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Materials Practice

The net-zero materials transition: Implications for global supply chains

The metals and minerals industries must adapt their supply chains to provide critical materials for the energy transition.

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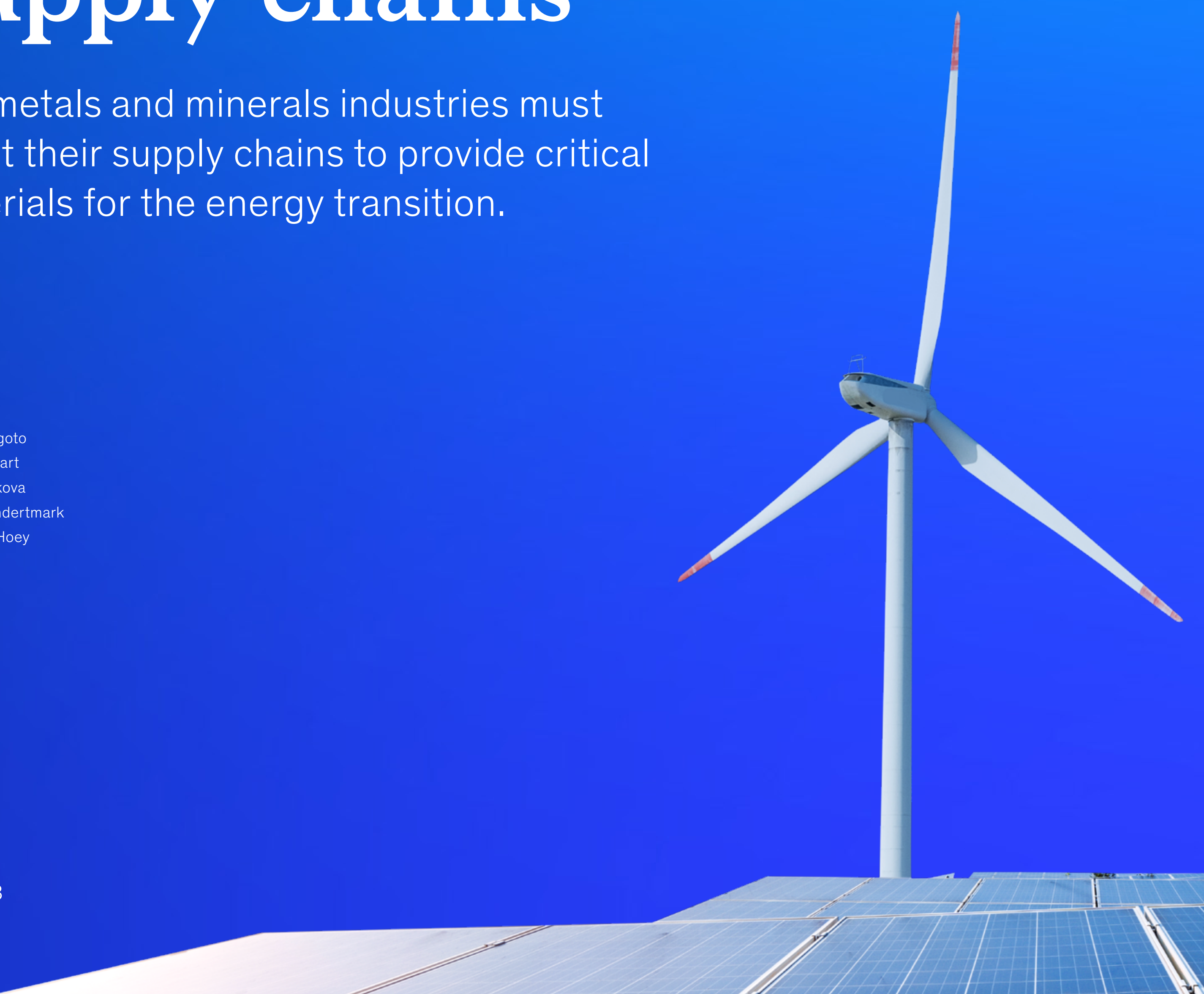

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Executive summary

Increasingly bold climate targets are changing global materials supply chains, to the extent that the transition to a net-zero emissions economy has sparked a "materials transition." This report aims to provide an integrated perspective on these supply-chain changes, including materials demand, shortages that can be expected, and key actions that will be required to balance the equation and safeguard the speed of the transition.

With these points in mind, our research explores the following key findings:

Materials are a critical enabler of the net-zero transition. The world has embarked on an ambitious decarbonization journey toward a net-zero emissions economy, which will require fundamental technology shifts across industries at an unprecedented speed. These technologies often require more physical materials for the same output when compared with their conventional counterparts during the construction phase. For example, battery electric vehicles (BEVs) are typically 15 to 20 percent heavier than comparable internal-combustion engine (ICE) vehicles and will therefore become a key driver for materials demand in the coming decades. Consequently, the extent to which global materials supply chains can keep up with new and accelerating sources of demand will be a critical determinant of global decarbonization rates.

Even with the current decarbonization trajectory trending toward 2.4° Celsius, the supply of many minerals and metals embedded in key lower-carbon technologies will face a shortage by 2030. While some materials, such as nickel, may experience modest shortages (approximately 10 to 20 percent), others, such as dysprosium, which is a magnetic material used in most electric motors, could see shortages of up to 70 percent of demand. Unless mitigation actions are put in place, such shortages would likely hinder the global speed of decarbonization because customers would be unable to shift to lower-carbon alternatives. Moreover, these shortages would lead to price spikes and volatility across materials, which in turn would make the technologies in which they are embedded more expensive and further slow adoption rates.

We will continue to see a high concentration of mineral and metals supplies in a handful of countries, including, for example, China (rare-earth elements), the Democratic Republic of the Congo (cobalt), and Indonesia (nickel). Combined with a regulatory landscape that is increasingly focused on regionalization—as seen through the US Inflation Reduction Act and the EU Green Deal Industrial Plan, for example—these concentrated supplies could affect regional access to materials within the scope of certain agreement areas, even when the global market is balanced. At the same time, such concentration could also offer opportunities to traditional mining countries to develop refining activities domestically.

Harmonized actions on supply, demand, innovation, and policy will be required to balance the equation and safeguard the speed of the transition.

