nickel production. Key nickel

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[2] The battery metals focused on for this analysis are lithium, nickel and cobalt. For analysis of other critical minerals, see IEA's The Role of Critical Minerals in Clean Energy Transitions report.

suppliers include: Jinchuan Group (China); BHP Group (Australia); Vale SA (Brazil); Tsingshan (China); Nickel Asia Corporation (Philippines); and Glencore (Switzerland).

Cobalt is predominantly mined as a by-product of copper or nickel mining. Over 70% of cobalt is produced in the Democratic Republic of Congo (DRC) and Glencore (Switzerland) is the largest global producer. Other key cobalt suppliers include: Jinchuan Group (China); CN Molybdenum (China); and Chemaf (DRC). Artisanal and small-scale mining is responsible for 10 – 20% of cobalt production in the DRC.

Graphite is the dominant anode material and can be found naturally or produced synthetically. Natural graphite mining is dominated by China (80%), though global production is becoming more diversified, with many greenfield graphite mining projects being developed including in Tanzania, Mozambique, Canada and Madagascar.

Manganese resources are more widely distributed around the world than the other battery metals and remain available at relatively low cost. There is a general expectation that there will not be an ore shortage in the near term. The leading producers of manganese ore include South Africa, Australia, Gabon and China.

Raw material processing

Batteries require high purity materials and therefore high-grade sources, as well as significant refining, is required to reach sufficient quality battery chemical precursors. These refining processes typically involve heavy industrial processes based on heat or chemical treatment (typically pyrometallurgy and/or hydrometallurgy) to refine the raw ore into the usual required chemicals, lithium carbonate or hydroxide, or cobalt and nickel sulphate. Adding complexity, certain raw materials are more or only suitable for the production of battery precursors. For instance, lithium carbonate is produced from lithium brine, which is useful for wider lithium demand, however, unsuitable for use in leading high-nickel Li-ion batteries. Lithium hydroxide is more suitable for high-nickel chemistries and is more easily produced from spodumene hard rock sources. Similarly, battery production typically requires nickel sulphate, typically only synthesised from Class 1 nickel, which is most economically produced from nickel sulphides. Class 2 nickel can be processed into Class 1 nickel but requires significant additional processing.

New processing technologies, however, are increasing the flexibility of nickel processing routes. These include:

- High-pressure acid leaching (HPAL) is a process which is able to produce Class 1 nickel from lower grade laterite resources.
- Mixed hydroxide precipitate (MHP), an intermediate product in nickel refining, can be further be refined into nickel sulphates at low cost from laterite resources.
- Nickel matte (a battery-grade nickel precursor) can be produced from laterite resources, but is more emissions-intensive than conventional production routes.

Raw material processing is highly concentrated. For example, in lithium carbonate and hydroxide production, five major companies are responsible for three-quarters of global production capacity. Often the refining is done by the mining company together with the extraction. For example, Ganfeng, a Chinese mining company, has evolved to include processing and refining lithium and is increasingly focussed on boosting their lithium hydroxide production. In other cases, it is exported to third parties to do the refining, with many processing companies in China, such as Chengxin Lithium Group or Zhejiang Huayou Cobalt. This is particularly the case for Australian spodumene as almost no miners yet produce integrated lithium chemical supply.

While manganese resources are widely distributed, production of high-purity manganese sulphate raises concerns around geographical concentration of supply. China currently accounts for around 90% of the global production capacity, raising the need for new, diversified manganese refining capacity. New manganese sulphate projects are starting to come online in Australia, Europe, Indonesia and United States.

Cell component production

Batteries are comprised of several highly specialised components including cathode and anode materials, electrolytes and separators. These components require advanced materials chemistry and engineering for their production. The most complex processing is required to form the battery active materials from the high purity chemicals produced from raw material processing, such as lithium hydroxide and nickel sulphate. These materials are further processed using specialised syntheses to produce active materials for the cathode and anode. The leading cathode active materials for Li-ion are transition metal oxides including lithium cobalt oxide, lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP). Seven companies are responsible for 55% of global cathode material production capacity. Key players include: Sumitomo (Japan); Tianjin B&M Science and Technology (China); Shenzhen Dynanonic (China); and Ningbo Shanshan (China).

The dominant anode active material is graphite which can be natural or synthetic. Producing graphite anode materials is more mature and established than cathode material production given graphite has been the dominant anode for a long time, though both graphite types require sophisticated processing. Flake natural graphite is used in batteries and is processed into spherical graphite to be more homogenous for use as anode material. Synthetic graphite is produced from refining hydrocarbon materials such as coke. To improve graphite anode performance, small and increasing fractions of silicon are being added to the graphite anode to increase energy density. Anode material production is even more highly concentrated with four companies responsible for half of global production capacity. The largest players include: Ningbo Shanshan (China);

BTR New Energy Materials (China); and Shanghai Putailai New Energy Technology (China). The top-six companies are all Chinese and account for two-thirds of global production capacity.

Separators are engineered microporous membranes, typically made of polyethylene or polypropylene and often ceramic coated for improved safety for EVs. Separator production is also concentrated with five companies responsible for half of the global production capacity. Key players include: Zhuhai Enjie New Material Technology (China); Shanghai Putailai New Energy Technology (China); and SK IE Technology (Korea). Electrolytes are made of a salt and solvent and both require synthesis and then mixing. Jiangxi Tinci Central Advanced Materials in China alone produces 35% of global electrolyte salt. The top electrolyte producing companies include: Zhangjiagang Guotai-Huarong New Chemical Materials (China); Shenzhen Capchem Technology (China); and Ningbo Shanshan (China). Most companies that engage in cell component manufacturing are highly specialised and only produce those components.

Battery cell and pack production

Producing the battery cells is a multi-step process with two broad stages: electrode manufacturing and cell fabrication. Though cell manufacturers have different cells designs, the cell manufacturing processes are similar, use mature technologies and are well established. These processes are energy intensive, being conducted in highly controlled clean and dry room conditions to avoid any impurities and moisture. Using low-carbon sources of electricity is key to reducing emissions in cell production. First electrodes are produced by mixing cathode or anode active materials with a binder, solvent and additives before coating on aluminium (cathode) or copper (anode) foil current collectors. The electrodes are rolled (calendared) and subsequently dried. The cell is then created by stacking the electrodes with a separator in between.

Manufacture of the battery pack may be completed either by the cell manufacturer or by the automaker. Cells are first housed together in module frames, then the battery pack is assembled through integration of modules, the battery management system, electronics and sensors, all encased in a final housing structure.

Battery cell production is a capital-intensive process and production is highly concentrated, with the top-three producers in 2021, CATL (China), LG Energy Solution (Korea), and Panasonic (Japan), accounting for 65% of global production. Cell manufacturers from Japan and Korea tend to be established conglomerates having decades of experience making batteries for consumer electronics. There are also Chinese companies that began producing batteries for consumer electronics in the 1990s and then specialised in batteries for EVs such as CATL and BYD. A third wave of new battery makers is taking shape in Europe and North America, but today they are mostly in planning or upscaling stages. With recent supply chain strains many battery and automakers are becoming increasingly involved in the mining and processing of critical minerals to ensure access to production; Tesla, CATL and LG Energy Solution have all become directly involved in upstream stages.

EV production

The battery pack is integrated into the EV by the automakers, where it is connected with the electric motor, on-board charge module, high voltage distribution box, electric transmission and thermal systems, depending on the vehicle architecture. Automakers focussing only on EVs must develop greenfield factories, while for incumbent automakers pre-existing vehicle assembly factories can be retooled and repurposed for EV production. EV manufacturing is currently concentrated in a small number of OEMs, with the top-six companies responsible for 52% of production in 2021. This is a slight decrease from 2020 where the top-six were responsible for 55%. The three largest producers, Tesla (United States), VW Group (Germany) and BYD (China), accounted for a third of EV production in 2021. The rapid growth of BYD has been particularly impressive, it was not even among the top-six producers in 2020, but ranked as the third-largest producer of EVs in 2021.

Re-use

Re-use or repurposing involves refurbishing EV batteries for less demanding second-life applications, typically in stationary storage. Spent EV batteries typically still have around 80% of their usable capacity, therefore, repurposing generates additional value from these batteries. Re-use requires disassembly of the pack, testing of the module/cells, and repackaging into new packs for new applications. The primary drivers of cost of refurbishing batteries are the logistics involved in their collection, testing of remaining useful life, and the physical disassembly and repacking of cells/packs. Re-use, however, faces economic and regulatory challenges including ensuring reliable grading of cells/packs, liability and ensuring the cost of repurposing is competitive with new batteries.

Recycling

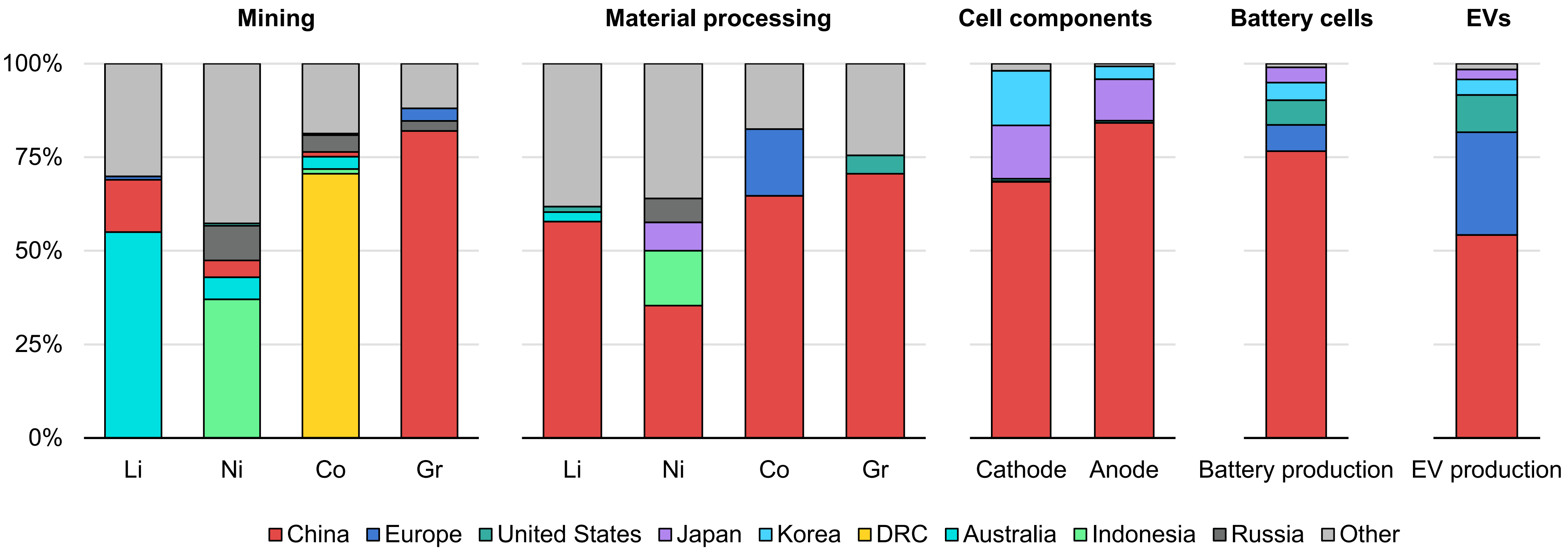
There are three primary methods for Li-ion battery recycling: pyrometallurgy, hydrometallurgy and direct recycling. Pyrometallurgy involves smelting the battery in a high temperature oven, recovering only a fraction of metals from the cathode. Hydrometallurgy involves a chemical leaching process to precipitate out individual metals. Currently, most battery recycling uses a combination of pyrometallurgy and hydrometallurgy as they are well suited to a poorly sorted feedstock of cells. These methods rely on reclaiming the expensive metals specifically nickel and cobalt, and often the copper and aluminium. Current global capacity for battery recycling is around 200 kt/year with China accounting for about half. This dominant position is expected to be retained due to announced additional capacity. Most battery recycling companies are independent recyclers, but OEMs, battery manufacturers, miners and processors are starting to enter the market.

Direct recycling is an emerging process, offering improved recycling efficiency, as it does not break down the cathode into elements, but instead retains the material crystal structure and regenerates the cathode material. This retains the embedded energy and economic value in cathode processing, avoiding the need to resynthesise from raw materials. It is well suited to cathodes containing little valuable metals such as LFP. However, it is limited by its inflexibility as it must be tailored to each cathode chemistry, and recovered cathodes can only be input into production of the same battery type. Though, new processing methods are under development to convert recycled chemistries into current chemistries e.g., NMC333 to NMC811.

Policy mandates, for instance, extended producer responsibility for battery recycling, are spurring the formation of joint ventures among OEMs, re-use and recycling companies. For instance, SK Innovation and Kia are developing both re-use and recycling initiatives; Kia evaluates used batteries and repackages ones suitable for re-use in stationary storage and the rest are sent to SK Innovation's recycling process for material recovery. Renault, Veolia and Solvay have formed a consortium for the same purpose. BMW, Umicore and Northvolt have also formed a consortium to create a closed-loop for battery cells, involving both re-use and recycling.

