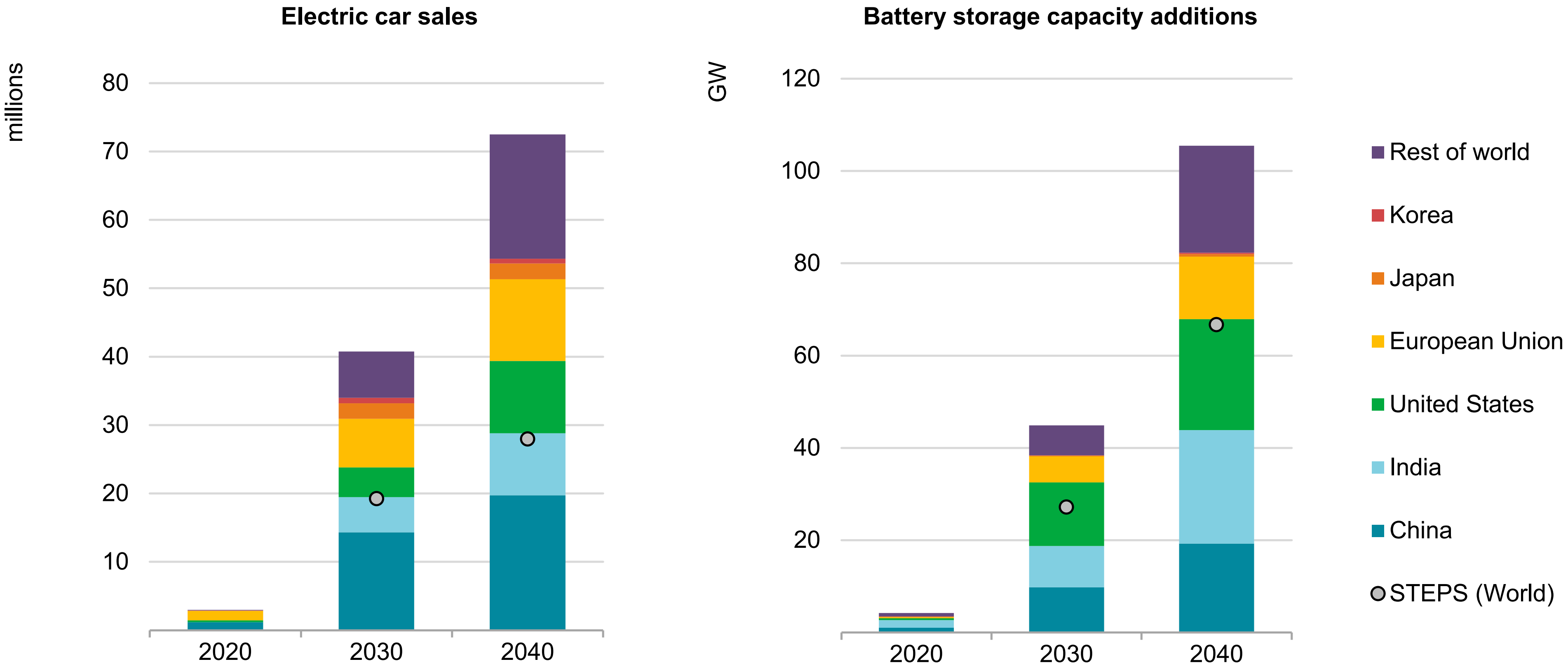
Electric vehicles and battery storage

The adoption of EVs and battery storage is set to accelerate rapidly over the coming decades

Annual electric car sales and battery storage capacity additions in the SDS



Notes: Electric cars include battery electric and plug-in hybrid electric passenger light-duty vehicles, but exclude 2/3-wheelers.
Source: IEA (2020c).

Policy support will continue to play a key role in accelerating the growth in EVs and battery storage, alongside a wider range of model offerings from automakers

EVs

Electric car sales worldwide climbed 40% in 2020 to around 3 million, reaching a market share of over 4% (IEA, 2021). As a result, more than 10 million electric cars are now on the road globally. However, to achieve global climate goals, their share of sales needs to climb rapidly to around 40% by 2030, alongside the rapid electrification of light commercial vehicles, buses and freight trucks.

Policy support has been a major driver of initial EV deployment, and will continue to play a critical role in accelerating the growth of the EV fleet over the coming decades. As of April 2021, over 20 countries and 70 subnational and city governments have announced 100% zero-emission vehicle targets or the phase-out of internal combustion engine (ICE) vehicles before 2050 (Cui et al., 2020; Hall et al., 2020; IEA, 2021; Wappelhorst & Cui, 2020).

Most major car markets currently offer some form of subsidy or tax reduction for the purchase of electric cars as well as support schemes for deploying charging infrastructure (IEA, 2020b, 2021). Provisions in building codes to encourage charging facilities and the "EV-readiness" of buildings are becoming increasingly common. So too are mandates to build fast charging infrastructure along highways.

Policy developments over the past year have been positive for EVs, and are discussed in further detail in *Global EV Outlook 2021* (IEA, 2021). In the European Union, increased stringency of the CO_2 emissions regulation for cars and vans in 2021 and beyond should contribute to maintaining the momentum for EV deployment. The European Commission is also in the process of revising the 2025-2030 targets for CO_2 emissions regulation for cars and vans, the Alternative Fuels Infrastructure Directive, the Batteries Directive and the EURO pollutant emissions standard.

Sales are likely to grow in Japan and Korea over the near term, with these governments significantly increasing EV subsidies. China has set a target of 20% of vehicle sales to be ZEVs by 2025, and announced plans to phase out conventional gasoline-powered vehicles by 2035 (General Office of the State Council of the People's Republic of China, 2020; Nishiyama, 2020). In India, national, state and city governments have announced efforts to accelerate the adoption of EVs. For example, New Delhi recently announced major EV subsidies and awareness programmes to achieve its target for battery EVs to account for 25% of all new vehicles sales by 2024 (Times of India, 2021).

In the United States stimulus measures and longer-term goals adopted by the new administration will be critical to further accelerating EV deployment. In particular, the new administration appears likely to prioritise fuel economy standards, promote charging station deployment, provide tax credits and help factories making internal combustion engine cars retool to make EVs.

Several major automakers have announced plans to invest aggressively in EVs and to rapidly scale up model availability. There were around 370 EV models available in 2020, a 40% increase from 2019 (IEA, 2021). Automakers have announced plans to have an additional 450 models available by 2022 (McKinsey, 2020). General Motors recently announced plans to phase out conventional gasoline and diesel vehicles by 2035, while Volvo's CEO indicated that the company would only sell EVs by 2030 (Campbell, 2021).

Emerging technologies and business models such as shared and/or autonomous vehicles – expected to have much more intensive use patterns than privately owned vehicles – could alter demand projections for new vehicles and minerals over the longer term. However, given the uncertainty of their uptake, we do not consider these trends within the scope and timeline of this analysis.

Battery storage

As of the end of 2020, around 15.5 GW of battery storage capacity were connected to electricity networks. After annual installations of battery storage technologies fell for the first time in nearly a decade in 2019, they rebounded by over 60% in 2020 (BloombergNEF, 2021; IEA, 2020a).