- *Supply.* It is crucial to ensure the timely scale-up of projects that have already been announced, which will require mining to accelerate beyond historical growth rates for many materials while simultaneously doubling down on exploration to ensure further scale-up of supply beyond 2030. Investments in mining, refining, and smelting will need to increase to approximately $3 trillion to $4 trillion by 2030 (about $300 billion to $400 billion per year).[1] Labor capacity will need to be increased by 300,000 to 600,000 specialized mining professionals, and an additional 200 to 500 gigawatts of (ideally low-carbon) energy will need to come online by 2030 to power these assets, equivalent to 5 to 10 percent of estimated solar and wind power capacity by 2030. Finally, the scale-up will require smooth permitting processes, timely infrastructure deployment, equipment availability, and adequate water resources.

[1] This represents a 50 percent increase compared to the previous decade, in a context where mining investments have been declining in the recent past (approximately $260 billion in 2012 to approximately $150 billion in 2019, a decline of about 40 percent). Moreover, capital will need to be redirected toward new materials, with stable investments in iron ore but twice the investments in copper and an eightfold increase in investments in lithium expected.

- *Demand.* Downstream industries will need to shift demand patterns toward proven technologies that are less materials-intensive or that require different materials for which supply is less constrained.

- *Innovation.* Investments in materials innovation and breakthrough technologies should be amplified. On the demand side, this might involve exploring material substitution options for long-term-constrained or regionally concentrated materials. On the supply side, investors could consider focusing on enhanced recycling practices for new materials such as rare-earth minerals, as well as innovative solutions to increase the throughput of existing assets.

- *Policy.* New policies may facilitate the scale-up of supply, such as by streamlining permitting procedures for new asset developments. Policies could also enable a demand shift toward alternative technologies by guaranteeing a level playing field across different technological options, for example, and safeguarding regional security of supply and industry competitiveness.

Stakeholders can increase the likelihood of success by developing strategies that offer optionality and resilience across a broad range of global responses to material shortages. As a first step toward mitigating risk and tapping into the vast opportunities presented by the materials transition, it will be critical for governments and companies alike to maintain or strengthen their understanding of the dynamics of the global materials supply chain and potential long-term scenarios. For governments, doing so could help shine a light on the security of supply and safeguard the long-term competitiveness of local industries. For companies, it can inform decisive actions that are more likely to position them as industry leaders in the years to come.

The materials transition

The world has embarked on an ambitious journey to reduce greenhouse-gas (GHG) emissions. Currently, 72 countries covering 82 percent of global emissions have committed to net-zero emissions,[2] several with targets set for as soon as 2050. McKinsey's research from 2022 highlights that the net-zero transition will be defined by six characteristics, including increased exposure to a risk of supply shortages, associated price increases, and market volatility.[3] Indeed, as governments and companies gradually shift their attention from setting bold ambitions to scaling climate technologies, questions are being raised about the effects of the large-scale technology deployment on global physical supply chains, including land-use change, materials, and manufacturing.

Materials in particular have emerged as a key topic of debate. This is because lower-carbon technologies are often more materials-intensive than their conventional counterparts during the construction phase and also require a new suite of materials that the world has produced only in limited quantities in the past, notably battery and permanent-magnet materials.

This report aims to provide an integrated perspective on how the transition will affect global materials value chains. It identifies any materials shortages that may be expected and the key actions that will be required to safeguard the speed of the transition. This report focuses on a subset of minerals and metals that are embedded in key low-carbon technologies, while addressing the implications for the broader materials industry such as plastics and building materials.

Such integrated perspectives will likely become increasingly important for governments as they reflect on the competitiveness of local economies, the security of supply, and trade relationships. Likewise, for companies, upstream market dynamics will increasingly inform strategic decisions ranging from vertical integration to long-term technology choices.

[2] Based on 2019 total global emissions.
[3] "Six characteristics define the net-zero transition," McKinsey, January 25, 2022. Increased exposure to risks is one of the six characteristics. The first of the other five is universality, meaning all major energy and land-use systems would need to be transformed and every country and economic sector would be affected. Furthermore, there will be significant spending on physical assets ($9.2 trillion annually, up from $3.5 trillion per year); front-loaded spending (rising to 8.8 percent of GDP from 2026 to 2030 versus slightly less than 6.8 percent today); uneven exposure affecting developing countries and fossil fuel–rich regions; and a richness of opportunities, including minimizing further buildup of physical risks and creating more-efficient operations from decarbonization, as well as new markets for low-emission goods and services.

The challenge for the materials industry will be how to capture this opportunity in a sustainable way while doubling down on operational efficiency to avoid price inflation beyond affordable levels.

The analyses presented in this report bring together insights from McKinsey's Global Energy Perspective on energy transition pathways, McKinsey MineSpans on minerals and metals, the McKinsey Center for Future Mobility (MCFM) on transport electrification, and McKinsey Battery Insights on battery technology adoption.

An industry in flux: Growth in materials

The materials industry[4] has been an important driver of the global economy over the past two decades, increasing its share of global GDP from about 4 percent in 2000 to 7 percent in 2022 (Exhibit 1). That said, the industry's growth has not been linear: coming out of a "super cycle" from 2000 to the 2008–09 financial crisis, mainly driven by China's industrialization, industry revenue flattened until 2020 as global economic growth slowed and prices for most materials either stabilized or gradually declined. The next two years were again marked by steep increases in both revenues and profitability, primarily spurred by supply chain disruptions and increased energy prices in response to the COVID-19 pandemic and the invasion of Ukraine. Since then, prices for most materials have come down, but industry revenue as well as profitability remain well above historical levels.