China dominates the entire downstream EV battery supply chain

Geographical distribution of the global EV battery supply chain



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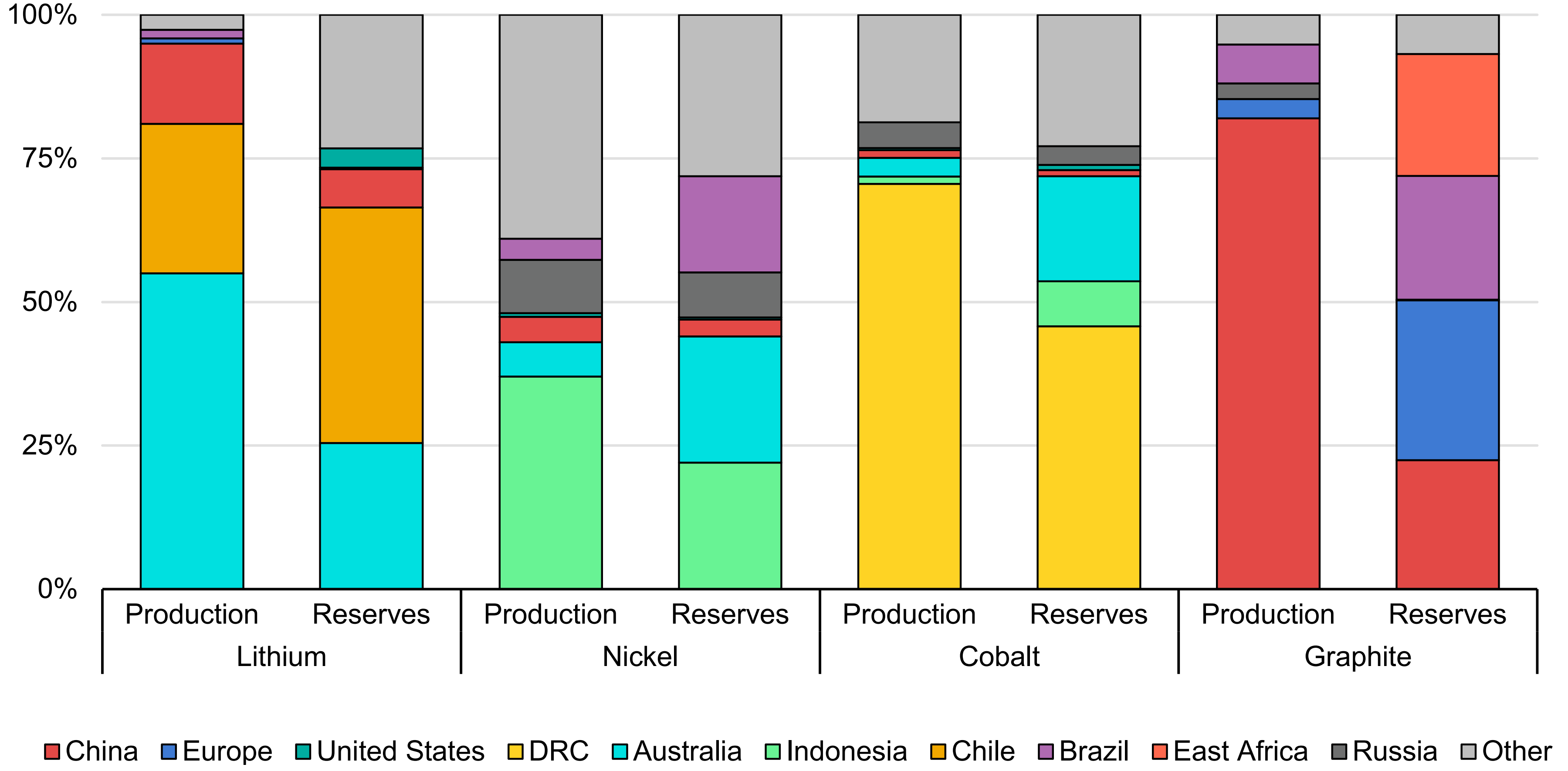
Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of Congo. Geographical breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production capacity data. Cell component production is based on cathode and anode material production capacity data. Battery cell production is based on battery cell production capacity data. EV production is based on EV production data. Although Indonesia produces around 40% of total nickel, little of this is currently used in the EV battery supply chain. The largest Class 1 battery-grade nickel producers are Russia, Canada and Australia.

Sources: IEA analysis based on: EV Volumes; US Geological Survey (2022); Benchmark Mineral Intelligence; Bloomberg NEF.

There are areas of unrealised potential for diversifying battery metal extraction

Current mining production versus reserves for battery materials



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Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of Congo. Reserves refer to economically extractable resource as defined and determined by the US Geological Survey.
Sources: IEA analysis based on US Geological Survey (2022).

China dominates the entire downstream EV battery supply chain, but investments are underway worldwide

China dominates production at every stage of the EV battery supply chain downstream of mining. Three-quarters of battery cell production capacity is in China, with the same for the specialised cathode and anode material production, for which China accounts for 70% of cathode and 85% of anode material global production capacity. Over half of global raw material processing for lithium, cobalt and graphite also occurs in China. With 80% of global graphite mining, China dominates the entire graphite anode supply chain end-to-end. Europe is responsible for over a quarter of EV production, but holds very little of the rest of the supply chain apart from cobalt processing at 20%, mostly plants in Finland. The United States has a smaller role in the global EV battery supply chain, with only 10% of EV production and 7% of battery production capacity. Both Korea and Japan have considerable shares of the supply chain downstream of raw material processing, particularly in cathode and anode material production. Korea is responsible for 15% of cathode, and 3% of anode material production capacity while Japan accounts for 14% and 11%, respectively.

In terms of raw material supply and extraction, battery metals are highly concentrated geographically and thus are relatively more vulnerable to supply shocks and constraints. More than half of the world's lithium is produced in Australia while 70% of the world's cobalt is produced in the DRC. Nickel supply is slightly more diverse; Indonesia has the largest share of production with almost 40% of total nickel supply, yet today little of it is used in the EV battery supply chain as it mostly produces Class 2 nickel. Not only is Russia the world's third-largest producer of nickel, more significantly, it is the world's largest producer of Class 1 battery-grade nickel with around 20% of the global supply.

The geographical distribution of mineral extraction is unlikely to shift significantly in the near term given today's project pipeline. However, when comparing current mining production to mineral reserves (reserves refer to the resources which could be economically extracted at the time of determination), there appears to be significant unrealised potential for diversification of extraction in the longer term. In particular, Australia, already the largest lithium producer, holds the joint largest reserves of nickel, alongside Indonesia, with 22% of global reserves. However, Australia is producing only 6% of current global production. Australia also has the second-largest reserves of cobalt with almost 20%, while accounting for a mere 3% of current production.

There is also significant potential to diversify natural graphite production with Europe holding the world's largest share with over a quarter of global reserves, primarily in Turkey. Brazil has significant potential for graphite and nickel, with 22% and 17% of global reserves, respectively. Nevertheless, there are several caveats which must be considered with reserves such as resource quality, particularly important for battery metals, investment and above-ground constraints which may limit potential as a reliable source of future supply.

There is a need for updated and improved geological surveys in emerging market and developing economies. Resource surveys in many low income countries were conducted long ago when battery metals were not in focus. An example is the East African Nickel Belt where the US Geological Survey indicates limited Africa nickel reserve numbers. However, in 2021, BHP struck a deal to invest USD 100 million in the Kabanga Nickel project in Tanzania, reporting it as one of the world's largest nickel sulphide deposits. Similarly, Bolivia has abundant identified lithium resources, yet no reported reserves. This highlights the potential that updated geological surveys can bring in today's market context.

On the other hand, the downstream supply chain distribution is set to change this decade, particularly for batteries. If current policies, announcements and investments are realised, by the end of this decade a quarter of battery production capacity will be located in Europe and the United States. Similarly, there have been recent announcements related to cathode materials production in Europe and the United States. For example, Volkswagen announced a new partnership with Umicore that aims to build cathode material production capacity in Europe. Redwood Materials and L&F aim to build a US factory producing cathode material for 5 million EVs per year by 2030, with similar plans for Europe. Northvolt, the European cell manufacturer, intends to produce over 100 GWh per year of its own cathode material.

Anode material production is likely to continue to be dominated by China as it holds the entire supply chain from mining through to anode material production. In addition, almost all of the top-ten anode material production companies are Chinese, which makes new anode production overseas largely dependent on foreign investment by these companies. Moreover, graphite anode material prices are not high enough to significantly incentivise new production capacity. Although there are exceptions, such as Nouveau Monde Graphite which is constructing both a graphite mine and graphite anode active material plant in Canada.

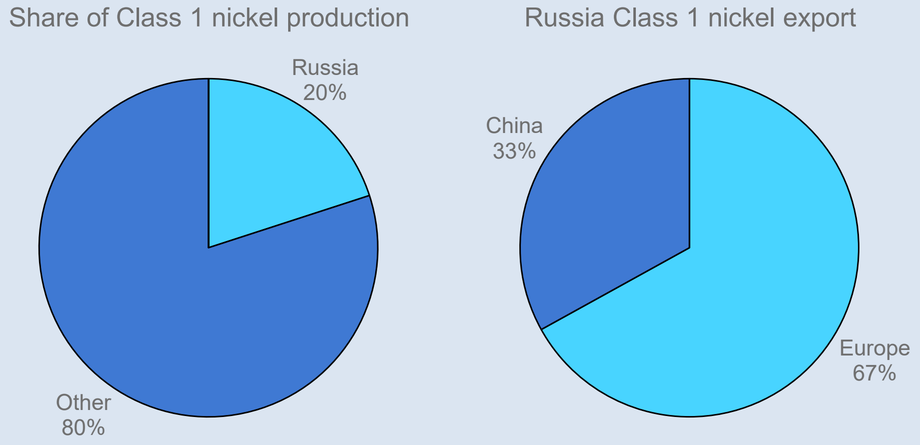
Impact of Russia's invasion of Ukraine on battery supply chains

Lithium, cobalt and graphite supply chains are less affected by the supply disruption caused by Russia's invasion of Ukraine as relatively little supply and processing is from either country. However, there is concern regarding nickel; Russia is the third-largest producer, supplying about 9% and processing about 6% of global nickel in 2021. Though, more critically, Russia is the world's largest Class 1 nickel supplier, producing about 20% of the world's Class 1 battery-grade nickel, most of which is supplied by Norilsk Nickel.

Recent concerns for the supply of nickel from Russia, coupled with financial speculation by the founder of Tsingshan, a major Chinese steel producer, pushed nickel prices to an unprecedented level of USD 100 000 per tonne (the average price in 2021 was USD 18 500 per tonne), resulting in the London Metal Exchange temporarily closing nickel trade. Much of the exceptional price rise was due to a short squeeze, however, there was an underlying increase in price driven by Russian supply concerns in an already tight supply market. Trading resumed and the nickel price stabilised at around USD 33 000 per tonne, still exceptionally high. Nevertheless, significant concerns for nickel supply from Russia remain, which will likely keep prices high.

Nickel supply from Russia is a key source for the developing EV battery supply chain in Europe. BASF (Germany) is building a major cathode material precursor plant in Finland and already has a long-term nickel supply agreement with Norilsk Nickel. It is possible that Australia and Canada could fill the gap of supply from Russia for nickel sulphate in Europe, as well as Indonesia once HPAL projects are operational, though Europe will also be competing with North American demand.

Class 1 nickel production, 2021



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Sources: IEA analysis based on Benchmark Mineral Intelligence and Bloomberg NEF .

EV battery supply chains and industrial policy

Governments aim to support integrated supply chains for EV manufacturing

Many countries have announced industrial strategies that aim to create and expand their prominence and within integrated supply chains. Major automotive manufacturing countries aim to extend their reach up the supply chain from making EV components and automobiles, to also securing stable upstream supply and refining capacity of minerals and metals

Some countries have identified battery and EV manufacturing to be strategic sectors and look to support domestic production. Some explicitly target investment in the sector to "future proof" economies, build a workforce to underpin a low-carbon future and secure a position to be a market leader in the high value-added steps in the burgeoning EV market.

China's rise to the largest share of global EV battery production capacity in the world (77%) is a direct result of over a decade of government policies that support the industry. Korea, which accounts for 5% of global production capacity, along with Japan, at 4%, have recently launched large funding packages to bolster the competitiveness of their battery and EV industries.

While the European Union has been investing significantly over the last few years in R&D and manufacturing capacity, it will likely take time to develop the supply chains needed for an EU battery production industry. Similarly, the United States recently renewed its focus on building domestic battery and EV supply chains, particularly leveraging its critical minerals supply and automotive sectors.

Other new entrants such as Indonesia and Thailand are putting a strategic focus on battery and EV production. They aim to become regional market leaders by leveraging their geographic proximity to Asian market leaders as well as upstream mineral and metal supplies. Indonesia and Thailand are attracting investments from major battery and EV manufacturers such as Great Wall Motors, Foxconn, LG Group and CATL.

Canada

- Share of global EV battery production capacity: 0%.
- EV battery production capacity in 2021: 0 GWh.