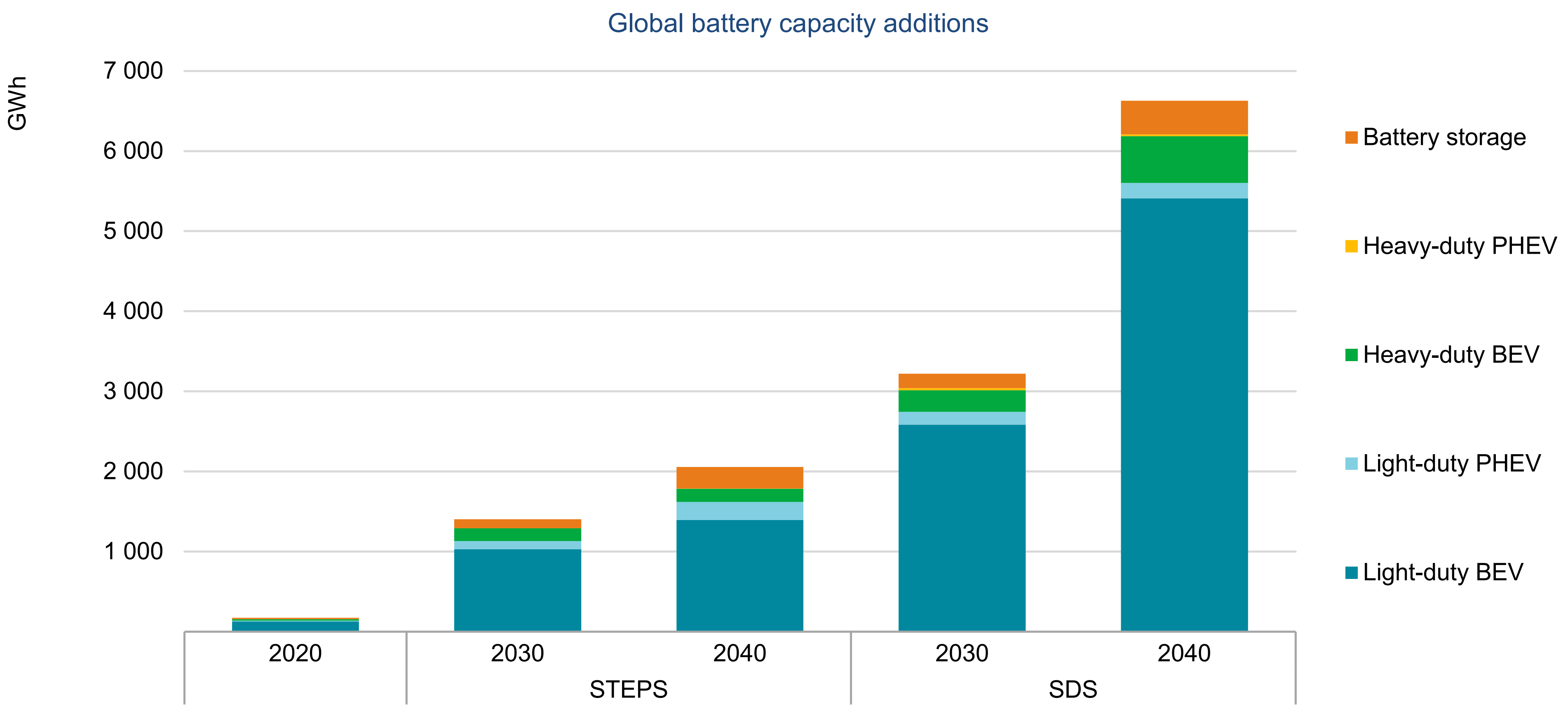
Prospects for battery storage systems look set to improve as advances in technological innovation and new business models emerge. Battery storage systems are well suited to short-duration storage that involves charging and discharging over a span of hours or days. This makes them a good partner for short-run fluctuations in the output from variable renewables, and there is a growing trend for battery storage paired with solar PV and wind.

In the SDS, global installation of utility-scale battery storage is set for a 25-fold increase between 2020 and 2040, with annual deployment reaching 105 GW by 2040 (IEA, 2020c). The largest markets for battery deployment in 2040 are India, the United States and China.

The growth of battery storage remains strongly dependent on effective regulation that reflects the value of the flexibility services it provides and enables fair access to markets. The need to properly value the high performance of battery storage systems, including their accurate and fast frequency response, is one aspect of a broader need for wholesale electricity market reform in the face of rapidly evolving power systems.

A number of regulatory barriers specific to batteries are starting to be addressed, including the rates applied to behind-the-meter batteries and the issue of double-charging, where energy storage systems are charged twice for using the grid – once when charging and again when discharging.

EV and battery storage deployment grows rapidly over the next two decades, with light-duty EVs accounting for around 80% of the total



Notes: Light-duty includes passenger light-duty vehicles, light commercial vehicles, and two- and three-wheelers. Heavy-duty vehicles include medium-sized freight trucks, heavy freight trucks and buses. BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; GWh = gigawatt hour.

Source: IEA (2020c).

A range of minerals are needed in EV motors and batteries

Most of the critical minerals in EVs are in two components: electric motors and batteries.

EV motors

The two most common electric motor technologies for plug-in EVs are permanent-magnet synchronous motors and asynchronous induction motors (Ballinger et al., 2019).

Permanent-magnet motors have the highest efficiency and power density, but their use of REEs make them expensive compared to other technologies. In addition to neodymium (0.25–0.50 kg/vehicle) and other REEs (0.06–0.35 kg/vehicle), permanent-magnet motors also require copper (3–6 kg/vehicle), iron (0.9–2 kg/vehicle) and boron (0.01–0.03 kg/vehicle) (Ballinger et al., 2019; Fishman et al., 2018; Nordelöf et al., 2019; Sprecher et al., 2014).

Induction motors have the advantage of lower costs, but only have moderate efficiencies due to electrical losses in copper windings. While induction motors do not require REEs, they require a substantial amount of copper (11–24 kg/vehicle) for the rotor cage and copper stator (Ballinger et al., 2019).

We assume that permanent-magnet motors remain the dominant EV motor. We discuss alternative motors and the implications of high REE prices at the end of the EV section.

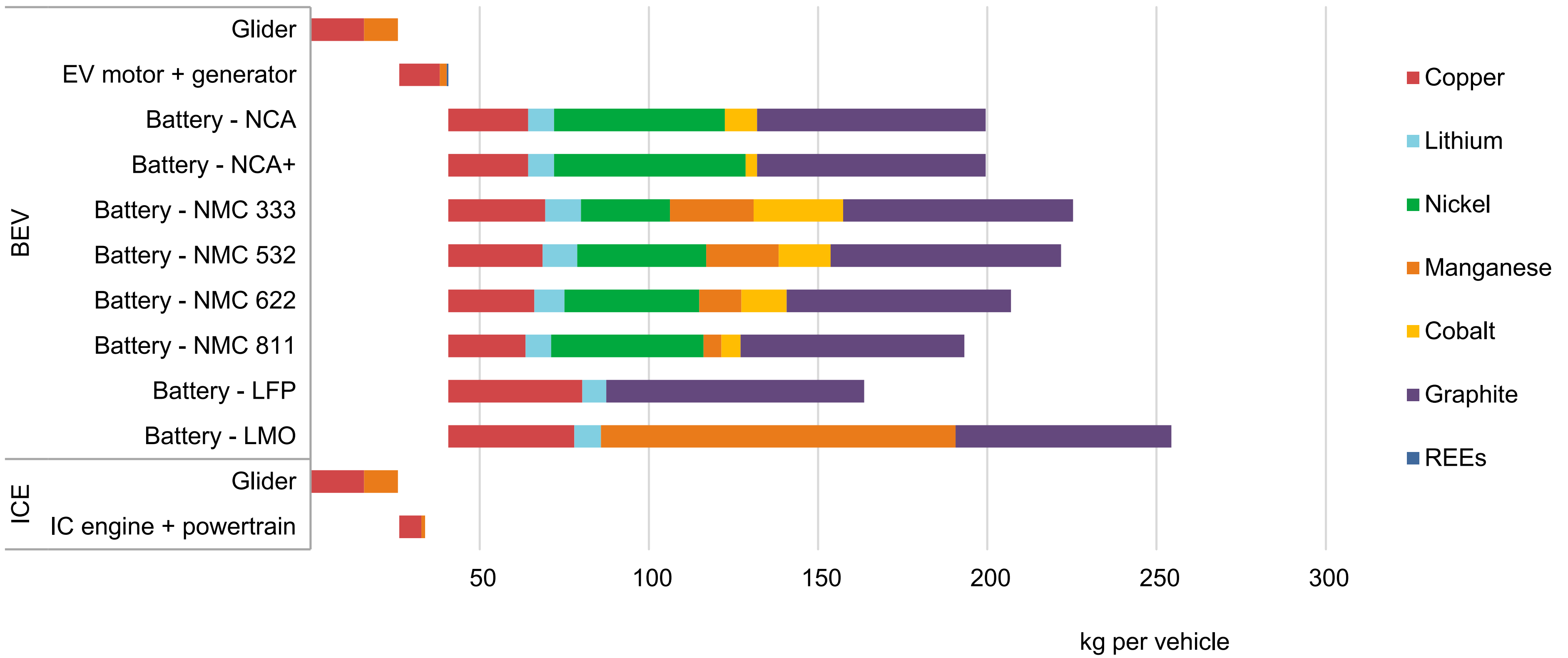
Batteries

Lithium-ion batteries used in EVs and energy storage are composed of battery cells contained in battery modules within a battery pack. Cells typically account for 70% to 85% of the total battery weight, and contain a number of minerals in the active cathode material (e.g. lithium, nickel, cobalt and manganese), anode (e.g. graphite), and current collector (e.g. copper) (Argonne National Laboratory, 2020a). The remaining modules and pack components consist mostly of aluminium, steel, coolants and electronic parts.

The need for each mineral varies considerably depending on the cathode and anode chemistries. For example, nickel manganese cobalt oxide (NMC) 111 batteries typically require almost eight times more cobalt than nickel cobalt aluminium oxide (NCA+) batteries, but half as much nickel. Lithium iron phosphate (LFP) batteries do not require nickel, cobalt or manganese, but need about 50% more copper than NMC batteries.