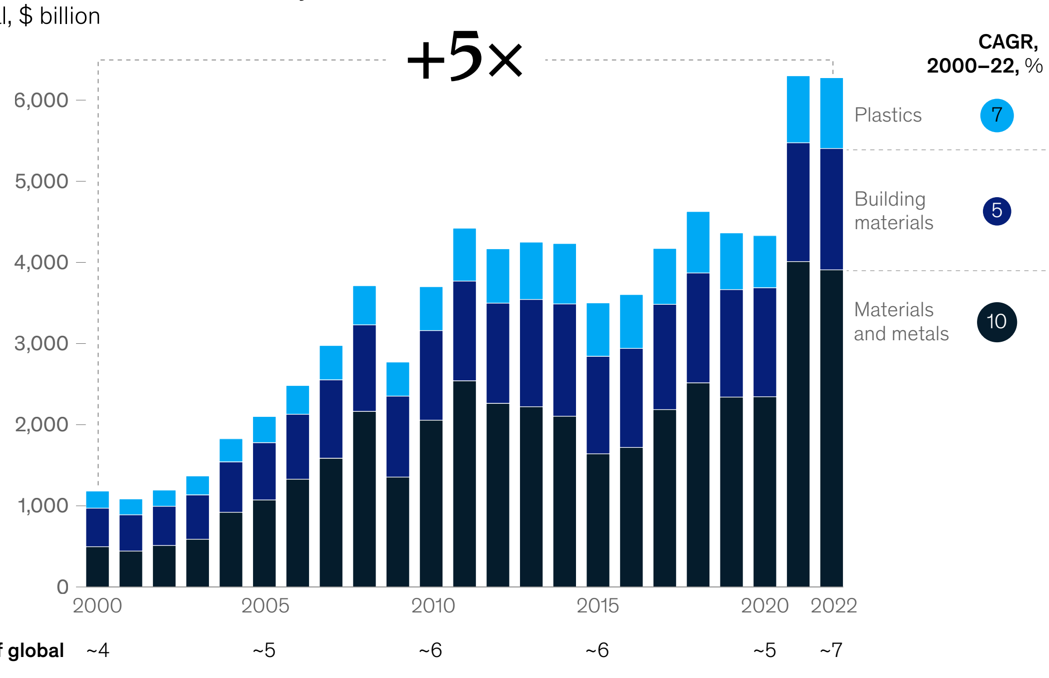
Projections for the materials industry show that revenue growth could outpace GDP growth in the coming decade, propelled partially by

[4] Including metals and minerals, plastic resins and synthetic rubber, wood, cement, and glass.

Exhibit 1

Over the past two decades, the global revenue of the materials industry has increased about five times over.

Revenues of the materials industry,[1] nominal, $ billion



[1]Excluding coal and uranium.
Source: Eurostat; ITC Trade Map; World Bank; McKinsey MineSpans; McKinsey analysis

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growing demand but also by the inflation-driven steepening of global mining and metals cost curves, ore-grade deterioration,[5] and labor shortages, among other factors.

The challenge for the materials industry will be how to capture this opportunity in a sustainable way while doubling down on operational efficiency to avoid price inflation beyond affordable levels (see sidebar "The materials trilemma"). This report focuses specifically on availability of a subset of minerals and metals, with the understanding that sustainability and affordability can and likely will further shape technological pathways.

Materials demand and the role of the net-zero transition

Materials demand over the next few decades is expected to be driven by three factors:

— a growing global population, which is expected to increase from 7.8 billion people in 2020 to 9.6 billion in 2050, with the largest growth in Sub-Saharan Africa (more than 1.0 billion) and India (more than 0.3 billion)

— continued development of the middle class,[6] which accounts for about 3.2 billion people today and is expected to grow to 5.0 billion to

[5] For example, global primary copper mines' average head grade reduced from approximately 1.8 percent in 1970 to 0.7 percent in 2021, and global primary sulfide mines' average head grade reduced from approximately 3.3 percent in 1970 to 0.4 percent in 2019.
[6] The middle class is defined as share of the global population with an expenditure range of $10 to $100 per day at 2011 purchasing-power parity.

The materials trilemma

The materials trilemma refers to the industry's need in the coming decades to balance priorities related to availability, affordability, and sustainability.

Availability. The industry will need to meet growing demand from continued population growth, middle-class development, and—increasingly—the deployment of lower-carbon technologies in support of the net-zero transition. At the same time, the industry will need to ensure security of supply in a context of a high concentration of mining and refining supply in select countries and a changing regulatory landscape that is increasingly focused on regionalization, recently exemplified through policies or legislative proposals such as the Inflation Reduction Act in the United States and the Critical Raw Materials Act in the European Union.[1]

Affordability. The industry will also need to maintain competitive prices to ensure affordability of materials and the products and applications that are built from those materials. Next to the parameters that can be directly influenced by the industry—such as operational efficiency—regulatory incentives, including taxes, subsidies, or "hard" targets on technology shifts, can affect the relative competitiveness of technologies and, consequently, the affordability threshold across materials.

Sustainability. The industry should comply with or exceed the environmental, social, and governance standards and requirements set out by governments, customers, and industry associations alike. Although the industry will need to focus on reducing its emissions footprint, which currently accounts for about 20 percent of global greenhouse-gas (GHG) emissions (approximately ten metric gigatons of CO_2 equivalent[2]), sustainability extends well beyond GHG emissions to include water consumption, land use and biodiversity, and working and wage conditions, among others. Earlier research by the McKinsey Sustainable Materials Hub[3] has shown that industry leadership in sustainability can be a significant source of commercial value. For example, players offering lower-carbon steel products in certain markets can capture 20 to 30 percent price premiums, compared with average prices.

[1] For more, see "Inflation Reduction Act of 2022," US Internal Revenue Service (IRS), updated June 1, 2023; and "Critical raw materials: Ensuring secure and sustainable supply chains for EU's green and digital future," European Commission, March 16, 2023.
[2] Based on emissions from 2021, primarily driven by iron and steel (about 7 percent), cement (about 5 percent), and plastics (about 3 percent).
[3] "Sustainable Materials Hub," McKinsey, accessed June 1, 2023.

6.0 billion by 2050, with the largest growth in China and India

— the net-zero transition and the associated deployment of lower-carbon technologies, including renewable power, energy storage, and hydrogen, among others

With these factors in mind, the net-zero transition could directly propel materials growth in two ways. First, lower-carbon technologies are often more materials-intensive than their conventional counterparts at the construction phase. For example, an offshore-wind turbine is about six times more materials-intensive than a gas-based installation on a megawatt basis, while battery electric vehicles (BEVs) are 15 to 20 percent heavier than internal-combustion engine (ICE) vehicles on average. Second, lower-carbon technologies require a new suite of materials that have been produced in only limited quantities in the past, such as lithium, a critical battery material, or rare-earth elements such as dysprosium and neodymium, which are used in permanent magnets.

The transition could also indirectly drive demand for materials used in processing raw materials—for example, sulfuric acid, which is used in processing of nickel and lithium, among others—

The challenge for the materials industry will be how to capture this opportunity in a sustainable way while doubling down on operational efficiency to avoid price inflation beyond affordable levels.

or in manufacturing the technology itself, such as high-purity quartz, which is used as a crucible in the manufacturing of solar panels.