In April 2022, the federal government and provincial government of Ontario announced a CAD 518 million (USD 398 million) package to supplement General Motor of Canada's existing CAD 2.3 billion (USD 1.8 billion) investment in upgrading facilities in Ontario, which includes retooling facilities to produce EVs. In addition, Ontario received its largest automotive industry investment in history of CAD 5 billion (USD 4 billion) with a joint venture between LG Energy Solution Ltd. and Stellantis N.V. to produce EV batteries with a production capacity of 45 GWh. The governments worked closely to foster this investment, such as providing favourable electricity prices and provincial and federal subsidies (which are being negotiated).

China

- Share of global EV battery production capacity: 76%.
- EV battery production capacity in 2021: 655 GWh.

China's leading role in EV battery production capacity is a direct result of more than a decade of policies that prioritise the development of an integrated domestic supply chain. China has long viewed batteries as a strategic industrial sector.

Released in mid-2021, China's 14th Five-Year Plan (2021-2025) focusses on "strategic emerging industries", which includes new energy vehicles (NEVs). It provides guidance for state and local governments to develop plans, including a focus on higher quality and standards for NEV manufacturing, as well as focussed R&D efforts for next-generation battery chemistries. Of particular note, are plans to promote the development of the Na-ion battery industry during the 2021-25 period, using industry and product standards to achieve scale, lower cost and improved battery performance. Regional five-year plans (e.g. Beijing, Shanghai, Guangdong, Tianjin, Jiangsu, Fujian and Shaanxi) focus on integrating NEV production with related industies (i.e., battery manufacturing and recycling systems) in collaboration with large industrial EV car, component and battery manufacturers. They aim to bolster NEV production in industrial development zones through incentives such as tax exemptions, preferable loans and co-financing, and to develop industrial production bases.

Also released in mid-2021, China's 14th Five-Year Plan for Circular Economy Development (2021-2025) aims to standardise management of resources from the battery recycling industry, as well as to introduce both NEV battery traceability and battery recycling traceability management systems. Administrative measures for the re-use of NEV batteries released in August 2021 aim to standardise and further develop the industry by requiring battery re-use enterprises to be responsible for managing the whole life cycle of re-used product design and production, packaging, transportation and recycling of the batteries, ensure product quality, product certification and environmentally responsible disposal.

The Ministry of Industry and Information Technology in November 2021 released two draft guidelines for comment on the development of the Li-ion battery industry in order to strengthen management of the sector. The guidelines propose plant expansions to only occur if production can be assured to exceed 50% of capacity, technical standards on minimum energy density (no less than 180 Watt-hours per kilogramme), cycle life and the encouragement of the use of solar power in the manufacturing process. In January 2022, technical specifications for pollution control and treatment for waste Li-ion batteries was implemented (for a trial period).

European Union

- Share of global EV battery production capacity: 7%.
- EV battery production capacity in 2021: 60 GWh.

The European Union has a strategic focus on the development of domestic battery supply chains.

In March 2022, the European Battery Alliance and the US Li-Bridge Alliance announced a collaboration to accelerate the development of Li-ion and next-generation batteries, including critical raw materials.

The Important Projects of Common European Interest (IPCEI) is a key strategic instrument with regard to the implementation of the European Union Industrial Strategy. **A two-part IPCEI has been implemented to promote battery production: the IPCEI on Batteries and the IPCEI European Battery Innovation (EuBatIn). Both have in common that their participants represent the complete value chain, from material through the cells to the battery system and recycling. There is also a high degree of networking between the companies and the two IPCEIs.** The Batteries IPCEI, established in 2019, brings together companies headquartered in seven EU member states from various parts of the battery value chain. The EuBatIn, established in 2021, brings together 12 EU member states and 40 companies to focus on battery supply chains and has secured funding for EUR 2.9 billion (USD 3.4 billion) for the period to 2031.

The European Commission proposed revisions to the EU Battery Directive to elevate it to a regulation as part of actions taken for the Green New Deal in late 2020. They introduce mandatory carbon footprint declarations for batteries sold in Europe, along with minimum requirements for recycled content and requirements for collection and recycling of automotive EV batteries. As of March 2022, the latest update indicates the European Parliament has reached a consensus on the proposed revisions with a few amendments. Of note, this includes the addition of a new battery category, “light means of transport” (e.g. electric bicycles) and minimum targets for recovered cobalt, lead, lithium or nickel from waste. The proposals are to be discussed with the member states in the Council of the European Union.

The Batt4EU Partnership was launched in June 2021 to combine efforts of the European Commission and members of the Batteries European Partnership Association, which includes industry and R&D stakeholders within the battery supply chain. The partnership will fund battery R&D and innovation projects within the framework of the Horizon Europe Programme. A MoU was signed between the two parties stating that the European Commission will direct up to

EUR 925 million (USD 1 billion) in funding between 2021 and 2027 for battery research and innovation.

In February 2022, the European Commission granted EIT InnoEnergy EUR 10 million (USD 11.8 million) towards the European Battery Alliance Academy to help bridge a growing skills gap for the work force across the European battery value chain.

In France, a EUR 30 billion (USD 35 billion) overall investment plan was presented in 2021. It provides for up to EUR 4 billion (USD 4.7 billion) to support the automotive industry to produce 2 million EVs by 2030. In Germany, EUR 1 billion (USD 1.2 billion) in funding through 2022 was allocated by the Federal Ministry for Economic Affairs and Climate Action to establish the country as a global leader in battery cell production.

India

- Share of global EV battery production capacity: 0%.
- EV battery production capacity in 2021: 0 GWh.

India's Production Linked Incentives scheme has a strategic focus on advanced automotive technology and components (including EV) and advanced chemistry cell battery (ACC) sectors. The automotive and auto components sector was allocated close to INR 259 billion (USD 3.5 billion). With an aim to build capacity of 50 GWh, the ACC sector was allocated INR 181 billion (USD 243 million). Subsidies are to be provided over a span of five years based on performance metrics such as energy density (ACC only), battery cycle life (ACC only) and number of units sold or components manufactured in India.

A request for proposals was launched in January 2022 for both schemes, with the government to award contracts by March 2022. For the ACC scheme, bids totalled 130 GWh, close to three times the amount of the manufacturing capacity to be awarded . A total of 95 applicants were approved. Final recipients include both large auto manufacturers and OEMs as well as small and medium enterprises in the industry. For the advanced automotive technology and auto components scheme applications totalled a proposed INR 450 billion (USD 6.1 billion) for all vehicle categories, and were submitted by both incumbant automotive OEMs and new market entrants.

Japan

- Share of global EV battery production capacity: 4%.
- EV battery production capacity in 2021: 36 GWh.

Japan released a Strategic Energy Plan in 2021 which re-emphasised targets under the 2020 Green Growth Strategy for increasing domestic production for vehicle batteries to 100 GWh by 2030.

The Battery Association for Supply Chains, formed in April 2021, includes key Japanese OEMs. Its founding document urged the government to provide financial subsidies for battery production facilities. After consultations, the Japan's government announced a package of JPY 100 billion (USD 910 million) for the fiscal year 2021 supplementary budget for domestic battery production.

Korea

- Share of global EV battery production capacity: 5%.
- EV battery production capacity in 2021: 41 GWh.

The mid-2021 announcement of the K-battery blueprint renews government focus on expanding tax incentives and R&D spending. The stated ambition is for Korea to be the number one EV battery manufacturing country in the world by 2030.

The formation of a "grand-alliance" between the top-three Korean (and global) domestic battery manufacturers (LG Energy Solution, Samsung SDI and SK Innovation) aims to build an industrial network. A fund of KRW 80 billion (USD 69 million) will be established, with contributions from the government, companies and financial institutions, to support battery technology, parts and materials development in collaboration with other companies and academia. An additional KRW 1.5 trillion (USD 1.3 billion) will be made available to support battery development in Korea through tax incentives, R&D and capital investments.

United States

- Share of global EV battery production capacity: 7%.
- EV battery production capacity in 2021: 57 GWh.

An executive order in early 2021 mandated a thorough assessment of US supply chains. This includes the identification of risks in high-capacity battery supply chains.

With this focus on battery supply chains came a host of strategic policy announcements and blueprints. One included the release of the National Blueprint for Lithium Batteries (2021-2030), which elaborates a vision to establish secure battery materials and technology supply chains within the country. It aims to set guidance for policy makers, industry and investors for the long term by creating goals across the entire supply chain. These include: securing upstream raw and critical minerals and materials processing base; creating domestic electrode, cell and pack manufacturing sectors; end-of-life critical material recycling; and R&D efforts on battery technology development.

In October 2021, the US Department of Energy Argonne National Laboratory announced the creation of Li-Bridge. It is a new public-private partnership to bridge gaps in the domestic lithium battery supply chain. It marks the first collaboarion of its kind in the US battery industry.

In June 2021, USD 60 million was awarded for 24 projects to reduce CO_2 emissions from passenger cars and light/heavy trucks. This includes projects to accelerate innovation for EV batteries, electric drive systems and new mobility system technologies (automated, connected, electric and shared vehicles). The government approved close to USD 3 billion to boost production of advanced battery supply chains in February 2022 under the Infrastructure Investment and Jobs Act (Bipartisan Infrastructure Law). This includes funding for upstream battery materials and refining as well as for production plants, battery cell and pack manufacturing facilities and recycling facilities.

Southeast Asia

- Share of global EV battery production capacity: 1.0%.
- EV battery production capacity in 2021: 8.7 GWh.

Thailand, which has one of the largest automotive production centres in Southeast Asia, released guidelines to promote EVs and states its ambition to have 30% of all cars produced domestically to be EVs in 2030. Recent statements by government officials signal an intent to strive for 100% ZEV sales by 2035.

Thailand's Eastern Economic Corridor (EEC) is providing incentives for strategic manufacturing companies (including EVs) such as corporate tax breaks, infrastructure development and low interest loans. This spurred deals for EV and battery production facilities, such as with Chinese automaker Great Wall Motors in June 2021 and a USD 1 billion 8 GWh battery production plant both in the Rayong EEC. PTT, the state-owned oil and gas group, signed a joint venture deal with Foxconn to make EVs starting in 2024 with a capacity of 50 000 electric cars per year and targeted to expand to 150 000 by 2030.

Indonesia has a production target of 600 000 electric LDVs and 2.45 million electric two-wheelers by 2030. It aims to leverage its large raw nickel ore reserves upstream while offering incentives further downstream for EV component producers and manufacturers. This follows on from the Presidential Regulation to prioritise domestic EV production. It aims to ensure a certain percentage of Indonesian sourced EV components and nickel are used in EV production.

The Indonesia Battery Corporation, a state-owned battery manufacturer, was formed in March 2021 by the Ministry of State-Owned Enterprises and four other state-owned entities. The investment needed for this holding is Indonesian rupiah (IDR) 238 trillion (USD 17 billion). The corporation's production target is up to 140 GWh of battery cells by 2030, of which 50 GWh will be for export. For context, current global battery production capacity is about 871 GWh.

A memorandum of understanding (MoU) was signed in July 2021 for an EV battery factory between the Ministry of Investment and Hyundai Motor Company with a capacity of 10 GWh, with a price tag of USD 1.1 billion. The factory, to be built with Korean LG Group, aims to incorporate battery precursor production with pack production, as well as mining, smelting and recycling facilities. This deal is a part of a larger MoU signed by Indonesia's government and a consortium led by the LG Group for USD 9.8 billion to develop integrated EV supply chains. The consortium signed a non-binding agreement with PT Aneka Tambang Tbk, the state-owned mining company, and Indonesia Battery Corporation.

Other potential deals include a USD 5 billion lithium battery plant with projected production in 2024 between China's Contemporary Amperex Technology (CATL) and Indonesia's PT Aneka Tambang. In early 2022, Foxconn signed a MoU with the Indonesia's Ministry of Investment and Chinese Taipei's electric scooter manufacturer Gogoro (known for battery swapping) to facilitate battery manufacturing, and the development of EV supportive industries such as energy storage systems and battery recycling. This include Foxconn's production of solid-state and lithium iron phosphate batteries.

Harmonised technical regulations for the safe and sustainable deployment of EVs

In addition to policies, financial incentives and market penetration targets, technical regulations have an essential role to ensure the safe and sustainable deployment of EVs. The World Forum for Harmonization of Vehicle Regulations (WP.29), hosted by the United Nations Economic Commission for Europe, develops legally binding regulations covering technical requirements to improve vehicle safety and lower environmental impacts.

UN Regulation No. 100 / UN GTR No. 20 on Electric Vehicle Safety prescribes testing procedures to ensure EVs are safe for use. It details methodologies to test EVs and protect users from electrical shocks, ensure fire, water, vibration and mechanical resistance of key EV components, among other safety tests.

UN GTR No.22 on In-Vehicle Battery Durability was adopted in March 2022 and prescribes minimum performance requirements for the durability of batteries in electrified vehicles. It requires manufacturers to certify that the batteries fitted in their EVs will lose less than 20% of initial capacity over five years or 100 000 km and less than 30% over eight years or 160 000 kms.

The durability standard aims to prevent the use of low quality batteries and to ensure that only durable batteries are installed in EVs. This is crucial to increase consumer trust and to improve the environmental performance of EVs beyond their low emissions output. Making sure each battery lasts longer would help to ease the pressure on demand for critical raw materials needed for their production and reduce waste from used batteries. Similar provisions are now being developed for heavy-duty electric vehicles (e-buses and e-trucks).