EVs use around six times more minerals than conventional vehicles

Typical use of minerals in an internal combustion engine vehicle and a battery electric vehicle



Notes: For this figure, the EV motor is a permanent-magnet synchronous motor (neodymium iron boron [NdFeB]); the battery is 75 kilowatt hours (kWh) with graphite anodes.

Sources: Argonne National Laboratory (2020b, 2020a); Ballinger et al. (2019); Fishman et al. (2018b); Nordelöf et al. (2019); Watari et al. (2019).

The evolution of cathode and anode chemistries could drive mineral use for batteries in varying directions

From the perspective of global energy transitions, the last ten years have proved to be the decade of the lithium-ion battery. The 2019 Nobel Prize-winning innovation not only transformed the world of electronics and realised the dream of electric mobility more rapidly than any of its predecessors, but it is also widely considered to be a vital missing piece of the puzzle integrating greater shares of variable renewables into our conventional electricity networks.

The fundamental advantage of lithium-ion batteries over alternatives like lead acid or nickel cadmium batteries is their much higher energy density. While lead acid batteries have specific energies in the range of 35 to 40 watt-hours per kilogramme (Wh/kg), lithium-ion batteries have a range of around 90–260 Wh/kg. This allows them to be stacked into far lighter and more compact battery packs than those made of other materials. The four main components of a lithium-ion cell are the cathode, anode, liquid electrolyte and separator. The lithium-ion donor from the cathode that travels through the liquid electrolyte is the primary determinant of cell properties and gives the technology its name.

Cathode chemistries

Lithium-ion batteries are often categorised by the chemistry of their cathodes. The most commonly used varieties are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). The different combination of minerals gives rise to significantly different battery characteristics.

Among the variants, LCO has the greatest energy density. Its high specific energy (150–190 Wh/kg) and technological maturity makes it a popular choice for portable electronics. The main drawback of the LCO battery is its thermal instability and its relatively short cycle life (500–1 000 full cycles). Coupled with safety concerns, LCO batteries are not favoured for application in EVs.

The LMO battery has a high specific power, a longer cycle life (1 000–1 500 cycles) and much better thermal stability than LCO. Being cobalt-free is often considered as a key advantage of this chemistry. However, it has a notably lower energy density, in the range of 100–140 Wh/kg. Presently, it finds use in the production of electric bikes and some commercial vehicles.

The LFP battery offers thermal stability even at high temperatures, low cost and high durability (up to 2 000 full cycles while maintaining its performance). However, its relatively low specific energy (90–140 Wh/kg) is a limitation for use in long-range EVs compared with other chemistries. Nevertheless, LFP batteries could be particularly favoured in stationary energy storage applications and heavy-duty vehicles like trucks where the size and weight of a battery are secondary considerations. Automakers in China are showing renewed interest in using LFP technology for manufacturing electric cars as they are cheaper, safer, simpler to package and do not require the use of cobalt or nickel. Volkswagen recently announced plans to use LFP batteries in its entry-level models (S&P Global Platts, 2021).

The NCA battery has the highest specific energy range (200–250 Wh/kg) in the current class of technologies as well as high specific power, combined with a lifetime of 1 000 to 1 500 full cycles. NCA is the technology preferred by manufacturers like Tesla, and has immense potential for use in power systems in backup and load shifting applications. However, they are more expensive than other chemistries.

NMC batteries have longer cycle life (1 000–2 000 cycles) compared to NCA, but a lower energy density (140–200 Wh/kg). It has dominated the BEV and PHEV markets since its commercialisation in the early 2000s. While NCA batteries have higher specific energy to their name, NMC batteries possess longer lifetimes, which makes them the favoured choice for PHEVs. Manufacturers producing both BEVs and PHEVs, such as General Motors, are known to use NMC variants of lithium-ion batteries.

Tug of war between nickel and cobalt

Advancement in lithium-ion battery technology involves more than just the challenge of improving energy density, durability, safety and cost. It also includes the effort to do so while minimising the environmental, social and political costs of acquiring their constituent materials.

Owing to price spikes and concerns over ethical mining practices in the 2010s, EV producers have been working to reduce the amount of cobalt in batteries over the past several years — this implies, in many cases, an increase in the quantity of nickel. NCA batteries transitioned to NCA+, a nickel-rich variant of NCA, and NMC 111 batteries have moved increasingly towards NMC 532, NMC 622 and NMC 811, and could move to even more nickel-rich chemistries (e.g. NMC 9.5.5). This trend of moving away from cobalt could therefore have major implications for the requirement for nickel.

Recent efforts to reduce the use of nickel capitalise on the potential of manganese, which is in relatively ample supply. SVOLT Energy Technology introduced battery cells that have a lower share of nickel and no cobalt by raising the use of manganese (Kane, 2021). A manganese-rich cathode is less expensive and safer than nickel-rich chemistries, but decreases the cathode’s stability, which can have impacts on performance over the longer term (Nunez, 2020).

Anodes must complement the cathode chemistries

Anode materials are selected for their charge collection capability. Graphite is currently the dominant choice for the anode in most lithium-ion batteries, although certain manufacturers also use lithium titanate instead of graphite. Efforts to replace some or most atoms of carbon in the graphite anode with silicon atoms are underway (e.g. Tesla, Porsche) and are expected to drastically improve the energy density of the cells. However, silicon anodes swell during charging, causing its surface to crack and performance to drop.

Another alternative to the graphite anode is pure lithium metal, which also has far greater charge collection capability than graphite. But this anode cannot be used with liquid electrolyte batteries due to undesirable chemical interactions between the electrolyte and the metal anode, which drastically reduces the lifetime of the cell. The use of a lithium metal anode may increase significantly with the advent of all-solid state batteries (ASSBs). Lithium-metal anodes do not have the expansion problem of silicon anodes, but they are expensive and present other technical problems.

Further technology innovation is needed to continue cost reductions

The average cost of lithium-ion batteries has declined by almost 90% over the past decade, falling to USD 137/kWh in 2020 (BNEF, 2020). These rapid cost reductions were made possible thanks to the remarkable growth in EV sales over the past decade and the continued penetration of high-energy density cathodes.

New pack designs and falling manufacturing costs can lead to further cost reductions in the near term. Costs are expected to fall below USD 100/kWh by the mid-2020s, a milestone often considered as one that will bring price parity between EVs and internal combustion engine vehicles (BNEF, 2020).

The path to lower battery costs could follow many routes, depending on a few major factors. First, as demand growth accelerates, maintaining a steady supply to meet that demand and preserve the drop in costs is likely to be increasingly challenging. Next, as we analyse in the next chapter, the sources and supply chains of the various critical minerals that are needed to bring these energy density improvements are often geographically concentrated in certain regions, and an uninterrupted supply cannot be taken for granted. Finally, as we reach the physical limits of improvement with current technology and materials, notable cost reductions can only be achieved by the disruption of the current technology – for example in the form of ASSB with lithium anodes or increased used of silicon in graphite anodes for existing chemistries. Therefore, the continued cost decline at a pace observed during the past decade cannot be taken for granted without a further acceleration in technology innovation.

Innovation on the horizon: The advent of all-solid state batteries

As current technology and materials bring us ever closer to the theoretical limits of improving energy density, and battery prices start to plateau by the middle of this decade, the world needs to look beyond the liquid electrolyte-based lithium-ion batteries. A significant improvement in the energy density of EV batteries and a steep decline in battery prices would require the disruption of the present technology. Such a breakthrough is expected from the advent of lithium metal anode all solid-state batteries (ASSBs).

Most state-of-the-art commercial batteries with NCA, NMC or LFP cathodes require a liquid electrolyte for ion transfer and a graphite-based anode. These two components fundamentally limit the functionality and energy density of lithium-ion batteries today. The flammability of the solvent in the electrolyte raises many safety concerns (Hess et al., 2015), and undesirable reactions between the solvent and the conductive lithium salt lead to capacity fading and ageing (Hendricks et al., 2015). Moreover, the electrolyte filling process makes the production line more cumbersome and expensive (Wood et al., 2015). A compact solid electrolyte not only circumvents these issues but also enables[3] the use of lithium metal as the anode (Varzi et al., 2016).

ASSBs equipped with lithium metal anodes could achieve a volumetric energy density up to 70% greater than today's lithium-ion batteries that have conventional graphite anodes (Janek & Zeier, 2016), making them the ideal batteries for EVs of the future. As an added advantage, ASSB do not require expensive cooling systems due to the absence of a flammable electrolyte. They have in fact displayed better functionality at higher temperatures due to increased conductivity.

While experts predict that current lithium-ion batteries could reach a maximum energy density of 300 Wh/kg after 2025, lithium metal solid-state batteries with densities of 320 Wh/kg have already been fabricated (Placke et al., 2017) and their maximum potential could be as high as 480 Wh/kg. This improvement in energy density would mean that batteries of the same size could contain much more energy in the future, thereby resulting in an effective reduction in the weight and cost of the new battery packs. The greatest challenge facing this new technology is scaling up the production to make it commercially viable, since a direct transfer of laboratory preparation methods to industrial-scale fabrication is not always successful.