The magnitude at which the net-zero transition affects global materials value chains will depend on the speed of decarbonization as well as the underlying design choices made for each technology (batteries, electric motors, electrolyzers, and so on). For this report, we considered three net-zero scenarios that are also used in our annual Global Energy Perspective (Exhibit 2).[7] We recognize that these scenarios might be decelerated for various reasons and that the world is currently not on a path to achieve existing commitments. At the same time, we want to illustrate how the materials supply–demand balance could be affected by different decarbonization pathways, shedding light on the additional complication that materials will pose to the transition.

Our analysis shows that future growth rates for many materials are expected to outpace historical growth rates across all demand scenarios, especially in absolute terms (Exhibit 3).[8]

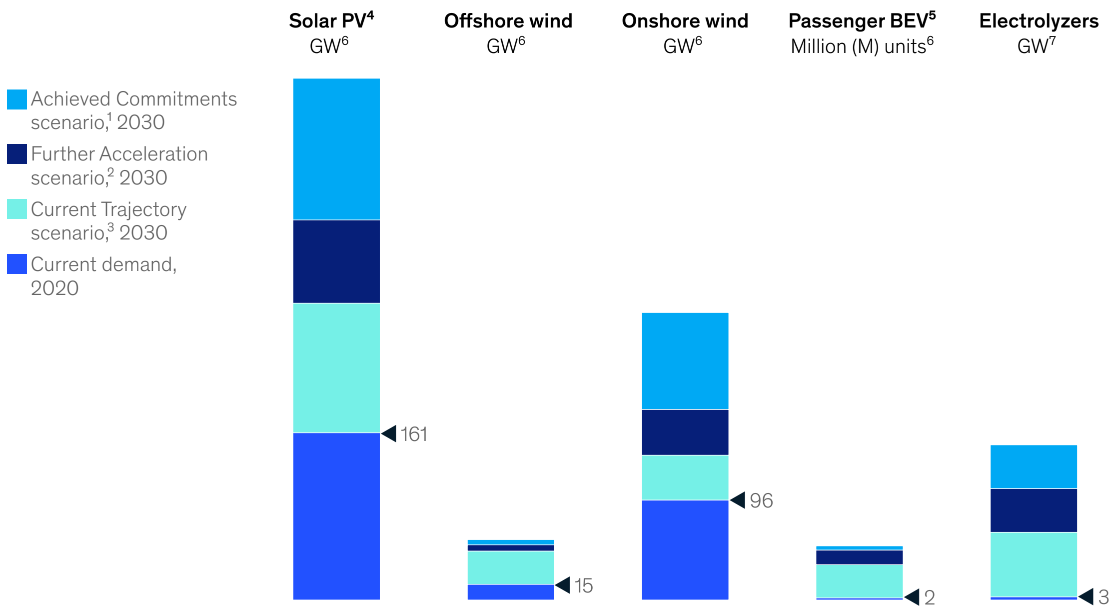
[7] For more on these scenarios, see *Global Energy Perspective 2022*, McKinsey, April 2022.
[8] Growth in materials is primarily driven by the growth of large-volume applications, including BEVs, wind turbines, and solar panels. For example, in 2030, more than 50 percent of rare-earth elements, 55 percent of cobalt, and 36 percent of nickel will be consumed by BEVs and the associated charging infrastructure.

Future growth rates for many materials are expected to outpace historical growth rates across all demand scenarios, especially in absolute terms.

Exhibit 2

These new technologies have a higher material intensity and require different materials than conventional technologies.

Demand scenarios and material intensity levels for new technologies, GW/M units



	Solar PV	Offshore wind	Onshore wind	Passenger BEV	Electrolyzers
Material intensity vs conventional technology[8]	1.4×	6.3×	2.4×	1.2×	–
Key metals and minerals contained (not exhaustive)					
Bauxite	●	●	●	●	●
Copper	●	●	●	●	●
Cobalt	○	○	○	●	●
Dysprosium and terbium	○	●	●	●	●
Graphite	○	○	○	●	●
Iridium	○	○	○	○	●
Lithium	○	○	○	●	○
Manganese	○	●	○	●	●
Neodymium and praseodymium	○	●	●	●	●
Nickel	●	●	●	●	●
Tin	●	●	●	●	●

[1]Scenario where net-zero commitments are achieved by leading countries through purposeful policies; followers transition at slower pace. [2]Scenario where transition is further accelerated, driven by country-specific commitments, though financial and technological restraints remain. [3]Scenario where current trajectory of renewables (cost decline) continues but currently active policies remain insufficient to close remaining gap to targets. [4]Solar photovoltaics. [5]Battery electric vehicle. [6]Gigawatts; energy capacity additions. [7]Gigawatts; energy capacity additions based on hydrogen capacity additions. [8]Minerals and metals only; renewables compared to coal and gas in kilograms (kg) per MW, and BEV compared to an internal-combustion engine in kg per unit.
Source: McKinsey MineSpans