The battery durability standard was adopted by many countries/regions that committed to transpose it into their national legislation. They are Australia, Canada, China, European Union, India, Japan, Korea, Malaysia, Norway, Russian Federation, South Africa, Tunisia, United Kingdom and United States. In the European Union, the provisions are expected to be part of the forthcoming Euro 7/VII legislation.

Countries rush to push policies to ensure stable supply of minerals critical for EV battery supply chains

Major battery mineral and metal producers around the world have begun to prioritise not only mining but refining capacity to be able to securely supply materials for EV battery supply chains around the world.

Australia

Australia is the largest producer of lithium in the world and one of the top producers of nickel globally. In September 2021, the government released an AUD 1.3 billion (USD 980 million) loan facility for Australian critical minerals targeted for advanced sectors including EV battery production. In addition, a AUD 2 billion (USD 1.5 billion) fund was announced to increase critical mineral processing capacity, including for battery minerals and metals.

In December 2021, the federal government awarded “Major Project Status” to a AUD 2.4 billion (USD 1.8 billion) battery minerals complex in New South Wales for a nickel and cobalt mine, materials processing and recycling facility. Having major project status allows access to additional financial support, co-ordination and streamlined regulatory approvals. The facility is planned to be powered almost entirely by renewables, making it one of the world’s largest battery metal producers operating on renewable energy.

Canada

To implement its Critical Minerals Strategy, the government allocated CAD 3.8 billion (USD 2.9 billion) over eight years in the 2022 budget – the first budget announcement of its kind. Of this, around CAD 1.5 billion (USD 1.2 billion) is for infrastructure investment to support critical mineral supply chains, CAD 79.2 million (USD 60.9 million) is for integrated data sets for critical mineral exploration and development, and a new 30% tax credit for critical mineral exploration.

Chile

Chile remains one of the largest producers of lithium in the world, though there has been slow growth in developing new projects. To counter this trend, in October 2021 the government launched a special auction for operating contracts to explore and produce 400 000 tonnes of lithium. Divided into five tranches of 80 000 tonnes each, it provides successful bidders a period of seven years to conduct geological exploration, studies and 20 years for production. The government will take a royalty payment, plus a variable payment during production.

China

China continues to dominate in the mid- to downstream EV battery supply chain, though it currently owns less than 25% of upstream mining capacity.

The 14th Five-Year Plan for the Development of the Raw Materials Industry (2021-2025) was released in December 2021. It aims to focus technological innovation in key materials for development, including promoting the R&D of new, more efficient and environmentally-sensitive mining technologies and minerals, including salt lake lithium. The plan also aims to develop “urban mines” to support large-scale recovery of lithium, nickel, cobalt and tungsten at recycling bases and industrial clusters.

European Union

Formed in 2020, the European Raw Materials Alliance (ERMA) was created as a part of the EU’s Action Plan on Critical Raw Materials. Along with working on regulatory bottlenecks and stakeholder engagement, its focus is to act as a pipeline to catalyse investment for projects. ERMA has announced plans to launch a raw materials investment fund planned for 2022

In November 2021, the European Parliament voted in the Critical Raw Materials Strategy with a focus on “open strategic autonomy”, i.e. access to alternatives and competition when sourcing critical raw materials. Other aspects include sourcing critical raw materials from within the European Union member states, increased recycling and circular use of resources, and investment in refining and separation capacities (including lithium). The European Parliament has asked the European Commission and member states to create an IPCEI on critical raw materials to focus on reducing criticality and dependence.

Indonesia

Indonesia is the largest nickel producer in the world. It aims to maintain that position as a key supplier for the EV battery manufacturing sector.

In 2020, Indonesia imposed a nickel ore export ban. This was followed in 2021 with consideration of imposition of a tax on the export of nickel products that contain less than 70% nickel content in an attempt to further develop domestic refining capacity. Today, most nickel products contain between 30-40% nickel and are generally exported to be further refined to have higher purity nickel products (70% or above) and could thus significantly impact exports.

United States

In March 2022, the United States invoked the Defence Production Act to rapidly boost US production of critical minerals for EV and storage batteries, focussing on lithium, nickel, cobalt, graphite and manganese.

Over the past year, the United States has made significant efforts to enhance EV battery supply chains, including critical minerals. In February 2021, the US Department of Energy awarded

USD 44 million to the Mining Innovations for Negative Emissions Resource Recovery Program for technological development to increase domestic critical element supplies. The fund focusses on commercial-ready technologies that are either net zero or net negative emissions for critical minerals needed for the clean energy transition.

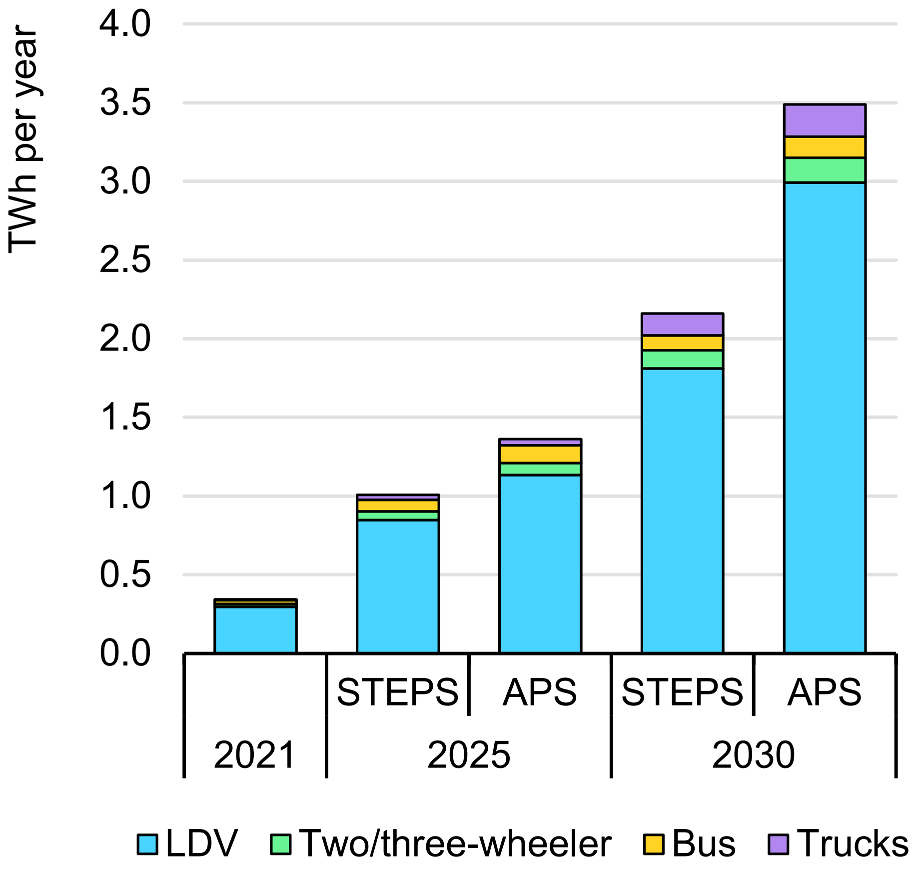
In April 2021, 13 critical mineral projects were selected to receive a total of USD 19 million. The fund focuses on projects that would help transition fossil fuel producing communities towards clean energy jobs, including increased recycling from critical mineral resources and waste streams, critical mineral and metal extraction from fossil fuel products and their waste streams for use in various applications including EV batteries.

In February 2022, the US departments of Energy, Defense and State signed a Memorandum of Agreement to support stockpiling of critical minerals that would facilitate the transition to clean energy, in particular for batteries and wind turbines, and to meet national security needs.

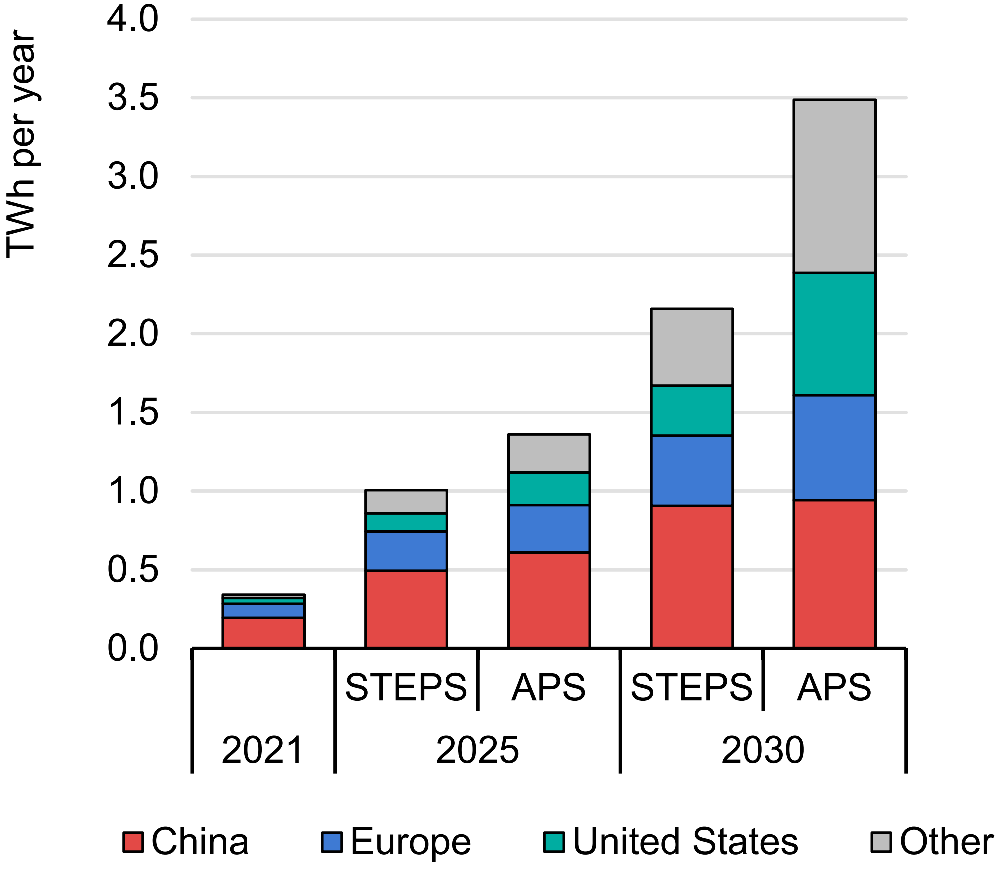
Outlook for batteries and critical materials

Battery demand surges in all regions driven by battery electric cars

EV battery demand by mode, 2021-2030



EV battery demand by region, 2021-2030



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; LDV = light-duty vehicle.

EVs increase battery demand sixfold and drive rapid expansion in all parts of supply chains

Increased EV sales necessitate a scale up of all elements of the battery supply chain. While for most components, EVs are not too different from conventional vehicles, batteries rely on distinct and critical materials dependent supply chains which must dramatically scale up this decade to meet projected demand. Most supply chain components can be scaled up rapidly; battery production factories can be built in under two years and the project pipeline is very large. On the other hand, raw material extraction requires investment long before production reaches scale.

Planned battery factories can meet 2030 demand

In the Stated Policies Scenario, battery demand from EVs increases in 2030 to 2.2 TWh and to 3.5 TWh in the Announced Pledges Scenario. This is a more than sixfold increase from the production level in 2021 for the Stated Policies Scenario and a ten-fold increase for the Announced Pledges Scenario. Achieving such production levels requires the manufacture of an additional 52 gigafactories of 35 GWh annual production capacity in the Stated Policies Scenario and 90 gigafactories in the Announced Pledges Scenario.

Battery demand is driven by electric cars which account for 85% of the projected total by 2030 in both scenarios. Not only will electric car sales increase, but current trends and new model announcements suggest that vehicles will have increasingly higher battery capacity due to demand for longer driving ranges and larger vehicles. This trend contributes to around a third of the rise in battery demand and is especially pronounced in North America.

China is projected to have the largest battery demand, though its global share shrinks from 60% in 2021 to 40% in 2030 in the Stated Policies Scenario and 25% in the Announced Pledges Scenario. The United States undergoes the fastest battery demand increase among major markets driven by rapid EV deployment as well as the largest battery capacity per vehicle, increasing share slightly in the Stated Policies Scenario with around 15% in 2030 from 11% in 2021 and increasing to above 20% in the Announced Pledges Scenario in 2030. The share of global EV battery demand is also projected to decrease in Europe from 25% in 2021 to 20% in both the Stated Policies and Announced Pledges Scenarios in 2030.