[3] Solid electrolytes act as a physical barrier to the formation of lithium dendrites that could form from the lithium anode and short-circuit the cell by connecting the anode and the cathode.

Solid-state lithium metal anode batteries are reported to mostly be designed with NMC cathodes; however, they could also be combined with new cathode chemistries. The use of sulphur in lithium-based cathodes (Li-S) is being viewed as a promising technological avenue because of its very high theoretical energy density. Current prototypes developed by start-ups (Oxis-energy) already reach cell-level energy densities of over 500 Wh/kg; however, they are limited to aerospace applications due to their low cycle life. Another study published by Samsung reported an anode made of carbon black, and silver nanoparticles (Ag-C) coated on stainless steel as the anode (Lee et al., 2020). This allows even better energy density than a lithium metal anode. Nevertheless, for this analysis the ASSB scope is limited to lithium-metal anodes combined with traditional NMC cathodes, due to greater availability of data and information on the prototypes of this technology.

After a robust and cost-effective scale-up process is found, the design of electric cars equipped with ASSB would take between three to five years; this explains why several manufacturers have already begun investing in R&D for this new battery technology. For example, Colorado-based start-up Solid Power already has partnerships with Ford Motor Company and BMW Group, and they believe the roadmap for commercial use of their ASSB in the automotive industry is well-defined. The company estimates a 10–15% reduction in the total cost of a battery pack compared to their liquid electrolyte counterparts, with most of the savings coming from enhanced packing density. If researchers and manufacturers find the solution to mass producing these new batteries within the next five years, ASSB would be competing with the incumbent lithium-ion batteries for space on the roads by the early 2030s and, thus, launch the next phase of electric mobility.

Synergies between EVs and battery storage

Historically, trends from the automotive industry have often transferred to the power sector. Progress on improvement in EV batteries could benefit stationary storage system technologies, while the converse may not necessarily be true. Batteries for EVs must be energy dense, small, safe and light, and have high cycle life. Energy storage systems, by contrast, do not have such strict requirements for size and weight, but instead prioritise cost, durability and safety.

Although NCA and NMC batteries might be considered too expensive for most large-scale energy storage systems, they are ideal for wall-mounted residential batteries used in combination with solar panels, and their price could also be justified in certain large-scale storage applications in cities with high population densities, where space is limited and energy density becomes crucial. A fair compromise between the two applications is the LFP battery, with lower energy density than NMC and NCA, but still small enough for buses and trucks, inherently safer chemical composition, non-reliance on cobalt and nickel, and lower prices more suitable for stationary applications.

Besides lithium-ion batteries, flow batteries could emerge as a breakthrough technology for stationary storage as they do not show performance degradation for 25–30 years and are capable of being sized according to energy storage needs with limited investment. One of the most modern commercial Vanadium redox flow batteries, with a lifetime of 12 000 cycles at full power, went online in eastern Spain to operate with the Vega wind farms in December 2019 (Bellini, 2020). However, flow batteries employ a completely different technology, wherein their specific energy depends on the volume of the electrolyte and specific power depends on the surface area of the electrodes, and they are therefore much too large for EV applications.

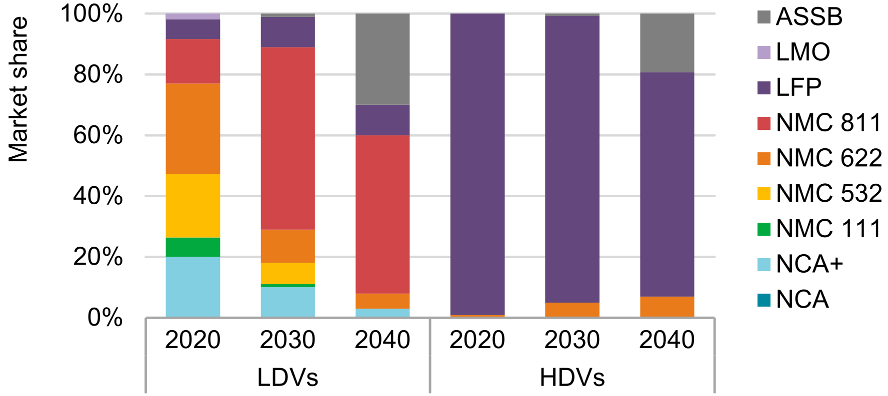
Passenger EVs shift from cobalt towards nickel-rich cathodes, with a slow uptake of solid state batteries

As it has become evident that reducing cobalt content in the cathode and striving for higher energy density are key concerns for most manufacturers and countries, the base case scenario sees a shift away from cobalt-rich chemistries. This is achieved in both NCA batteries and NMC variants, where the ratio of nickel and manganese are increased in the transition from NMC 111 to NMC 532, NMC 622 and ultimately NMC 811.

While most heavy trucks are reliant on LFP batteries in the medium term, our base case also sees modest growth in the market share of LFP for cars due to its increasing use in China and entry-level models from VW.

The base case sees ASSB becoming commercially available by around 2030 and requiring another 5 years for manufacturing capacity to build up. Even in 2040, ASSB remain more expensive than lithium-ion batteries and are therefore limited to premium vehicles and developed countries. In the longer term, heavy trucks operating long haul are likely to use ASSB as soon as they become available because of the great benefits of energy density improvement in these applications. They would enable increased payload, greater operating range and shorter charging times.

EV cathode chemistries in the base case



Notes: LDVs = light-duty vehicles (passenger cars and vans, light commercial vehicles, and 2- and 3-wheelers); HDVs = heavy-duty vehicles (trucks and buses).
Sources: IEA analysis complemented by Adamas Intelligence (2021a) and EV-Volumes (2021).

For the anode, natural graphite is expected to continue to account for the majority of market share. Even as artificial graphite starts to replace natural graphite for reasons of improved purity and hence energy density, a small number of manufacturers choose lithium titanate (LTO) instead of graphite for heavier vehicles due to its fast-charging advantages. The dominance of graphite declines very slightly over the years to make way for nanocomposite graphite doped with silicon and for lithium metal that emerges with the advent of ASSBs.