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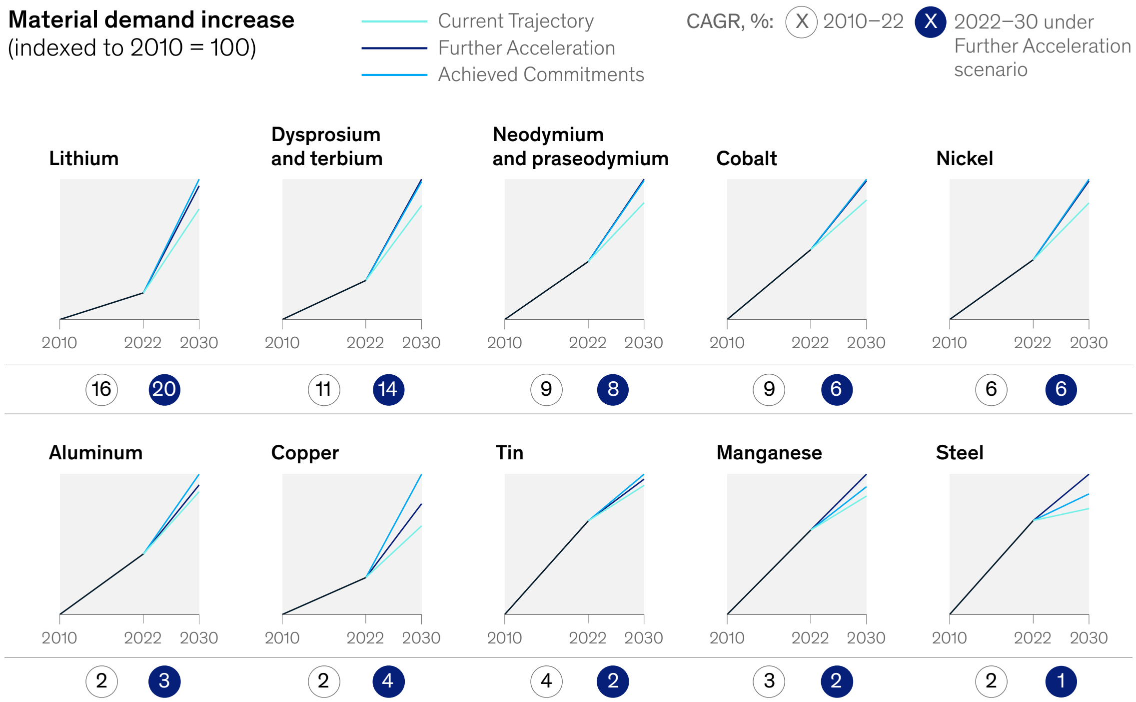
Exhibit 3

The future growth rate for many materials is expected to significantly increase by 2030.



Source: McKinsey Global Materials Insights; McKinsey MineSpans

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The growth dynamics vary significantly across materials, which can be attributed to the proportion of materials demand dedicated to lower-carbon technologies (Exhibit 4). For instance, lithium, predominantly used in the batteries of BEVs, is projected to account for more than 80 percent of total lithium demand in 2030. As a result, its growth over the next decade will be entirely linked to the rate of transport electrification. By contrast, manganese demand will be primarily driven by the demand for stainless steel, which in turn is driven by the consumer goods and construction industry (accounting for 70 percent of demand in 2030). Thus, manganese is expected to see a more modest growth rate of approximately 2 percent per year until 2030.

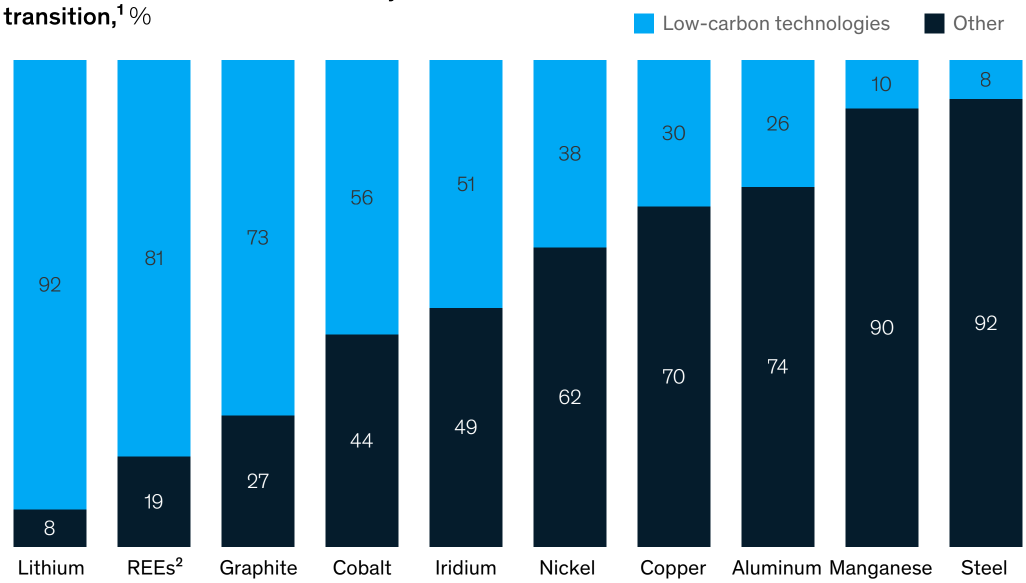
Supply–demand balance

In theory, the increase in demand could be met by scaling supply because none of the materials required in the production of lower-carbon technologies is scarce. In fact, resources and

Exhibit 4

The effect of the net-zero transition on share of demand by 2030 differs drastically across materials.

Share of materials demand in 2030 driven by the net-zero transition,[1] %



[1]Net-zero transition share includes demand from renewable power, energy storage systems, electric vehicles, and copper. Includes demand from added transmission lines in developed countries. Tin includes demand from semiconductors.
[2]Rare-earth elements.
Source: McKinsey Global Materials Insights; McKinsey MineSpans

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reserves for several metals and materials are at their highest levels since 2000 (Exhibit 5). However, because it typically takes five to 15 years—depending on the material, project characteristics, and regulatory environment—to develop new deposits from exploration to mining operations, temporary materials shortages could occur if demand growth outpaces initial industry expectations.

For this report, we developed two supply scenarios based on our research on the maturity and likelihood of individual projects for each material. The research is anchored in our MineSpans database, which contains more than 10,000 operating mines and mining projects across more than 130 countries[9]:

— *Base-case scenario.* This includes all operating mines (corrected for depletion where relevant) and projects currently under construction, as well as projects for which a feasibility study has been conducted and financing secured and projects for which a feasibility study is currently being conducted.

— *High-case scenario.* This includes projects for which a prefeasibility study has been initiated. Projects that have been announced but so far have not initiated any prefeasibility study are not included in the forecasts.