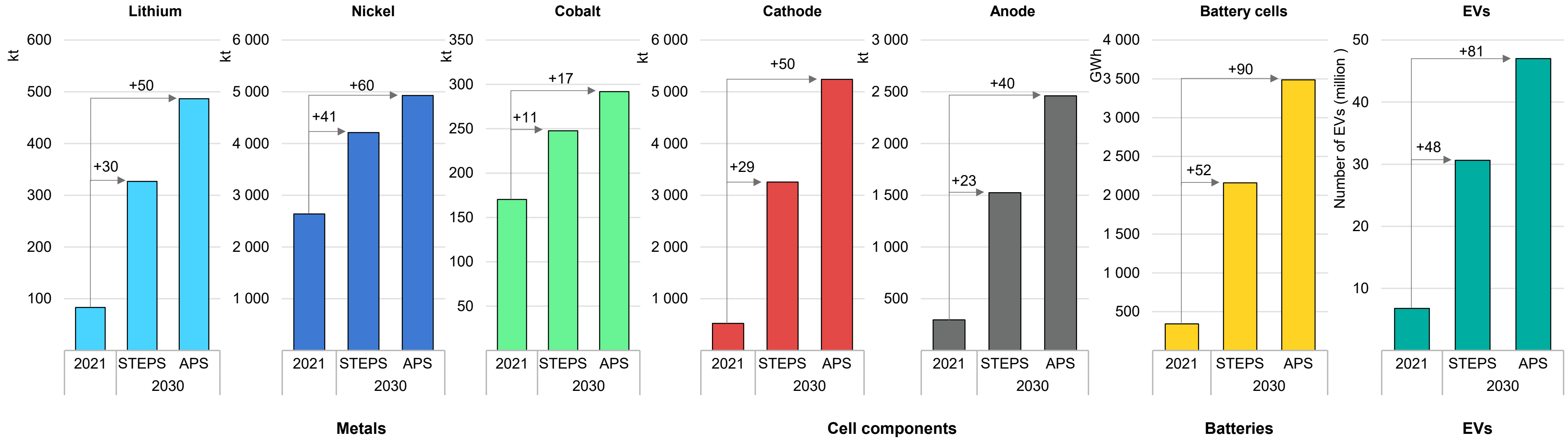
According to recent accounting by Benchmark Mineral Intelligence, the announced battery production capacity by private companies for EVs in 2030 amounts to 4.6 TWh, a higher value than for both the Stated Policies Scenario and Announced Pledges Scenario demand. If all the announced capacity successfully came online by 2030, using total battery demand, the utilisation factor of battery manufacturing would be 47% in the Stated Policies Scenario, slightly higher than in 2021 (43% based on nameplate capacity). Battery production capacity will still be concentrated in China (70%), yet more investments are being directed to other regions, with a quarter of battery production capacity expected in Europe and the United States by 2030.

Anode and cathode production is slowly becoming more geographically diversified

Scaling up cell and battery production will require additional output from anode and cathode manufacturers. In the Stated Policies Scenario, there is a sixfold increase in cathode demand and a fivefold increase in anode demand in 2030 relative to 2021 production. For the Announced Pledges Scenario, cathode demand increases ten-fold and anode demand eightfold. In the Stated Policies Scenario, cathode production reaches 3 300 kt and anode production 1 500 kt in 2030, requiring around 29 additional cathode material plants and 23 additional anode material plants. For the Announced Pledges Scenario, cathode demand is 5 200 kt and anode is 2 500 kt, requiring about 50 cathode and 40 anode plants. For each GWh of battery production, 1.5 kt of cathode and 0.9 kt of anode material are required. Current cathode and anode material production are highly concentrated; together China, Japan and Korea account for 97% of current cathode and and 99% of anode production. Looking forward, the picture does not change much in the near term. Assessing all current announced and under construction cathode and anode material production plants, which are set to be online by 2025, shows the United States and Europe together will only produce around 4% of cathode material and 2% of anode material in 2025. Increased diversification is expected in the longer term based on announcements of planned production in Europe and North America. For example, by BASF with a planned cathode material production plant in Canada.

All elements of EV battery supply chains expand significantly to meet projected demand

Number of mines to produce required levels of metals, anode/cathode production plants, battery gigafactories and EV plants required to meet projected demand in 2030 relative to 2021



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Number of additional mines/plants/factories required to meet projected demand from the 2021 demand level is shown by the arrows. Projected demand is annual. Metal demand is total demand including EV and non-EV demand. Assumes the average annual production capacities: lithium mine - 8 kt; nickel mine - 38 kt; cobalt mine - 7 kt; cathode plant - 94 kt; anode plant - 54 kt; battery gigafactory - 35 GWh; and EV production plant - 0.5 million vehicles. Nickel demand does not distinguish between Class 1 and Class 2 nickel.

Sources: IEA analysis based on S&P Global ; Bloomberg NEF; Benchmark Mineral Intelligence.

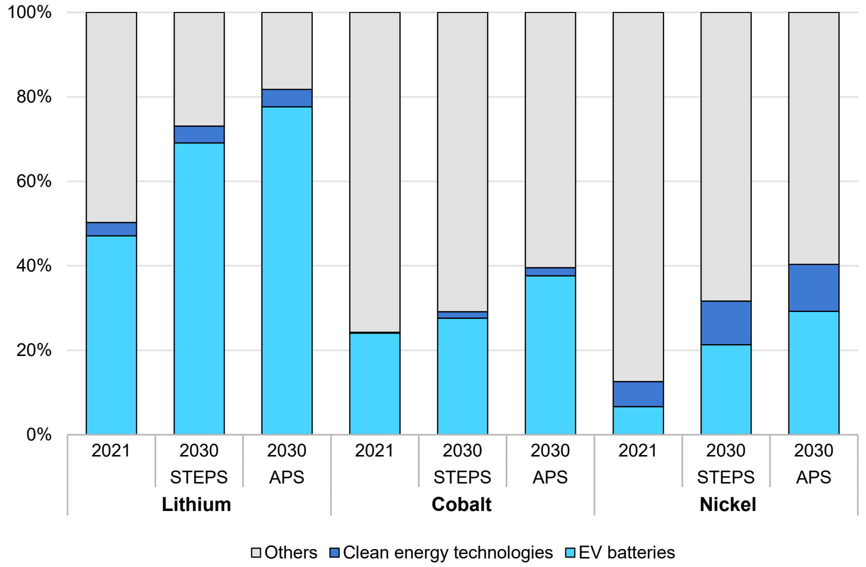
Demand for EV batteries drives a surge in metal demand

Lithium is the most critical metal for EVs as it has no commercially available substitute at scale. Therefore, it experiences the fastest demand growth of the battery metals. Practically, all of the increase in demand for lithium to 2030 is projected to come from EV batteries in both scenarios.

Lithium demand in the Stated Policies Scenario reaches about 330 kt by 2030, a fourfold increase relative to 2021 production (80 kt). For the Announced Pledges Scenario, lithium demand reaches 500 kt, a sixfold increase from 2021 driven by higher EV sales across all modes. EV batteries were responsible for almost half of global lithium demand in 2021. In 2030 this rises to 70% in the Stated Policies Scenario and almost 80% in the Announced Pledges Scenario. In order to meet this surge in lithium demand, around 30 new lithium mines are needed in the Stated Policies Scenario by 2030 and 50 new lithium mines in the Announced Pledges Scenario, assuming an average annual lithium mine production capacity of 8 kt.

By 2030, nickel is facing the largest absolute demand increase as high-nickel chemistries are the current dominant cathode for EVs, and are expected to remain so. High-nickel Li-ion batteries require far more nickel than even lithium. For example, a NMC811 battery requires almost seven times more nickel than lithium by weight. For cobalt, the opposite is true as battery makers continue to move to lower cobalt content chemistries (and even cobalt-free chemistries by 2030) to reduce costs and due to environmental, social and governance concerns. However, the surge in global demand for EV batteries still increases total cobalt demand this decade.

Share of total demand for battery metals from EVs and clean energy technologies, 2021 and 2030



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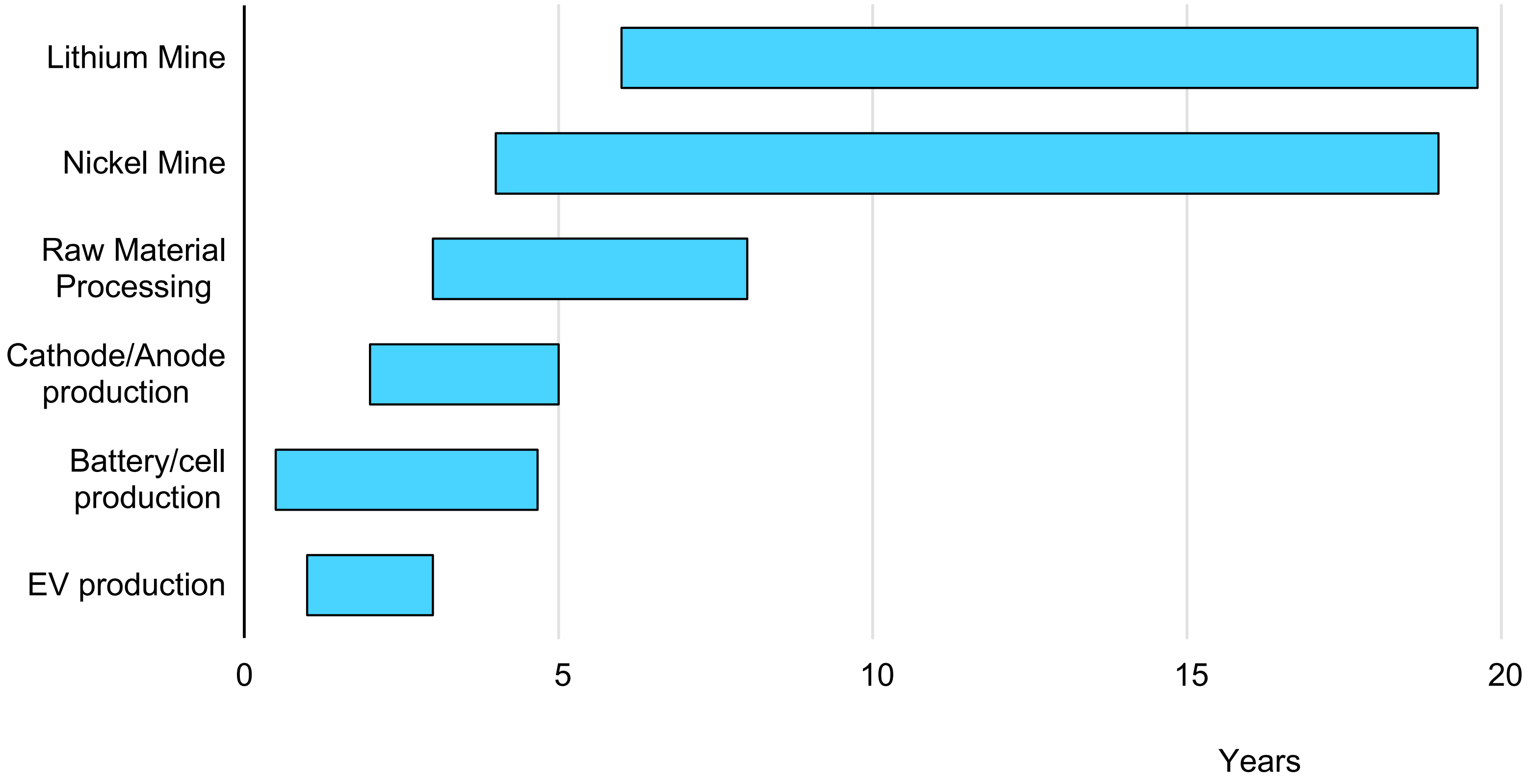
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Clean energy technologies include: stationary energy storage batteries, renewables, nuclear, hydrogen technologies and grid technologies.
Sources: IEA analysis based on S&P Global.

In the Stated Policies Scenario, total nickel demand rises 60% to around 4 200 kt by 2030 while total cobalt demand increases 45% to 250 kt. Out of total demand for nickel, EV batteries account for a fifth of demand in 2030 and about a quarter of demand for cobalt in the Stated Policies Scenario. In the Announced Pledges Scenario, nickel and cobalt demand from EV batteries is 65% higher than in the Stated Policies Scenario, with an EV share of 30% and 40%, respectively. To meet the projected demand in 2030 in the Stated Policies Scenario, 41 nickel and 11 cobalt additional mines are needed – a significant scaling up requirement. For the Announced Pledges Scenario, 60 nickel and 17 cobalt new mines are required in 2030, (assuming average annual mine production capacity of 38 kt for nickel and 7 kt for cobalt).

Meeting battery metal demand in 2030 and beyond requires investment to be mobilised now, particularly in new mining capacity

Range of typical lead times to initial production for selected steps in EV battery supply chain



Notes: Lead times for mines are calculated from completion of the preliminary feasibility study to the start of production. For other elements, lead times are calculated from investment decision to production.

Sources: IEA analysis based on Heijlen et al. (2021); Benchmark Mineral Intelligence; S&P Global.

Investment is needed now to meet battery metal demand in 2030

To meet the demand for projected EV deployment various elements in the supply chain will need to expand. Ramping up of countries' climate-related amibitions and pledges will also increase demand further for metals to supply the necessary EV batteries. As observed in 2021, demand for EVs can increase very rapidly though scaling up supply requires time, as mines and factories cannot be brought online overnight.

Elements of the supply chains have various lead times. The downstream stage, EV vehicle assembly, is the most dynamic, since automobile production capacity is much higher than demand, automakers can retool existing factories to manufacture EVs. For example, work to retool (convert a plant from ICE vehicles to EVs) at Volkswagen's Zwickau factory in Germany began in 2018 and the first EVs were produced in November 2019. Similarly, Tesla's EV factory in Shanghai was completed in roughly one year after breaking ground in early 2019.