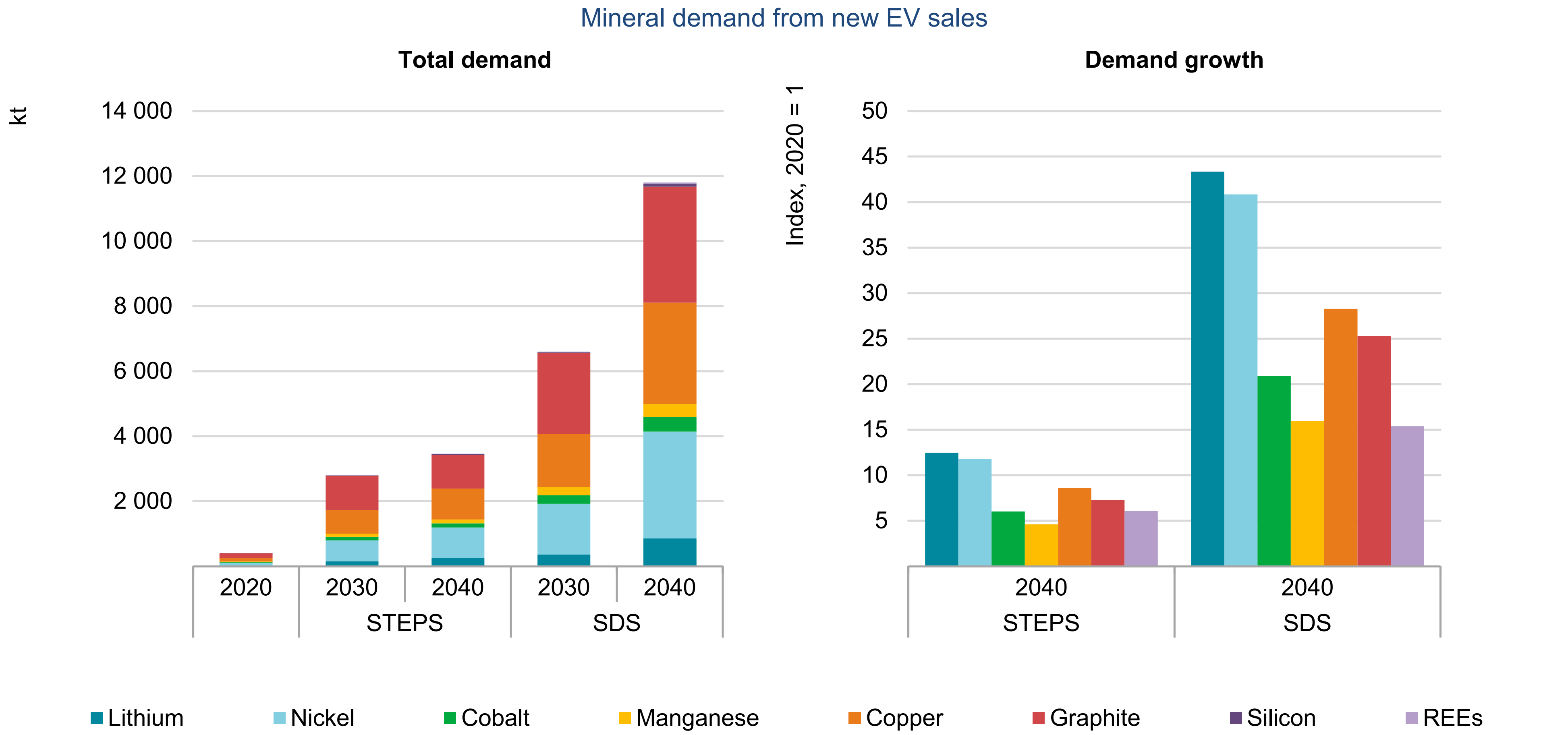
Results

In the SDS, battery demand from EVs grows by nearly 40 times between 2020 (160 GWh) and 2040 (6 200 GWh). Overall demand for minerals under the base case assumptions grows by 30 times between 2020 and 2040, from 400 kt to 11 800 kt. In the STEPS, battery demand from EVs grows just 11 times to nearly 1 800 GWh in 2040, with demand for minerals growing ninefold to around 3 500 kt in 2040.

In the SDS, nickel demand grows by 41 times to 3 300 kt, while cobalt increases by only 21 times, as cathode chemistries shift away from NMC 111 towards lower-cobalt chemistries (NMC 622 and NMC 811). Lithium demand grows by 43 times, while copper grows 28 times.

Graphite demand grows 25 times from 140 kt in 2020 to over 3 500 kt in 2040. Silicon registers the largest relative growth, up over 460 times, as graphite anodes doped with silicon grow from a 1% share in 2020 to 15% in 2040. Demand for REEs grows 15 times to 35 kt in 2040.

Mineral demand for EVs in the SDS grows by nearly 30 times between 2020 and 2040, with demand for lithium and nickel growing by around 40 times



Note: Silicon is excluded from the demand growth graph due to its very high growth (over 500-fold increase), starting from a low base.

Alternative cases for EVs

The base case projections are founded on a set of assumptions, which, when altered due to reasons of technology advancements, could result in scenarios that produce very different results. We therefore built three alternative scenarios and assessed how the demand outlook for various minerals could change under varying technology evolution trends.

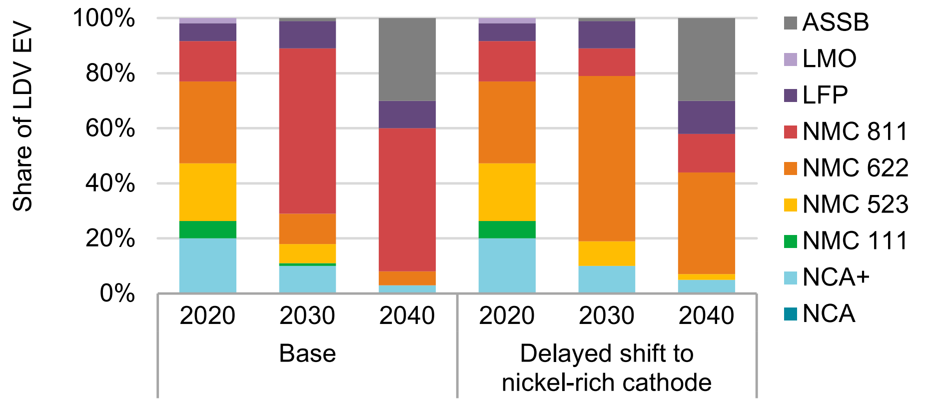
Delayed shift to nickel-rich cathode

On the cathode side, price spikes and social concerns surrounding cobalt mining a few years ago triggered efforts to reduce cobalt content in lithium-ion batteries. But cobalt currently appears to be well supplied, at least in the short term. Instead, a rapid move towards nickel-rich chemistries may be causing signs of tightness in the nickel supply chain. The near-term supply prospects for Class I nickel depend on whether planned projects in Indonesia can be carried out smoothly (see Chapter 3).

The first alternative case therefore explores the outcome of the growing concerns about nickel supply and potential price increases in the medium term. Should there be delays and cost overruns at planned projects, it is not inconceivable for battery-grade nickel prices to rise, in conjunction with relatively stable cobalt prices, to slow shift towards the nickel-rich chemistries.

In this case, we study the impact of a delayed shift to nickel-rich chemistries for NCA and NMC batteries due to supply uncertainties for nickel, while LFP, the emergence of ASSB and anode materials remain as they are in the base case.

Cathode chemistries for light-duty EVs in the delayed shift to nickel-rich cathode case



A delayed shift to nickel-rich chemistries (and away from cobalt-rich chemistries) results in nearly 50% higher demand for cobalt and manganese in 2040 compared to the base case. Nickel demand is 5% lower in 2040 compared to the base case.

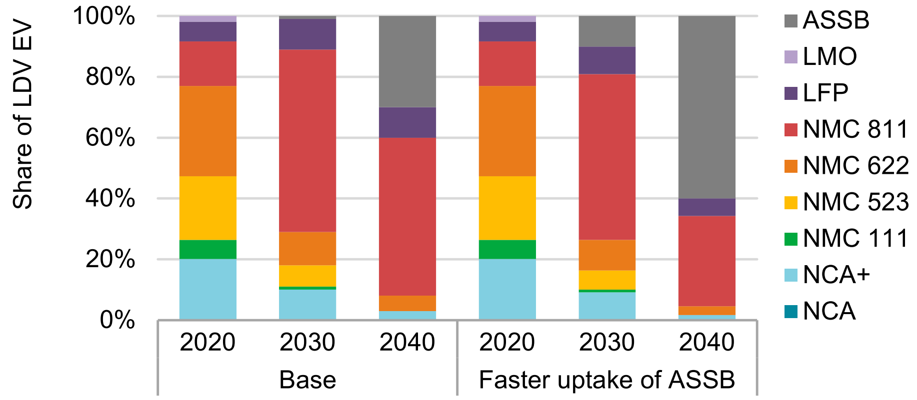
Faster uptake of lithium metal anode all-solid state batteries

While we assumed ASSB to take off meaningfully in the 2030s given the challenges around scale-up, much earlier commercialisation and faster penetration of ASSB in the EV market could alter the outlook for minerals considerably. This would reflect major breakthroughs in ASSB that have been made in recent years. ASSBs are safer as they do not contain a flammable liquid electrolyte and could be cheaper as their cell structure is simpler and does not need cooling mechanisms for safety. They represent disruption of current technology, rather than incremental improvements in existing lithium-ion technologies.

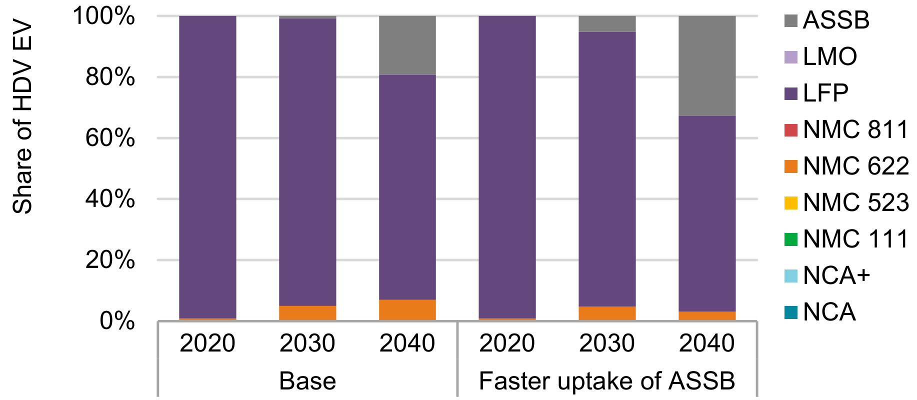
We explore a much faster uptake of ASSB in the EV market, starting with a small market share as early as the late 2020s. Its presence in the market then grows significantly in the 2030s, even taking up more than half the market by 2040 and ultimately capturing around three-quarters of the electric car market by 2050. This case would imply higher consumption of lithium, as ASSBs considered in this report use pure lithium metal anodes instead of graphite. (Lithium metal can only be used as the anode in ASSBs; undesirable interactions with the liquid electrolyte in lithium-ion batteries rapidly reduces the lifetime of the battery.)