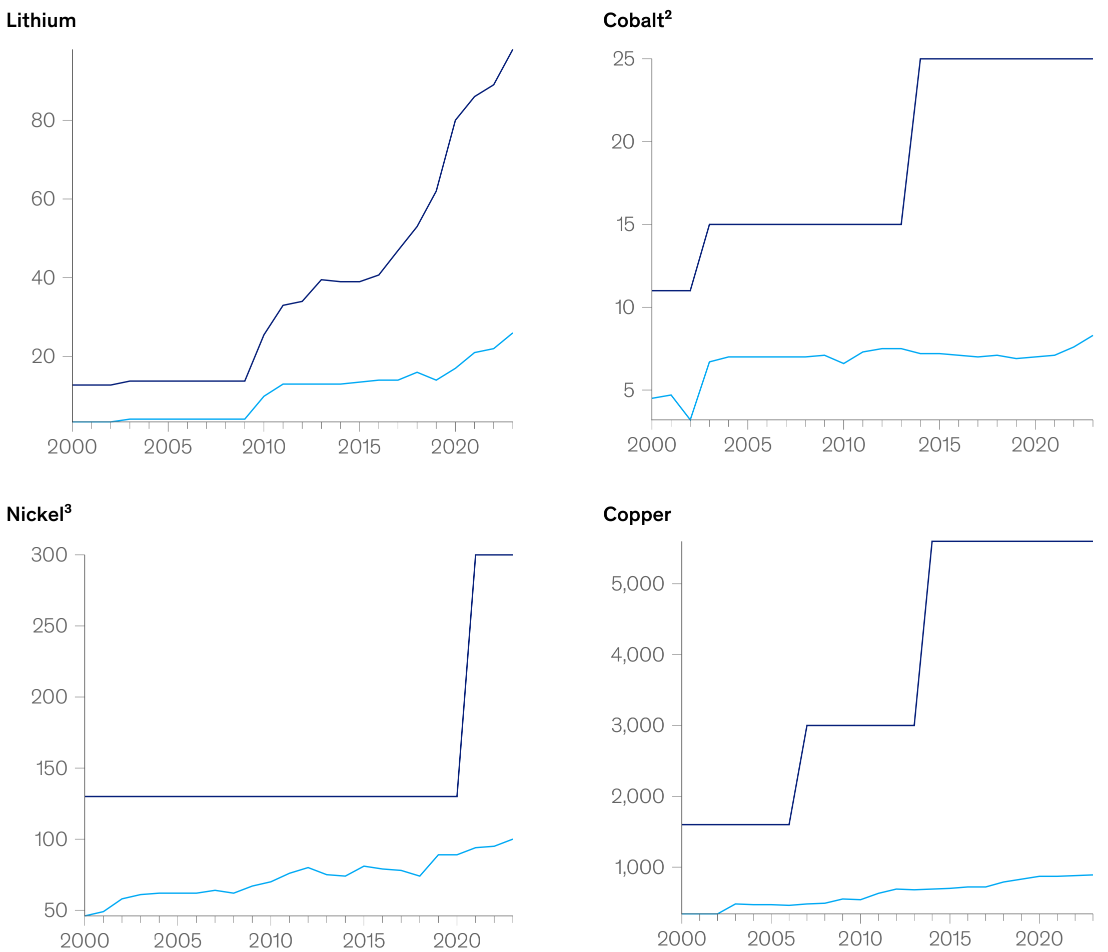
[9] Recycled materials have been consistently included in both supply scenarios, based on assumptions on average end-product lifetimes and collection and recovery rates. Conversely, potential changes in production quota, such as those on rare-earth elements in China, have not been considered in any of the scenarios.

Exhibit 5

On the supply side, resources and reserves of metals and materials are at an all-time high.

Materials resources and reserves,[1] million metric tons

Resources Reserves



[1]Resources are a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust, while reserves are what could be economically extracted or produced at the time of determination.
[2]Most recent projects have been high-pressure acid leach (HPALs).
[3]Resources of > 1% Ni for 2000–20 and > 0.5% Ni for 2021–23.
Source: United States Geological Survey; McKinsey Global Material Insights; McKinsey MineSpans

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To put this into perspective, there are approximately 500 cobalt, copper, lithium, and nickel mines operating today. The base-case scenario would require the addition of 196 mines (an increase of approximately 40 percent) by 2030, while the high-case scenario would require the addition of 382 mines (an increase of approximately 80 percent).

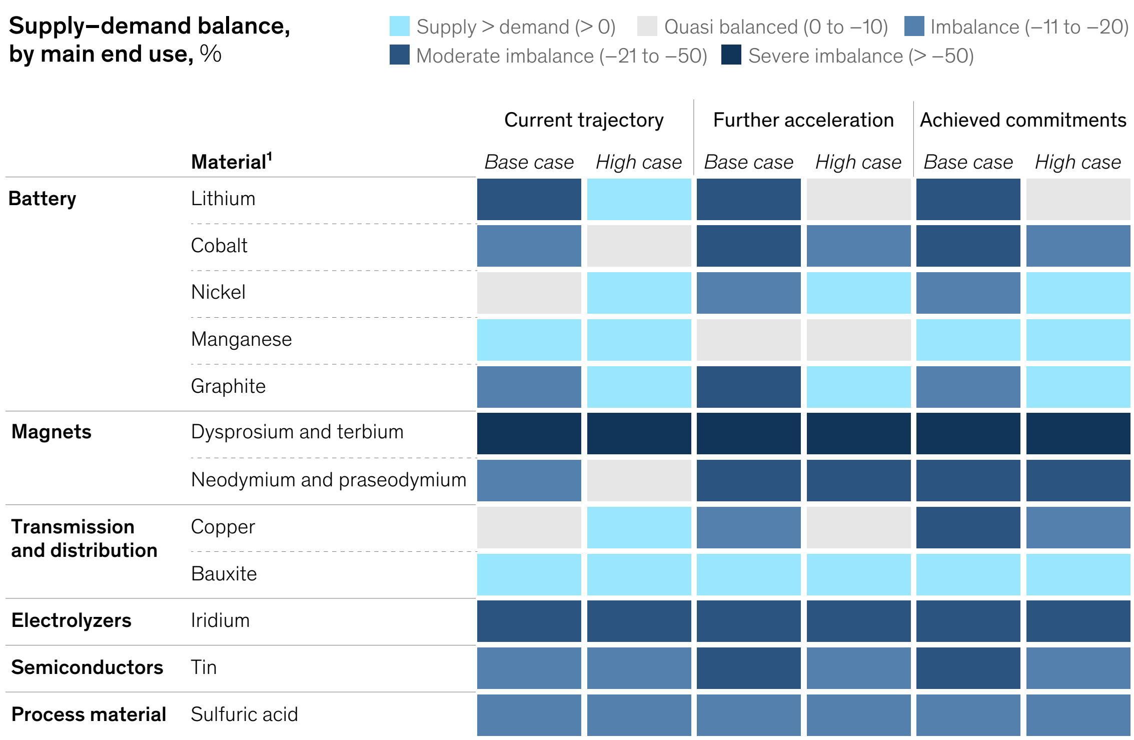
Both scenarios carry inherent uncertainty, given the conditions that need to be fulfilled for a project to come online as planned, including timely delivery of permits (which notably requires a compliant environmental impact assessment for most jurisdictions), availability of skilled labor, closing of project financing, timely delivery of equipment, availability of freshwater (notably in the Lithium Triangle in South America) and processing materials (such as sulfur), timely deployment of infrastructure upgrades, and a stable regulatory framework.