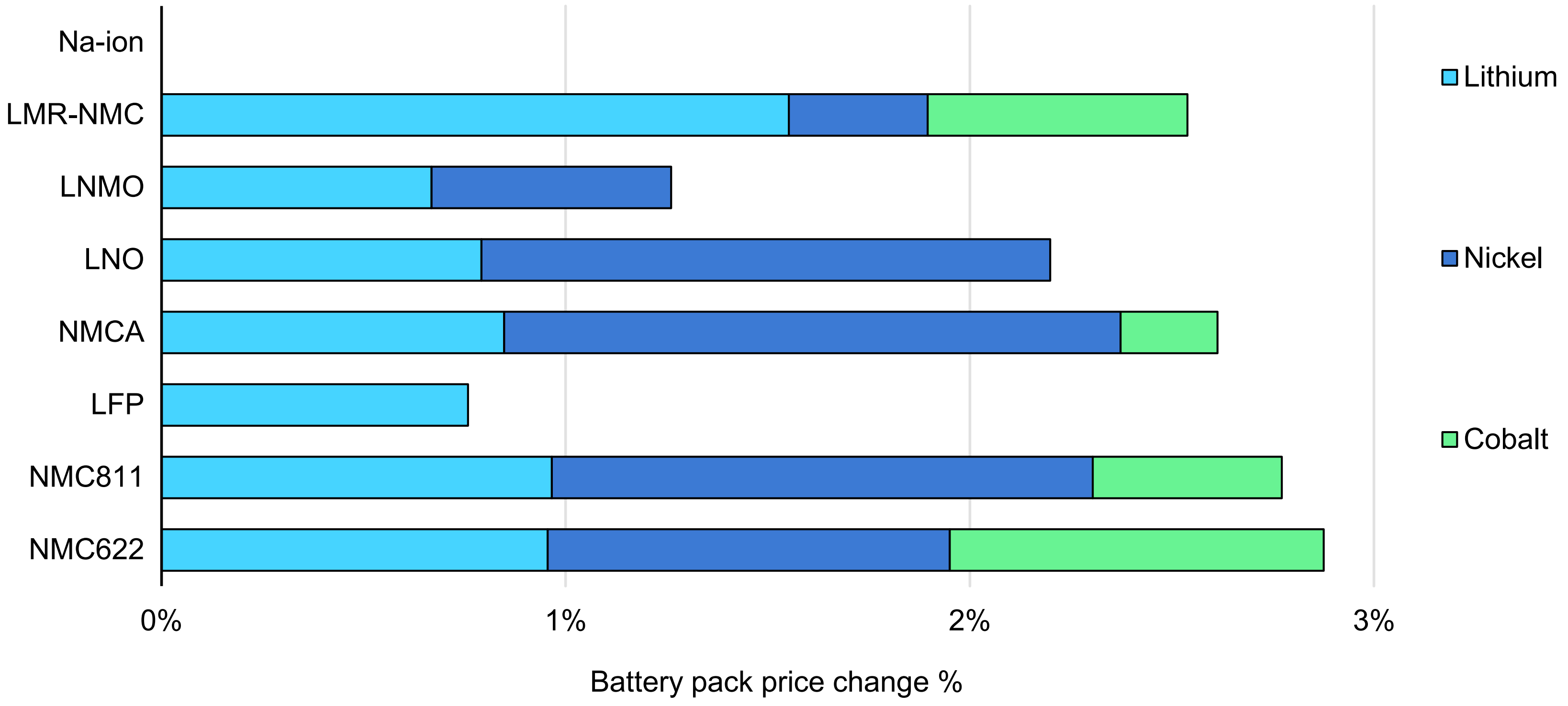
Battery production lead times can be more varied. In China, CATL has been able to deliver a new cell manufacturing facility in under one year due to experience in their production, while four years elapsed between the announcement of Northvolt's first factory in Sweden and the beginning of production. Anode and cathode plants have lead times that are typical for chemical plants, which vary by region. Umicore announced production plans for a plant in Poland in 2018, which is expected to begin commercial production in 2022, thus requiring four years. In China, cathode factories can be built in less than two years due to previous experience and the use of existing sites for expansion.

By far the longest lead times are in the extraction of raw materials. After an extractable resource is identified through exploration, it can take from four to more than twenty years for a mine to begin commercial production. Four to sixteen years can be required for the necessary feasibility studies, and engineering and construction work. Long lead times are often required to secure financing and the necessary permits. Securing permits can take from one to ten years due to some countries requiring multiple permits or due to permitting delays. There is some evidence that over the decades, the time required to bring mines online has increased and this can be partially attributed to longer permitting and feasibility study lead times.

In addition to the time required to begin commercial production, mines often require around ten years before they reach nameplate production capacity. An analysis of lead times across the supply chain indicates that with sufficient investment, downstream stages of the EV battery supply chain can ramp up to meet even rapid increases in demand in the 2030 time frame. However, upstream mineral extraction can cause major bottlenecks unless adequate investments are delivered well in advance.

Battery chemistries have notably different sensitivities to commodity prices

Impact of 10% commodity price change on the battery pack price for selected battery chemistries



Notes: Na-ion = sodium-ion. Manganese-rich chemistries: LMR-NMC = lithium-manganese-rich NMC; LNMO = lithium nickel manganese oxide. LNO = lithium nickel oxide. NMCA = lithium nickel manganese cobalt aluminium oxide. LFP = lithium iron phosphate. NMC = lithium nickel manganese cobalt oxide (NMC622 and NMC811). Battery pack price sensitivity to commodity prices. All chemistries modelled with graphite anode. Cathode thickness kept constant at 120 µm with cathode loading adjusted. Modelled with 2021 average commodity prices as the base and then with 10% increase in lithium, nickel and cobalt prices. Na-ion contains no lithium, nickel or cobalt.
Sources: IEA analysis based on BatPaC (2022); Dhir et al (2021); Greenwood et al (2021); Bloomberg NEF.

Battery chemistries are evolving in response to tight supply

The evolution of battery chemistries will determine which metals will face the greatest demand. Given the long lead times required to increase metal production, optimising and diversifying battery chemistries will play an important role in reducing demand for specific critical metals.

Today, lithium-ion batteries for EVs are either nickel-based (NMC and NCA) or lithium iron phosphate (LFP). The former have higher energy density and account for the vast majority of EV batteries outside of China. LFP has lower energy density but also lower cost and is widely used in China for both light- and heavy-duty vehicles.

Battery chemistries will be more diversified by 2030 as manufacturers select battery chemistries to serve specific vehicle characteristics. As exemplified by Volkswagen's announcement, chemistries will be adapted to the vehicle category: premium vehicles can be expected to use the most high energy density batteries available, likely higher nickel content chemistries such as NCA95, NMCA and NMC9.5.5, or potentially those with even higher energy density, such as lithium nickel oxide (LNO) or lithium-manganese-rich NMC (LMR-NMC) if research challenges can be solved and commercially viable cycle life is achieved. For lower end, high volume and principally urban vehicles, LFP will be the primary chemistry as driving range is not the priority, and instead it is cost. Moreover, due to high commodity prices for nickel and cobalt and the expiry of key patents, LFP is set for major growth in volume models in Europe and the United States in the coming years. Announcements have been made by key automakers such as Tesla and Volkswagen for LFP use for standard range EVs in both markets. The possibility of battery packs containing both LFP and high-nickel recently became reality with NIO announcing their CTP pack including both LFP and NMC cells to utilise the benefits of both chemistries.

For mid-range vehicles, the manganese-rich chemistry (lithium nickel manganese oxide [LNMO]) is a strong contender as it has a higher energy density than LFP, yet does not reach the levels of the high-nickel chemistries. The larger proportion of manganese in LNMO reduces material costs and commodity exposure considerably compared to high-nickel chemistries. However, LNMO is still under development. Volkswagen has indicated its long-term strategy to pursue manganese-rich chemistries for mass-market EV models.

For medium and heavy-duty vehicles, LFP will account for the vast majority of installations as cost and reliability will be more important for the early applications of electric trucks. LFP has the best cycle life of the leading chemistries which suits frequent, short trips and being recharged often. On the other hand, longer range electric trucks are likely to use nickel-based chemistries with the highest energy density, but their deployment in the period to 2030 is limited.

The future of battery chemistries is not set in stone. There are advantages and disadvantages of the various chemistries. A sustained period of high battery metal prices may therefore have a dramatic impact on battery chemistries, accelerating the shifts already underway and anticipated due to current high prices. Sustained high commodity prices would support a shift towards chemistries with lower critical mineral intensity. Two primary impacts can be expected. First, a stronger shift to commercial chemistries with lower critical material intensity, particularly LFP which contains no nickel or cobalt. Second, an acceleration in the development of new chemistries which rely on less critical minerals, such as the manganese-rich cathode chemistry LNMO and even alternative lithium-free battery chemistries similar to Li-ion such as sodium-ion (Na-ion).

Sodium-ion batteries

While researchers across the world are working to develop battery chemistries that do not use lithium, the closest most viable option today is Na-ion technology. Na-ion is currently being developed by one of the world's largest battery makers, CATL, which commercially introduced Na-ion in 2021 and plans to form a basic industrial supply chain by 2023. Alongside the developments from CATL for Na-ion, the Chinese government plans to promote the development of the Na-ion battery industry in its 14th Five-Year Plan, with industry standards to achieve scale, lower cost and improve performance. Na-ion cells will have just over half the energy density of leading high-nickel chemistries and therefore, will not be used for high energy density applications. However, it is comparable with LFP with only around 20% lower energy density than the leading LFP cells. Therefore, for applications where energy density is not critical, for example urban EVs or grid-scale storage, Na-ion is suitable. CATL is also mitigating the energy density limitations through their new AB battery pack design which can integrate both Li-ion and Na-ion cells in one pack.

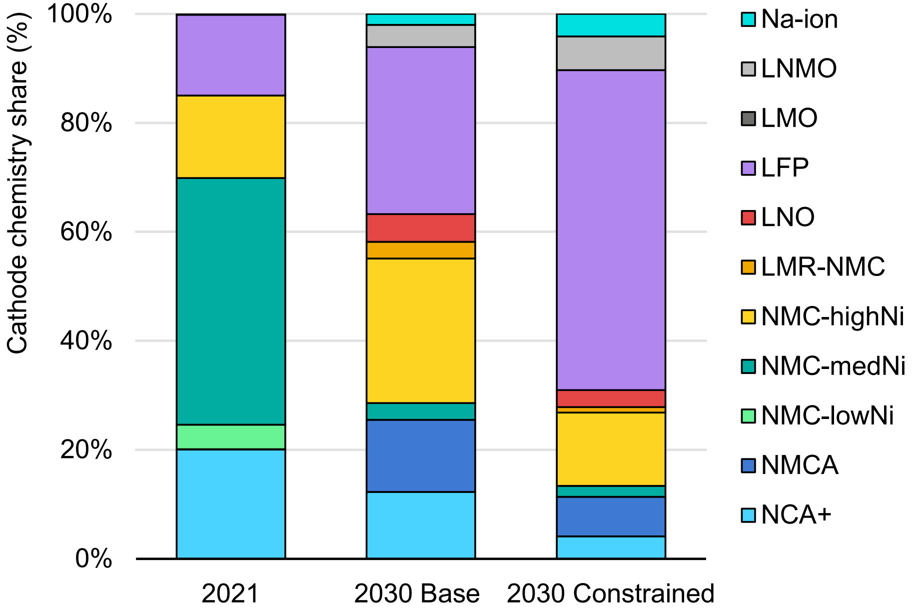
The critical advantage of Na-ion over Li-ion is that it relies on abundant and low cost minerals. The cathode material for the CATL Na-ion battery (Prussian White) is made of low cost elements sodium, iron, nitrogen and carbon. Na-ion cannot use graphite anodes, so instead uses hard carbon. In addition, less copper is required as Na-ion can use aluminium anode current collectors, unlike Li-ion. While Na-ion has advanced beyond the research stage with demonstration of commercially viable performance, there are no supply chains today for its cathode and anode materials. The main uncertainties around the deployment of Na-ion is the scalability of the production processes for these materials and the time required to develop an industrial scale supply chain. Fortunately, due to the similarity of Na-ion and Li-ion, it is relatively simple to adapt current cell factories to the production of Na-ion cells.

Constrained Chemistry Case

To illustrate the impact of the possible trends, we present the Constrained Chemistry Case. It focusses on cathode chemistries to assess the impact of prices remaining high for longer, coupled with a strong reaction from automakers to high prices. The most significant change is major substitution from high-nickel cathode chemistries to LFP. In the Constrained Chemistry Case for the Stated Policies Scenario, global demand for nickel is reduced by 10% or about 440 kt per year, while the demand for cobalt is reduced by 15% equivalent to 35 kt per year. The reduction in nickel is substantial as it is almost twice the 2021 total production of nickel in Russia (the world's largest Class 1 nickel producer). For the Announced Pledges Scenario, the demand reduction is even more significant with 15% total demand reduction for nickel and 20% for cobalt.