The faster uptake of lithium metal anodes and ASSB results in 22% higher lithium demand in 2040 compared to the base case, but also much lower demand for graphite (down 44%) and silicon (down 33%).

Cathode chemistries for light-duty EVs in the faster uptake of ASSB case



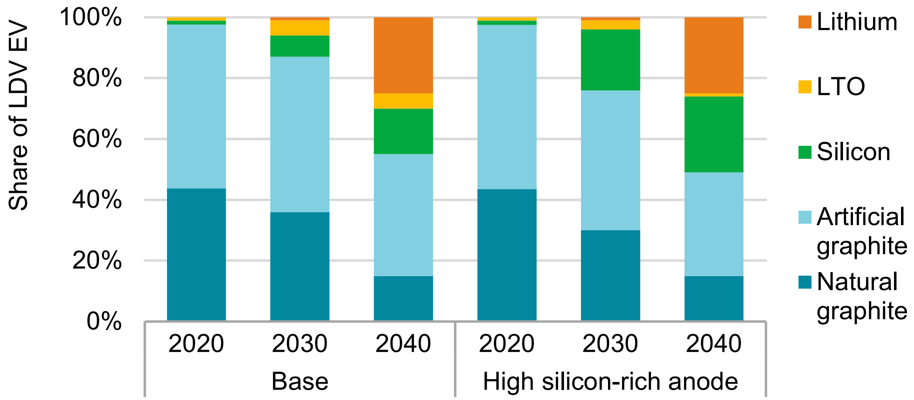
Cathode chemistries for heavy-duty EVs in the faster uptake of ASSB case



Moving more rapidly towards a silicon-rich anode

For the anode, silicon (and lithium) have roughly 10 times as much capacity to hold electrons as graphite and, thus, can improve the energy density of a battery by 20–50%. Many major manufacturers of lithium-ion batteries are increasingly venturing into higher silicon quantities in the anode in order to improve energy density. In this alternative case, we consider the result of achieving higher-level (around 20%) silicon doping for graphite anodes compared to the base case by 2030, and further improvement in the technology leading to even higher doping levels by 2050.

Anode shares for light-duty EVs in the high silicon-rich anode case

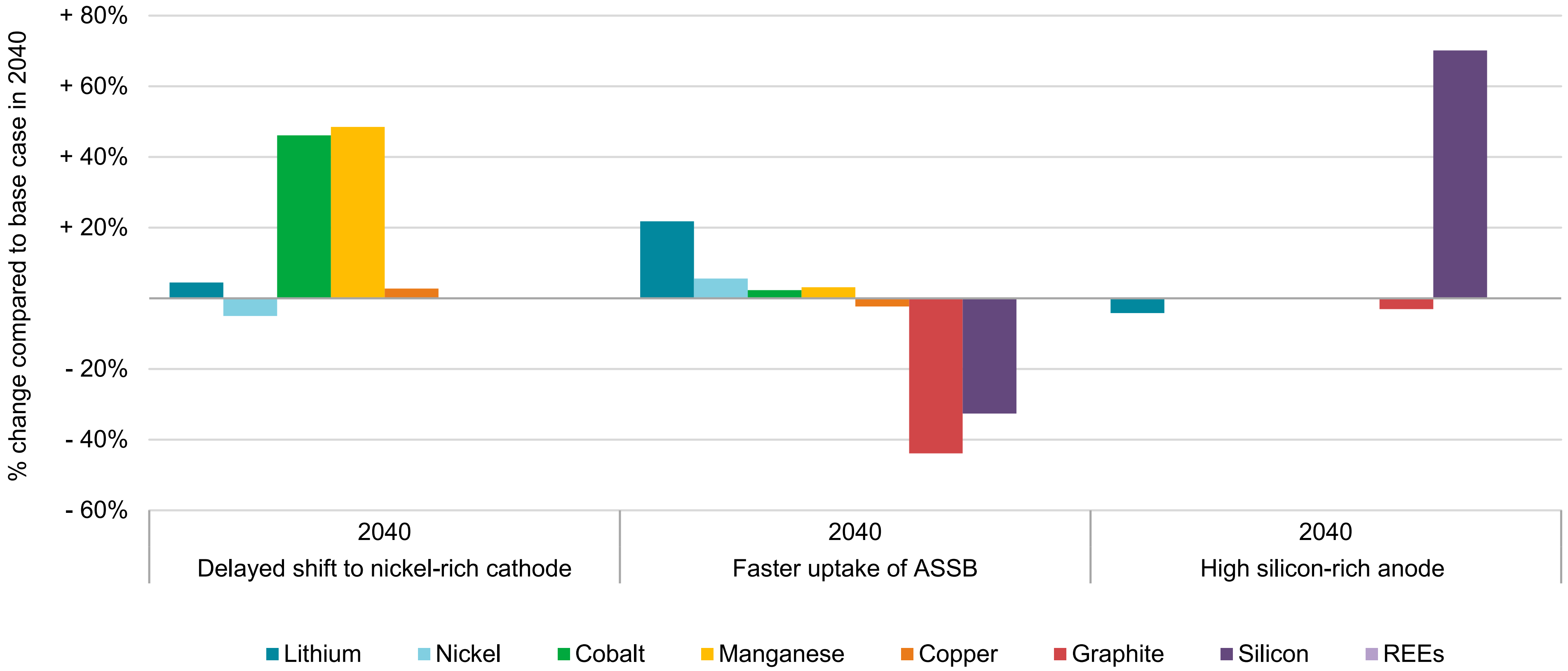


Note: LTO = lithium titanate oxide.

Moving rapidly towards a silicon-rich anode results in nearly three times as much silicon demand in 2030 compared to the base case, and a slight decrease in graphite demand (down 6%). By 2040 silicon demand is only 70% higher, owing to a higher adoption of silicon-rich anodes even in the base case.

The alternative cases demonstrate the considerable sensitivity and uncertainty of mineral demand to the future mix of EV battery chemistries

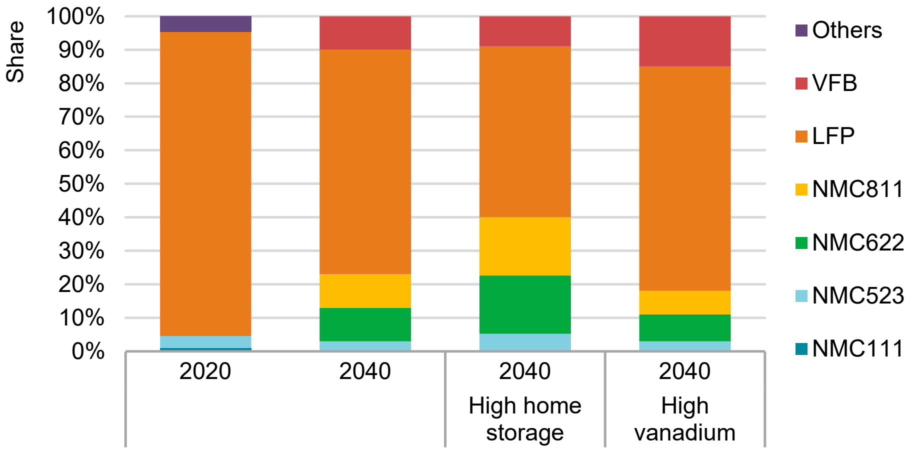
Change in mineral use for EVs in alternative cases relative to the base case in the SDS



Utility-scale storage is expected to dominate the battery storage market

Safe and cheap LFP batteries for utility-scale storage are expected to dominate the overall battery storage market. The remaining demand is covered by the more expensive, but energy-dense, NMC 111 and NMC 532 used predominantly for home energy storage. The NMC variants transition towards NMC 622 and NMC 811 in a similar way to the market for EV batteries, albeit with a delay owing to the time needed for transfer of technology and sufficient reduction in prices. Vanadium flow batteries (VFBs) first become commercially suitable in 2030 with a small share, growing modestly to capture a wider market for storage applications in large renewables projects.