That said, an assessment of supply–demand balances shows that most materials within the scope of this report would face a shortage by 2030 across all scenarios (Exhibit 6):

— *Lithium, cobalt, nickel, manganese, and graphite (batteries).* Most battery materials, especially lithium and cobalt, would be constrained despite ongoing shifts in battery chemistry, including the reduction in cobalt intensity and the partial shift from

Exhibit 6

Even in a high-case supply scenario, most materials are expected to see a global supply–demand imbalance by 2030 or sooner.



[1]Including recycled materials.
Source: McKinsey Global Materials Insights; McKinsey MineSpans

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nickel-manganese-cobalt (NMC) toward lithium-iron-phosphate (LFP) batteries.

— *Dysprosium and terbium, and neodymium and praseodymium (permanent magnets).* All magnet materials are expected to fall short, with rare-earth elements such as dysprosium and terbium being the most constrained. This would limit the production of permanent magnets used in the electric motors of most BEVs and the drivetrains of wind turbines (as approximately 20 percent of onshore and 70 of offshore wind turbines are currently using permanent magnet drivetrains).

— *Copper (electric wiring).* Copper is also expected to fall short in most scenarios, which would affect the build-out speed of transmission and distribution lines that connect renewable-power sources to the grid and consequently the risk profile of renewable-energy projects.

— *Iridium (hydrogen electrolyzers).* Iridium is part of the platinum group metals and is one of the scarcest materials in the world, with a global production of approximately 7,900 metric tons in 2021.[10] It is expected to see a growing shortage as the demand for electrolyzers—especially proton exchange membranes—used in the production of low-carbon hydrogen likely increases exponentially in the coming years.

— *Tin (semiconductors).* Approximately 50 percent of tin demand is driven by solder in semiconductors for electronic devices, in which it is used to attach components to printed circuit boards or other substrates. Because tin is expected to see a modest shortage, semiconductor supply chains could become constrained, which would directly affect the supply chains of most lower-carbon technologies.[11]

In addition to the materials physically embedded in lower-carbon technologies, supply chain disruptions for materials required in the processing of these materials could also affect the transition. For instance, sulfur, which is used in refining nickel,[12] lithium, manganese, and copper, is expected to fall short because it is produced primarily from the desulphurization of oil and natural gas. In fact, sulfur is already in short supply today (by less than 5 percent). This gap is being bridged by the consumption of oil sands from sulfur pyramids in Kazakhstan and Alberta, Canada—a temporary measure that is expected to last only until the end of 2024, after which stocks will be depleted.

Based on current supply and technology outlooks, the materials shortages and associated inability to shift to lower-carbon technologies would lead to the release of an additional 400 to 600 metric megatons of CO_2-equivalent emissions in 2030 alone. In the scenarios considered in this report, shortages of dysprosium and terbium would be the primary causes of the increase in GHG emissions, which shows that bottlenecks in just one or a few materials can delay the deployment of lower-carbon technologies across multiple industries (in this case, electric vehicles [EVs] and wind turbines[13]) and thus slow the transition to net-zero emissions.

Supply concentration

Minerals and metals have historically been a global industry, with materials flowing from mining mineral-rich countries across the world to a few countries for refining (notably China) and final consumption and processing in industrialized countries. The mining and refining of the materials within the scope of this report will likely continue to be concentrated in select countries. Some countries are expected to retain their market

[10] As reported by United States Geological Survey (USGS).
[11] As an example, see the impact of semiconductor shortages on the automotive industry in 2021: Ondrej Burkacky, Johannes Deichmann, Philipp Pfingstag, and Julia Werra, “Semiconductor shortage: How the automotive industry can succeed,” McKinsey, June 10, 2022.
[12] In Indonesia, an increased demand for sulfur and sulfuric acid is expected for nickel laterite high-pressure acid leach (HPAL) processing, which is more intensive in sulfuric acid compared with nickel sulfide and nickel laterite leaching used in other regions.
[13] Assuming the inability to meet demand for EVs (delta of 150 million to 250 million units) and for wind turbines (delta of 150 to 200 gigawatts).

shares; for example, the Democratic Republic of the Congo will likely continue to provide approximately 75 percent of the global cobalt mining supply.[14] Other countries are expected to further strengthen their position. Indonesia is increasing its market share in nickel production from 33 percent in 2021 to 58 percent by 2030, while the Philippines and Russia, the second- and third-largest producers are projected to represent only 7 and 6 percent of the market, respectively. Finally, some materials are likely to see a more diversified supply by 2030. For instance, Australia's share of global lithium production will likely decrease from approximately 43 percent in 2021 to 24 percent in 2030, in favor of Argentina, among others, which could see its market share increase from around 6 percent to 19 percent over the same period.

On the refining side, China is expected to retain its position as the global center of activity, processing more than 40 percent of all materials in scope,[15] although for select materials such as lithium, China's market share is expected to decline from more than 90 percent in 2021 to about 60 to 70 percent by 2030, based on current project announcements.

Overall, this high level of concentration combined with a changing regulatory landscape that is increasingly focused on regionalization—for example, the US Inflation Reduction Act and EU Green Deal Industrial Plan—could affect the security of supply of materials and long-term industry competitiveness in individual regions even when the global market is balanced.

At the same time, the high level of concentration could also offer countries that have traditionally been mineral extractors the opportunity to invest into domestic value-adding activities, including refining and processing, to capture the full value of their natural resources.[16] Several countries have already taken steps in this direction. For instance, the Democratic Republic of the Congo and Zambia announced the development of battery production earlier this year.[17] In such a context, materials-consuming countries would need to rethink their agreements with producers to ensure security of their supply chains.

Four key actions to bridge the gap

To address the materials imbalance and uphold the momentum of the net-zero transition, concrete actions can be taken in four areas: supply, demand, innovation, and policy.