Lithium demand would be slightly reduced in the Constrained Chemistry Case, with only a 3% reduction in both the Stated Policies and Announced Pledges Scenarios mainly due to LFP having a slightly lower lithium intensity per kWh than high-nickel chemistries so its much larger deployment also reduces lithium demand. LNMO also has lower lithium intensity so it supports lithium demand reduction. The introduction of Na-ion by 2030, being the only chemistry that does not contain lithium, notably decreases lithium demand with only a small share. Therefore, in the short term, lithium demand cannot be significantly reduced, though there is potential in the longer term.

Light-duty vehicle battery chemistry projections, Constrained Chemistry and Base cases, 2021 and 2030



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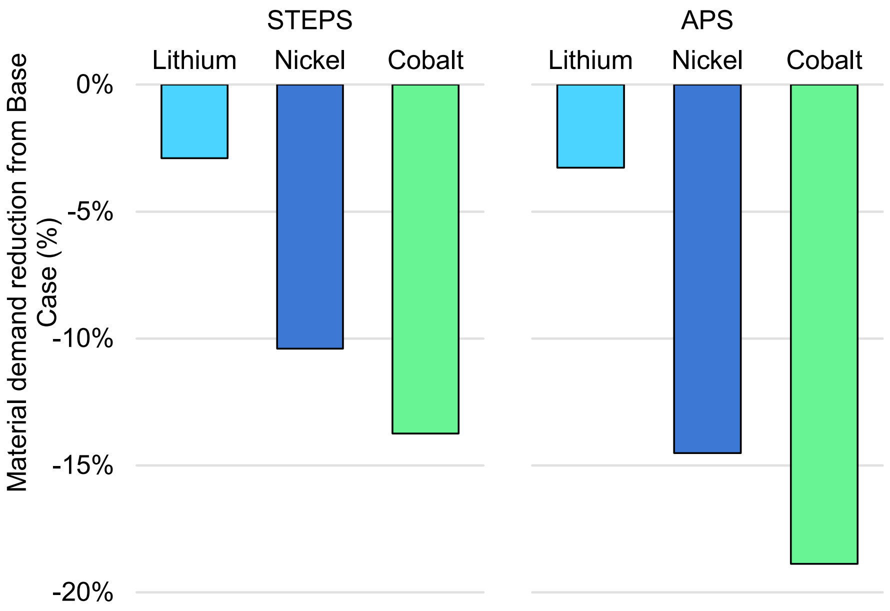
Notes: Battery cathode chemistries include: Na-ion = sodium-ion. LNMO = lithium nickel manganese oxide. LMO = lithium manganese oxide. LFP = lithium iron phosphate. LNO = lithium nickel oxide. LMR-NMC = lithium-manganese-rich NMC. NMC = lithium nickel manganese cobalt oxide. NMC-highNi includes: NMC811 and NMC9.5.5. NMC-medNi includes: NMC532, NMC622 and NMC721. NMC-lowNi includes: NMC333. NMCA = lithium nickel manganese cobalt aluminium oxide. NCA = lithium nickel cobalt aluminium oxide. NCA+ includes: NCA85, NCA90, NCA92 and NCA95. The Base and Constrained Chemistry cases refer to different battery chemistry shares in 2030. The Base Case is what is expected taking into account optimal allocation of chemistries to appropriate use-cases as well as recent price movements. The Constrained Chemistry Case depicts the consequence of a prolonged period of high commodity prices, coupled with strong reactions by automakers to price signals.

Battery metal demand reduction in Constrained Chemistry versus Base cases



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Notes: STEPS =Stated Policies Scenario; APS = and Announced Pledges Scenario. The percent of total metal demand reduction in the Constrained Chemistry Case is relative to the Base Case including EV and non-EV demand.

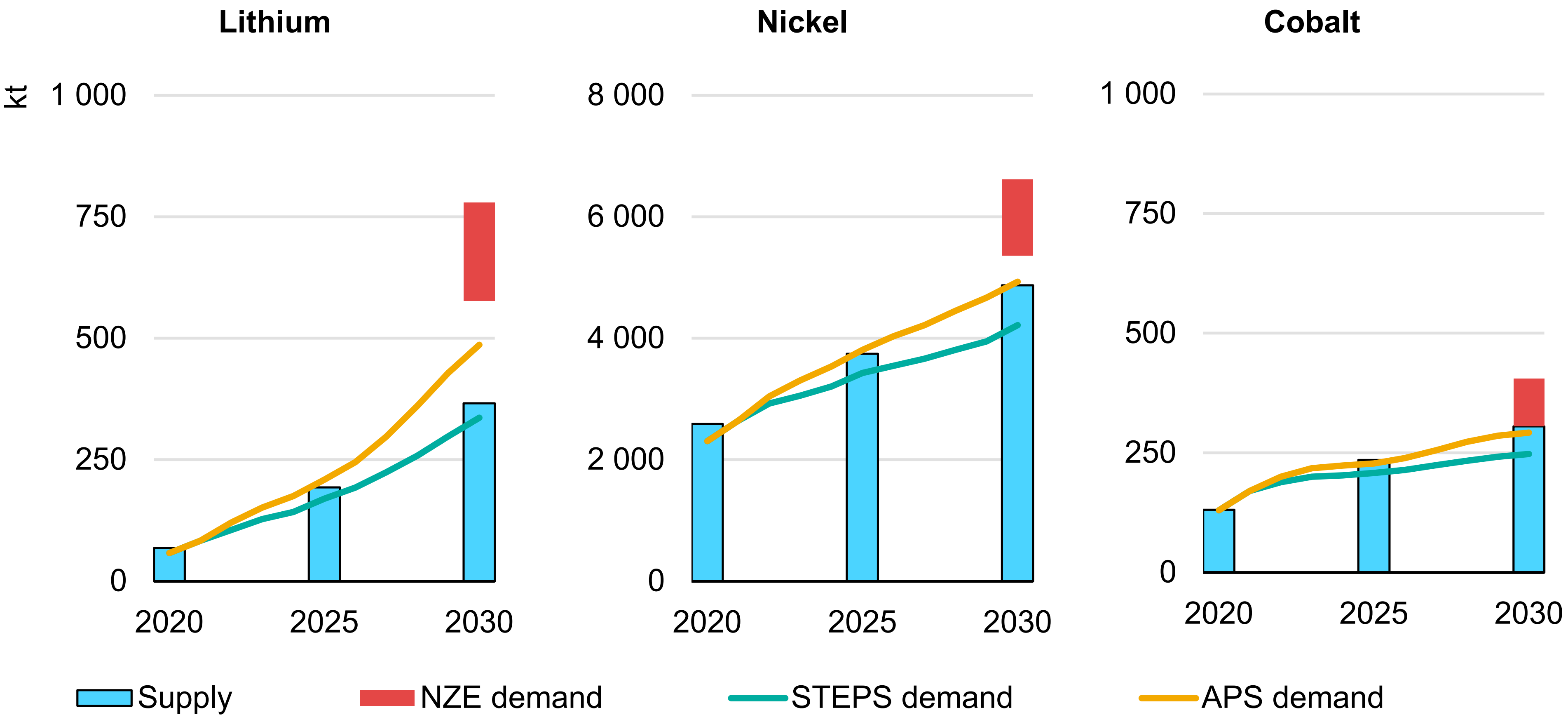
Solid-state batteries

All-solid-state batteries (ASSBs) are the anticipated next step-change improvement in battery performance. ASSBs can enable the use of a lithium metal anode which can result in battery energy densities around 70% higher than the current best Li-ion batteries with graphite anodes, dramatically improving driving range capability, opening other applications and eventually driving down costs. There has been considerable activity and industry announcements for ASSBs recently from both start-ups and established battery makers. For instance, Nissan is starting pilot production in 2024 and aims to produce EVs with ASSBs in 2028, having just opened a prototype production facility in Kanagawa, Japan. Quantumscape and Volkswagen have a joint venture that plans a pilot production line to start in 2024. Samsung SDI began construction of a pilot solid-state battery production line in March 2022, and aims to develop prototype cells by 2025 and start mass production in 2027.

Despite the activity and announcements, major technical challenges remain to be solved before ASSBs can make significant impacts. Current state-of-the-art performance often relies on impractical pressures to solve the contact problem, or on currently unscalable, expensive production processes to reach viable performance. Though progress is being made, ASSBs are not expected to have a significant impact until after 2030.

Supply projections appear sufficient to meet metal demand in the Stated Policies Scenario…

Total demand and supply for lithium, nickel and cobalt, 2020 - 2030



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Notes: NZE = Net Zero Emissions by 2050 Scenario; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The NZE bar represents variability in demand if demand-side measures are taken to reduce battery and critical metal demand.

Sources: IEA analysis based on Benchmark Mineral Intelligence for supply capacity.

…but more investment is required for the Announced Policies and Net Zero by 2050 scenarios

In comparing metal supply estimates by mining industry experts with the IEA demand scenarios, it appears that EV battery metals demand in the Stated Policies Scenario will likely be met for all metals up to 2025 if announced new supply comes online as scheduled. When looking to 2030, the situation is more uncertain, but a continuation of trends should generally be sufficient to meet demand for all metals if all anticipated supply comes online, though with a small margin. Nonetheless, this still requires a significant effort: dozens of mining projects will have to enter the market and reach capacity on schedule and tens of new mineral processing and precursor plants will have to be commissioned. Also, in order to translate this into EV deployment, tens of cathode and anode plants, gigafactories and EV production plants are required.

Demand for lithium will greatly exceed current supply projections by 2030 in the Announced Pledges Scenario. To meet climate and zero emissions targets, additional investments will have to flow into the mining industry. Lithium requires a 45% increase in demand in the Announced Pledges Scenario compared to the Stated Policies Scenario or a 33% increase from projected supply in 2030 – roughly 15 additional mines would be required on top of projected supply. For nickel, demand in the Announced Pledges Scenario is just over supply, however the total projected supply includes both Class 1 and 2 nickel whereas batteries require Class 1 or significant additional processing of Class 2 nickel. Therefore, significant investments are needed.

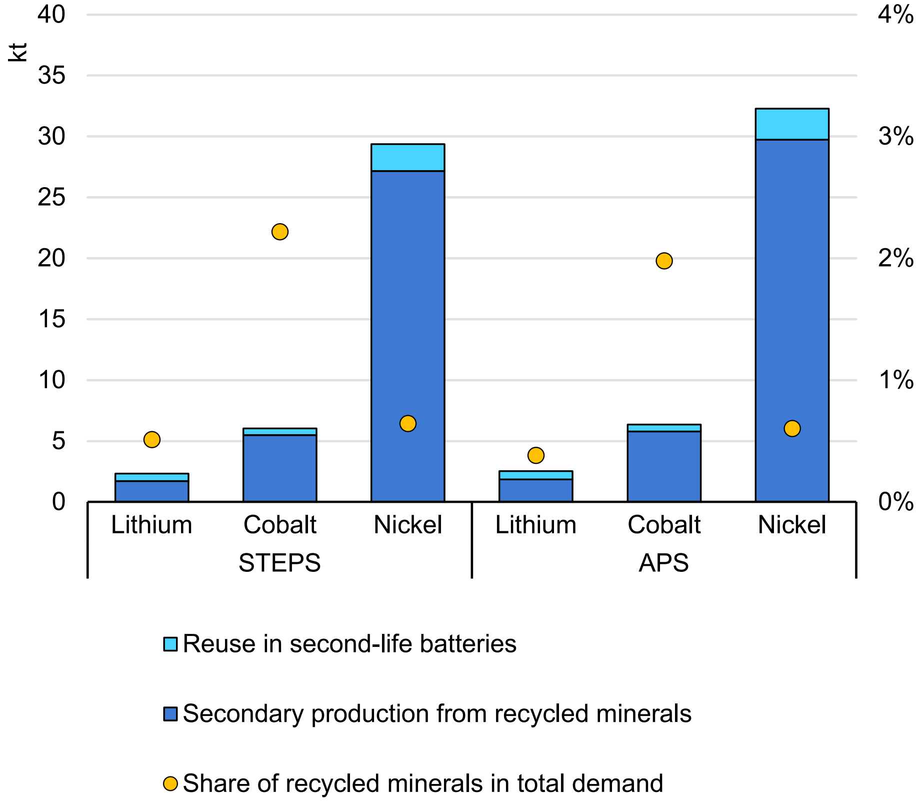
In the Constrained Chemistry Case, the demand for all metals will decrease, in particular for nickel and cobalt. Nickel demand in the Announced Pledges Scenario would be reduced to be the same as in the Stated Policies Scenario in 2030. For cobalt, the Announced Pledges Scenario demand is met by projected supply, but the Constrained Chemistry Case would reduce the Announced Pledges Scenario demand to 22% below supply estimates, a considerable supply surplus. For lithium, this would reduce the gap between the Announced Pledges Scenario demand and projected supply by 13%.

Though the price of cobalt is rising and the supply of cobalt is highly concentrated geographically and thus more vulnerable to supply shocks, it is expected that in the long term cobalt supply will likely not be as much of an issue as lithium and nickel. This is due to the trend of moving away from cobalt in cathode chemistries, coupled with the expansion of recycling as cobalt is the most valuable battery metal per kilogramme.