Cathode chemistries for storage

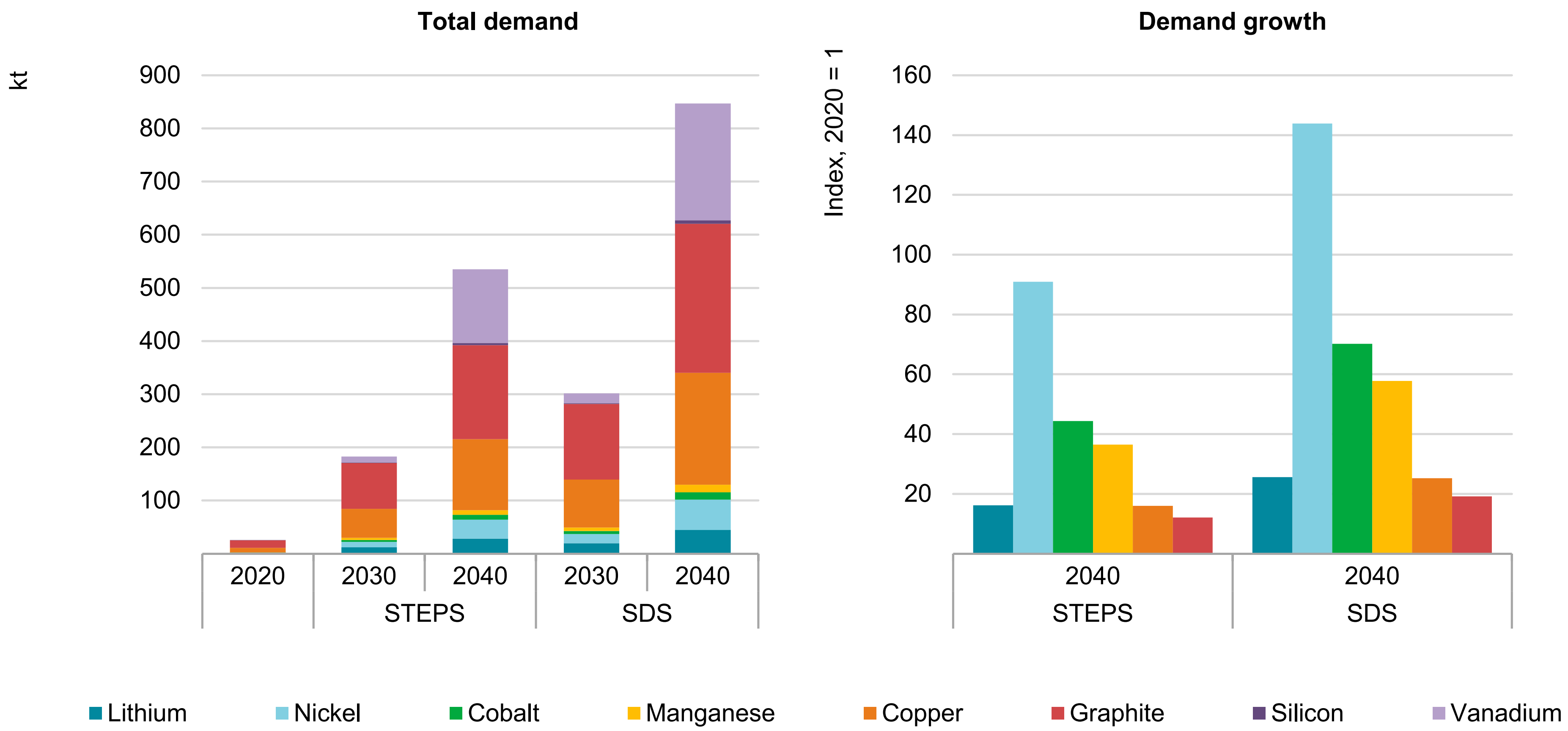


In the SDS, battery storage grows by 11 times between 2020 (37 GWh) and 2040 (420 GWh). Overall demand for minerals in the base case grows by 33 times between 2020 and 2040, from 26 kt to nearly 850 kt. Overall mineral demand outpaces battery demand growth, as the market share for LFP batteries is displaced by more mineral-intensive NMC chemistries.

The largest relative growth is seen in nickel, which grows more than 140 times from 0.4 kt in 2020 to 57 kt in 2040. Cobalt demand increases by 70 times while manganese demand increases by 58 times.

Mineral demand for storage in the SDS grows by over 30 times between 2020 and 2040, with demand for nickel and cobalt growing by 140 times and 70 times respectively

Mineral demand from battery storage additions in the SDS



Note: Silicon and vanadium are excluded from the demand growth graph.

Alternative cases for energy storage

The base case for energy storage systems is built on the assumption that utility-scale storage forms a major proportion of the demand, wherein cost (and not space) is the primary concern for the technology selection. However, several alternative scenarios could alter the base case projections. For instance, more rapid adoption of wall-mounted home energy storage would make size and thus energy density a prime concern, thereby pushing up the market share of NMC batteries such as those already used by the Tesla Powerwall. Conversely, if the technology for flow batteries, which have the advantage of virtually unlimited energy capacity and very long lifetimes, reaches a stage of widespread commercialisation earlier than expected, then utility-scale storage technology could shift away from LFP batteries towards VFBs.

Rapid adoption of home energy storage

In this alternative case, we investigate the outcome of a scenario where demand for storage beyond utilities grows rapidly. Here, the NMC battery share grows faster, achieving around a quarter of the market share by 2030 and almost half by 2050. They are used in applications such as home energy storage (e.g. storing solar electricity for self-consumption, time-of-use load shifting, backup power and increased off-grid applications). In many of these applications, space is one of the most important concerns, making the more energy-dense NMC more favourable than their LFP counterparts. The split between NMC 532, NMC 622 and NMC 811 evolves more or less as for the EV batteries base case. The trajectory for VFBs remains as for the base case.

The rapid adoption of home energy storage with NMC chemistries results in 75% higher demand for nickel, manganese and cobalt in 2040 compared to the base case. A faster uptake of silicon-rich anodes also results in 20% greater demand for silicon compared to the base case in 2040.

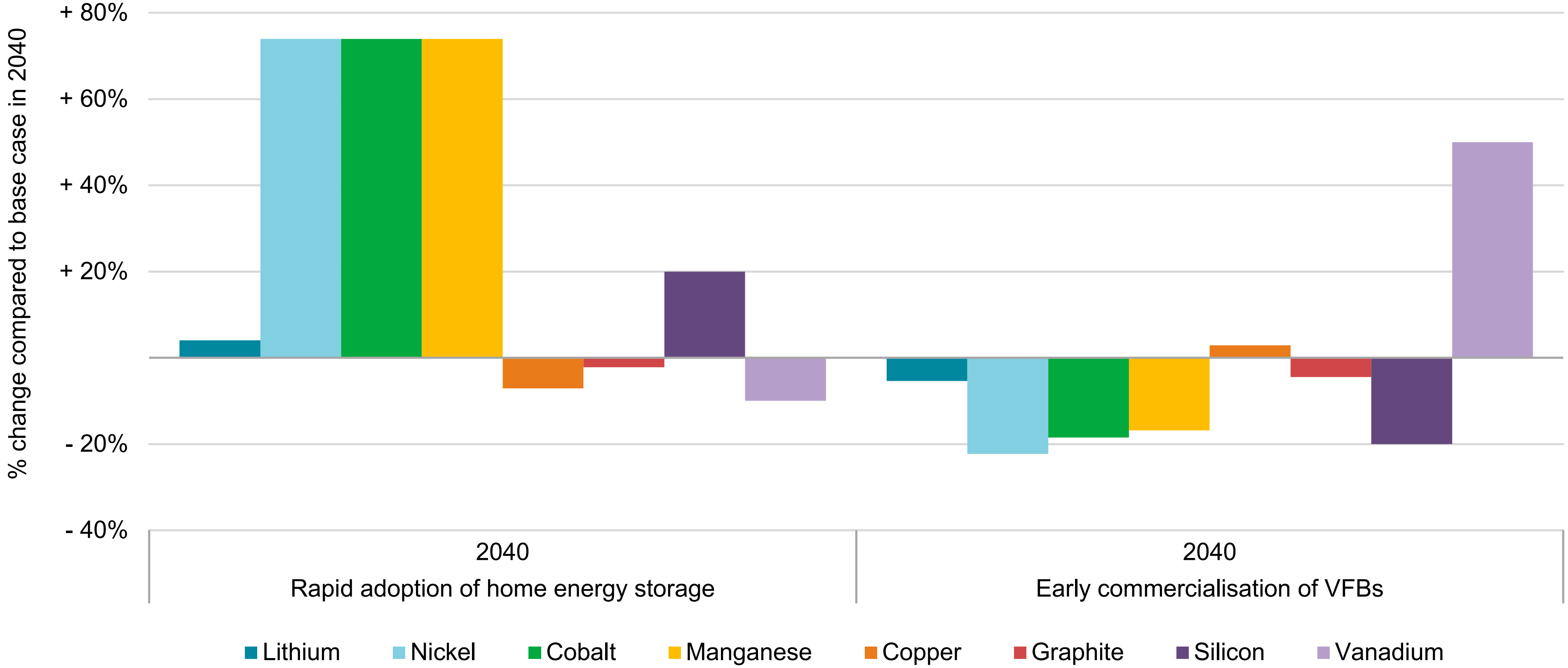
Early commercialisation of Vanadium flow-batteries

In this case, the technology for VFBs reaches the level of maturity required to be deployed in large-scale projects earlier than in the base case. They increase their market share from 2030 onwards and capture almost a third of the energy storage market by 2050, with maximum applications in large wind and solar farms.