In the long term, recycling will contribute significantly to supply. However, only small contributions from recycling are expected by

2030, particularly for lithium and nickel. From analysis of the dates of expected retirement of EV fleets and their battery chemistry compositions, there is less than 1% of total projected demand (in both scenarios) available from recycling for lithium and nickel by 2030. For cobalt there is a small contribution available from recycling, expected at around 2% of total 2030 demand for both scenarios.

Secondary battery production from recycling and re-use, 2030



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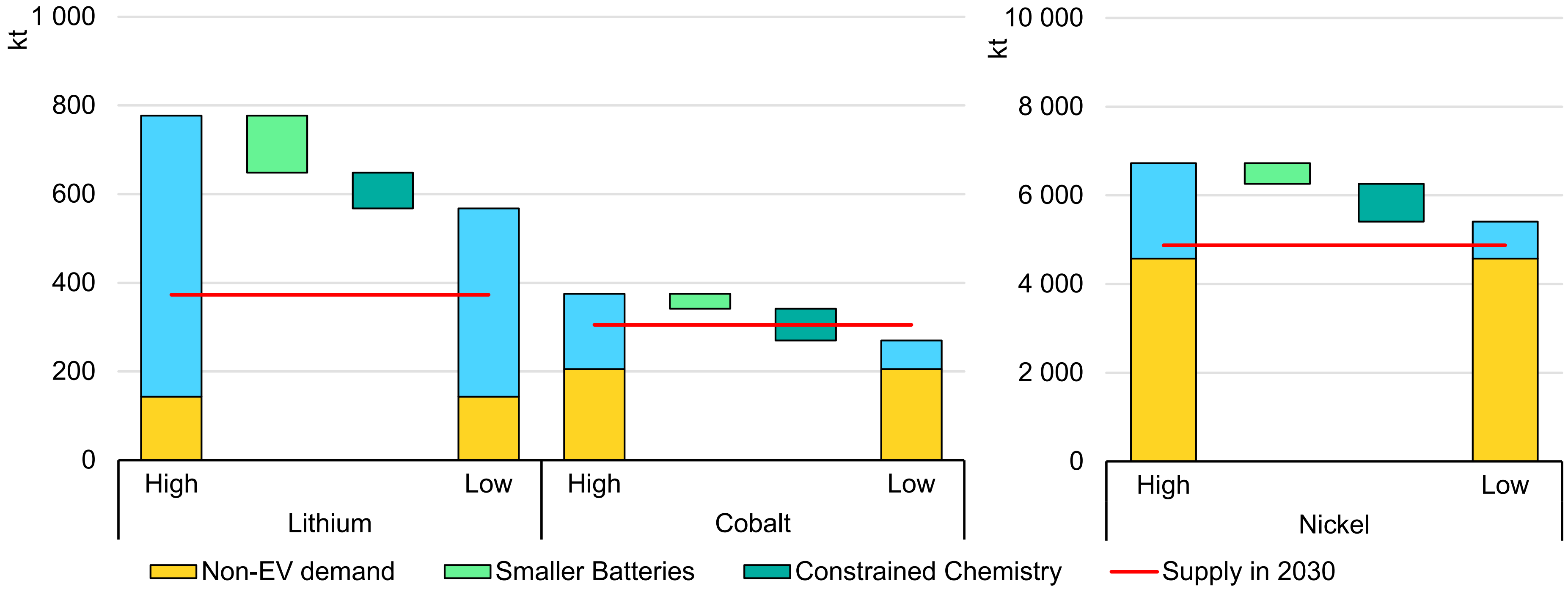
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

Demand side measures such as limiting the growth of battery size can help bridge the gap

Measures to lower metal demand in 2030 in the Net Zero Scenario



Notes: NZE = Net Zero Emissions by 2050 Scenario; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.
Sources: IEA analysis based on Benchmark Mineral Intelligence for supply capacity.

The Net Zero Emissions by 2050 pathway requires more supply than currently planned

The projected demand for battery metals in the Net Zero Emissions by 2050 Scenario (Net Zero Scenario) is significantly higher than current demand. Demand in this scenario in 2030 is projected to increase by 30% per year for lithium, 11% for nickel and 9% for cobalt. By comparison, supply of lithium in the past five years has increased 6% per year, nickel by 5% and cobalt by 8%. Therefore, meeting the Net Zero Scenario demand for electrification requires large investments in the supply of battery minerals – just as in all other clean energy technology sectors. However, actions can be taken to minimise demand by addressing two key levers: mineral intensity of batteries and average battery size per vehicle.

Average battery sizes increased by 60% between 2015 and 2021. This reflects both increased average driving range and increased average energy consumption, as a larger share of electric cars are SUVs. Vehicles with more than 110 kWh batteries are already being produced. In the coming years, if current trends continue, we expect battery sizes to continue to increase by up to 30% in 2030. In the Net Zero Scenario, this trend could be curbed by enacting policies that discourage vehicles with extremely large batteries, for example by linking incentives to battery sizes or, in the longer term, taxing EVs with large batteries. If by 2030 battery sizes remained equal to today, 16% of incremental battery metal demand could be avoided.

Innovative battery chemistries in the Net Zero Scenario scenario are developed more rapidly, following an increase in investment for innovation. For example, all-solid-state batteries are expected to enter the market earlier than in the Stated Policies Scenario. If innovation focussed on minimising the material footprint in the Net Zero Scenario, by following the Constrained Chemistries cathode mix, demand for the key battery metals would decrease by up to one-third.

In addition, the Net Zero Scenario investment in innovation may also bring forward novel extraction and processing technologies, such as DLE, clean HPAL and re-mining from mining waste, that can all contribute to increasing supply.

Innovation can help bridge the gap between demand and supply of metals for batteries

Direct lithium extraction can increase production from existing mines

Direct lithium extraction (DLE) is a process largely in the pilot stage today. It bypasses the time-intensive need to evaporate the unconcentrated brine water and chemical removal of impurities. Instead, DLE technologies directly extract lithium from unconcentrated brine either through adsorption, ion exchange or solvent extraction techniques. DLE relies on high selectivity technologies which can extract lithium from complex and varied brines and reject impurities.

As well as offering cost and lead time advantages, DLE has sustainability advantages and widens the pool of economically extractable lithium supply. For example, areas unsuitable for evaporation ponds such as lithium-rich geothermal brines, where there is significant resource, such as the Salton Sea in California. Environmental impacts can be considerably reduced compared to conventional hard rock mining and evaporative pond processes.

Nevertheless, achieving robust selectivity and scaling up DLE technologies remains challenging. For example, many DLE technologies must be tuned to the conditions of the brine. DLE is an emerging process yet to be tested at scale, however, several companies are leading in the development of DLE projects such as POSCO, Standard Lithium and Vulcan Energy. There are mining companies looking to use DLE as well as companies developing DLE technology, with a number of joint ventures being formed.

Novel nickel routes can increase the variety of supply sources

Batteries require Class 1 nickel, typically from sulphide deposits. Most production growth in the near future, however, is coming from regions with significant laterite resources, which produce Class 2 nickel, such as Indonesia and the Philippines.

There are novel technologies which can convert low grade laterite resources into Class 1 nickel. HPAL (high-pressure acid leaching) is a form of hydrometallurgy that uses acid separation under high temperature and pressure to produce nickel at Class 1 grade suitable for battery applications.

HPAL however, comes with significant challenges, predominantly due to cost and lead times. Capital costs for HPAL projects typically are double that of conventional smelters for oxide ore and take about four to five years to reach capacity. Recent projects have also suffered from major delays and cost overruns. Nevertheless, projects are coming online with China leading investment in HPAL projects, particularly in Indonesia. Indonesia's first HPAL battery nickel project, a joint venture between Indonesian company Harita Group and Chinese company Ningbo Lygend Mining Co. started operating in 2021. There are also concerns with the environmental impact of HPAL as it often uses coal or oil-fired boilers for heat, thus emitting up to three times more GHG emissions than production from sulphide deposits. There are companies attempting to make HPAL more sustainable such as Clean Teq, a company developing a solar-powered HPAL project in Australia, where steam and heat are also recovered.

Mixed hydroxide precipitate (MHP) is becoming increasingly important as an intermediate product produced from laterite, which can be refined into nickel and cobalt sulphates needed for batteries at low cost. MHP can also be processed into nickel and cobalt products from selective acid leaching, a process with a lower environmental footprint. MHP, often produced from HPAL, is becoming an important feedstock over nickel metal due to its lower cost and the expected increase in availability.

Another method being explored is the conversion of nickel pig iron (low grade 3-12% nickel) into an intermediate grade nickel matte (>50% concentration), a precursor to nickel sulphate used for batteries. This would significantly increase the pool of potential nickel able to be used in batteries, however, it is a highly emissions-intensive process (four times more than HPAL) and much more than conventional sulphide production. Tsingshan, the major Chinese steel producer, is pursuing this process and made its first shipment in 2022. The economics are uncertain with another facility in New Caledonia having closed as it was too expensive. Tsingshan is looking to utilise clean energy for its operation to reduce the impact, however, the process uses a significant amount of direct fuels, raising into question its realisable potential for reducing emissions in line with other techniques.

Re-mining from mining waste

Recovery from mining waste, refered to as re-mining, is a novel process of extraction of valuable minerals and metals from mine tailings, waste water and rock. This is a potentially significant source of supply that so far has been unrealised. For example, tailings for nickel and copper mining were 4 billion tonnes in 2017. There are several start-ups focussing on this including the Rio Tinto backed start-up Regeneration.

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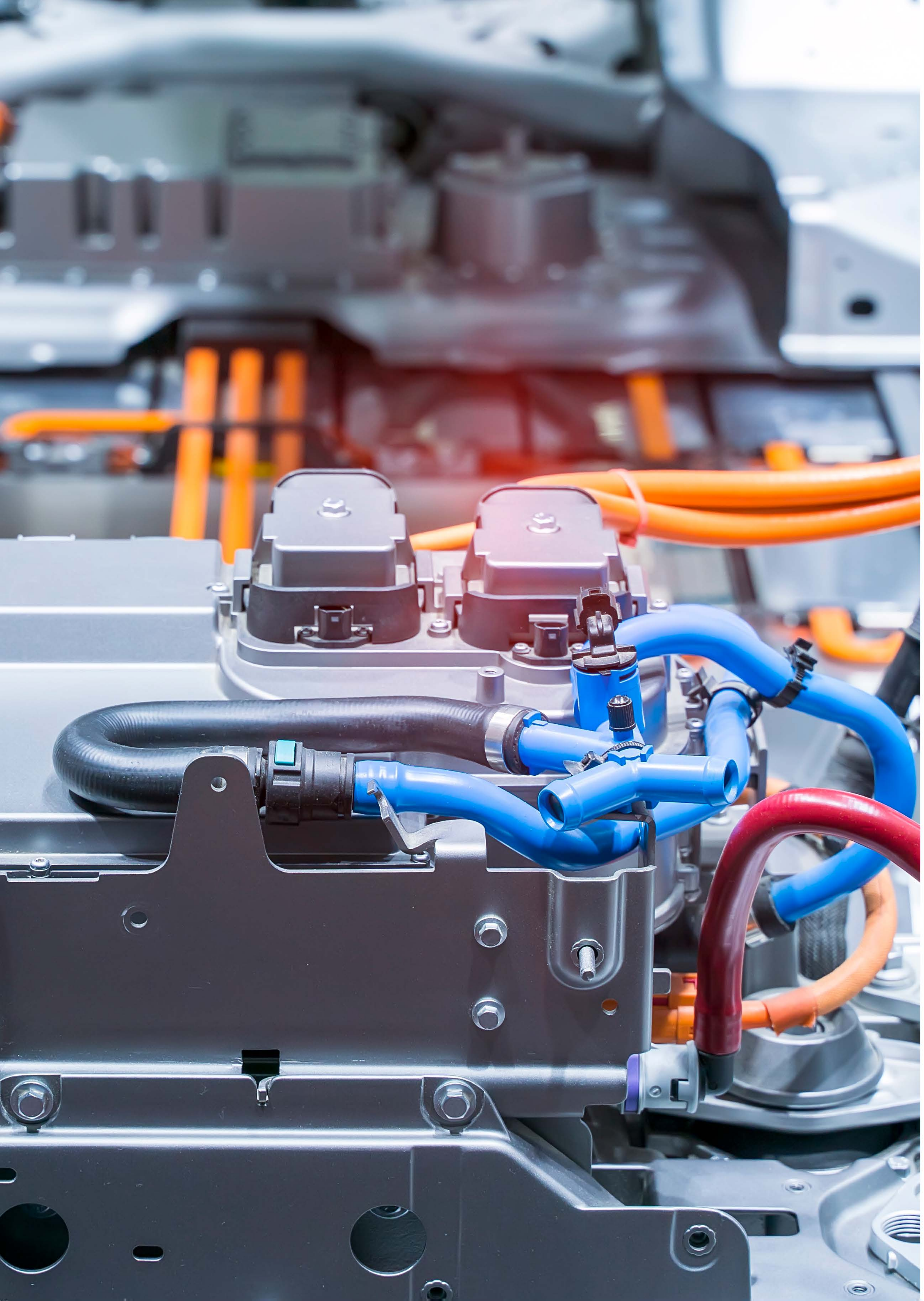

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