The early commercialisation of VFBs results in 2.5 times more demand for vanadium compared to the base case in 2030 and 50% more demand in 2040. As a result of lower market shares for NMC chemistries, demand for nickel, cobalt and manganese are about 20% lower in 2040 compared to the base case.

More rapid adoption of home energy storage could increase demand for nickel, cobalt and manganese – but these increases are dwarfed by demand from EVs

Mineral use for battery storage in alternative cases relative to the base case in the SDS



Could mineral prices be an obstacle for further battery cost declines?

The average cost of lithium-ion batteries has fallen dramatically over the past decade, reaching USD 137/kWh in 2020 (BloombergNEF, 2020). Further cost reductions are necessary for EVs to achieve the adoption rates observed in the SDS. In the near term, the US Department of Energy has set a target of reaching USD 125/kWh by 2022 for BEVs to attain cost parity with internal combustion engine vehicles. Tesla expects to slash costs by half between 2020 and 2023 to achieve pack costs of around USD 60/kWh (Irvine & Rinaldo, 2020). The SDS requires battery prices to reach USD 100/kWh by 2030.

Several automakers are scaling up battery production to drive further cost reductions. For example, Tesla’s first Gigafactory in Nevada began mass production of cells in January 2017, helping to reduce battery production cost by 30%. In addition to scaling up production volume, further cost reductions can be achieved by optimising cell fabrication to increase energy density, reducing manufacturing costs and enhancing pack assembly efficiency (Ding et al., 2019).

However, with major technological improvements achieved over the past decade, raw materials now account for the majority of total battery costs (50–70%), up from around 40-50% only five years ago (Argonne National Laboratory, 2020a; Pillot, 2017, 2019). Cathode (25–30%) and anode materials (8–12%) account for the largest shares. Labour costs account for around 2–4%.

Models used to project future battery costs typically rely on production volume assumptions and technology learning rates. However, the growing share of raw materials in total battery costs implies that this approach based on economies of scale and efficiency improvement might not provide a good guide to future cost developments, as raw material costs may well develop in a different direction from other cost components.

Given the importance of material costs in total battery costs, higher mineral prices could have a significant effect on achieving industry cost targets. For example, a doubling of lithium or nickel prices would induce a 6% increase in battery costs. If these events happen at the same time, the cost increase would eat up the anticipated learning effects associated with a doubling of capacity.

It is therefore of paramount importance for governments and industry to work to ensure adequate supply of battery metals to mitigate any price increases, and the resulting challenges for clean electrification.

High prices for rare earth elements could see a shift away from permanent-magnet motors towards induction motors, increasing demand for copper or aluminium

Over 90% of the EVs marketed today use permanent-magnet synchronous motors due to their high efficiency, compact size and high power density (Adamas Intelligence, 2021b; Pavel et al., 2017). However, their use of REEs such as neodymium, praseodymium, dysprosium and terbium – upwards of 1 kg per motor – raises concerns given the geographical concentration of raw material and processing in China, the lack of recycling pathways and high price fluctuations. For example, the price of neodymium has surged over the past six months from around USD 60/kg in June 2020 to over USD 120/kg in February 2021.

There are several pathways to reducing REE use in EV motors: (i) improving material efficiency in magnet production to obtain NdFeB magnets with less REE content but with similar performance; (ii) reducing the amount of NdFeB magnets in permanent-magnet synchronous motors; (iii) substituting permanent-magnet motors with REE-free motors.

Improved material efficiency in magnet production can reduce REE content in permanent magnets but with similar performance characteristics. For example, material efficiency for neodymium and praseodymium may improve by up to 30% between 2015 to 2030 in a permanent magnet of equal magnetic strength and cost (Pavel et al., 2017).

The use of permanent-magnet motors with less (or no) rare-earth magnets could also reduce REE use. For example, the BMW i3 uses a "hybrid" motor that uses around half the REE. Induction motors use no REEs, but require a substantial amount of copper (11–24 kg/motor) and are less efficient than those with permanent magnets. They are already used in several BEV models, including the Tesla Model S. There are options to also reduce copper use in induction motors: for example, the Audi e-tron uses an aluminium-rotor induction motor. Switched reluctance motors are also REE-free, but are still in the early stages of development.

Summary of motor types

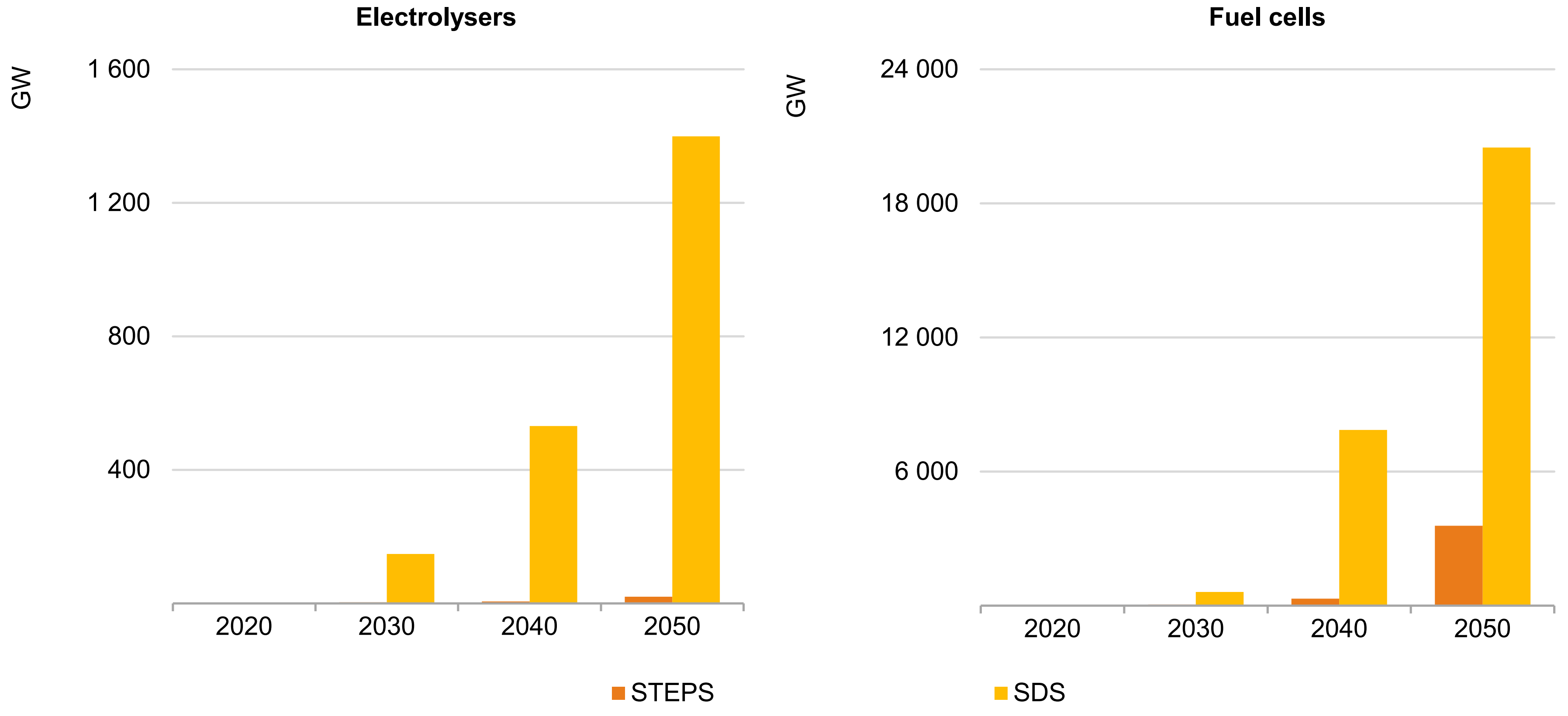
	Mineral use	Current status and examples
Permanent-magnet synchronous	Neodymium, dysprosium, dysprosium, terbium	Used in all HEV and most PHEV and BEV
Induction	No rare earths; but significant copper or aluminium use	Some BEVs (e.g. Tesla S, Mercedes B)
Permanent-magnet without REE	No rare earths; potentially some nickel and cobalt use	Prototypes using ferrite or AlNiCo magnets
Switched reluctance	No rare earths or copper	First prototypes

Note: HEV = hybrid electric vehicle.
Sources: Agamloh et al. (2020); Pavel et al. (2017); Widmer et al. (2015).

Hydrogen

Electrolysers that supply hydrogen and fuel cells that use it in vehicles are both major growth areas in the SDS, and present different mineral requirements

Global installed capacity of electrolysers and fuel cells in the SDS



Source: IEA (2020c).