- *Supply.* It is crucial to ensure the timely scale-up of needed supplies, which will require mining to accelerate beyond historical growth rates for many materials. Investments in mining, refining, and smelting will need to increase by approximately \$3 trillion to \$4 trillion by 2030 (about \$300 billion to \$400 billion per year), including capital expenditures for exploration and new and ongoing projects.[18] Labor capacity will also need to be increased by 300,000 to 600,000 specialized mining professionals, which could be particularly challenging given the recent decline in the number of mining engineering graduates. Energy supply is another consideration: it is estimated that an additional 200 to 500 gigawatts of (ideally green) energy will need come online by 2030, equivalent to 5 to 10 percent of estimated solar and wind power capacity by 2030. Finally, all this will require smooth permitting processes, timely infrastructure deployment, equipment availability, and adequate water resources.

- *Demand.* A significant shift in demand patterns toward proven technologies in the coming decade could require less material per product or different materials for which supply is less constrained.

[14] All numbers in this section are based on a high-case supply scenario.
[15] Value weighted based on 2021 price levels.
[16] "Reimagining economic growth in Africa: Turning diversity into opportunity," McKinsey Global Institute, June 2023.
[17] "DRC and Zambia to establish SEZs for electric vehicle production," *African Business*, April 11, 2023.
[18] This represents a 50 percent increase compared to the previous decade, in a context where mining investments have been declining in the recent past (approximately \$260 billion in 2012 to approximately \$150 billion in 2019, a decline of about 40 percent). Moreover, capital will need to be redirected toward new materials, with stable investments in iron ore but twice the investments in copper and an eightfold increase in investments in lithium expected.

- *Innovation.* Investments in materials innovation and breakthrough technologies should be amplified. On the demand side, this might involve exploring material substitution options for long-term-constrained or regionally concentrated materials. On the supply side, investors could consider focusing on enhanced recycling practices for new materials such as rare-earth minerals, as well as innovative solutions to increase the throughput of existing assets.

- *Policy.* New policies may facilitate the scale-up of supply via streamlining permitting procedures, among other options. Policies could also enable a demand shift toward alternative technologies by guaranteeing a level playing field across different technological options, for example, and safeguard regional security of supply and industry competitiveness.

These points in mind, each of these four imperatives will require collaboration among actors within various materials value chains to ensure smooth flows from producers to consumers.

Shifting demand patterns

Several actions can be taken on the demand side, including a reduction in the materials intensity of preferred technologies to fundamental technology shifts toward either existing technologies, which consume different materials for which supply is less constrained, or breakthrough technologies, which could be accelerated through increased investments in innovation.

Because the industry has repeatedly demonstrated its ability to respond to price volatility, it is reasonable to anticipate ongoing

To address the materials imbalance and uphold the momentum of the net-zero transition, concrete actions can be taken in four areas: supply, demand, innovation, and policy.

adaptability in the face of future challenges (see sidebar "Industry responses to supply challenges").

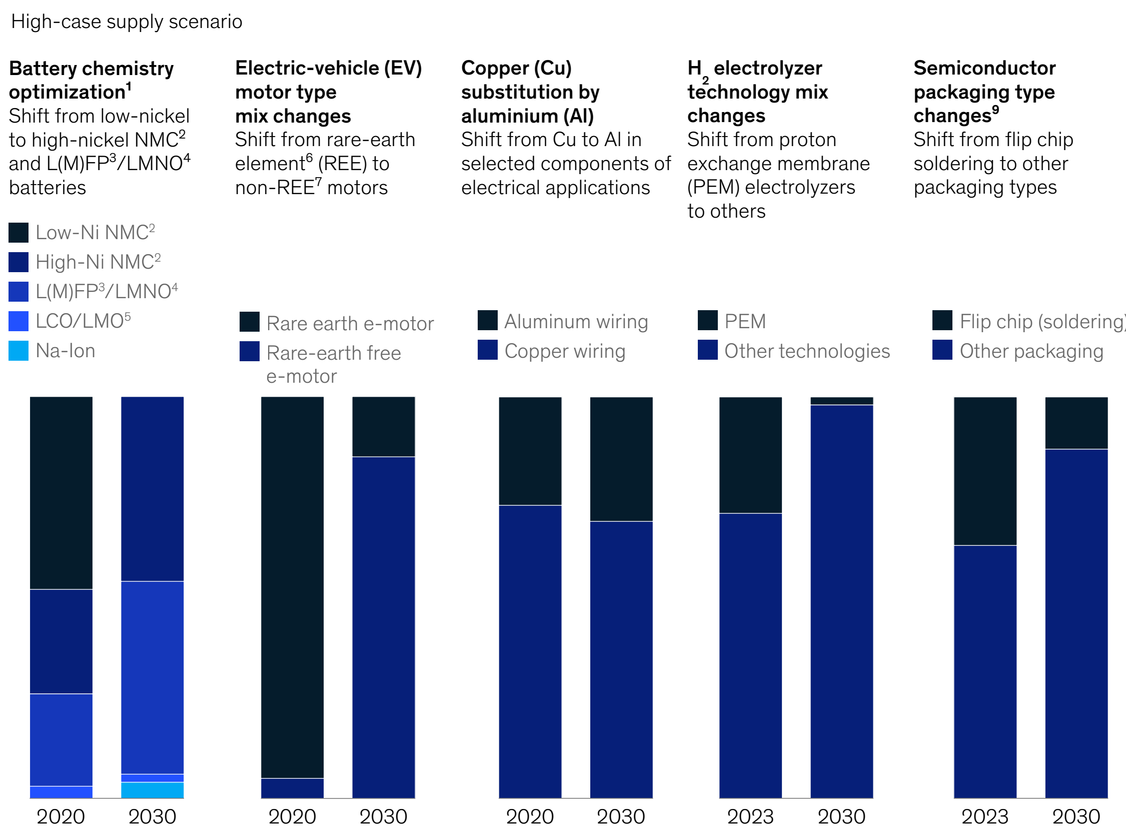
Although there are several ways to close the gap through shifts in demand patterns across industries, there is no guarantee that these shifts will follow a trajectory of the lowest system cost, which depends on the further development of the regulatory landscape and the speed of innovation in the coming years. In our illustrative scenario, we lay out one possible framework (out of many) that would allow a supply–demand balance for all materials by 2030 while retaining the desired speed of decarbonization if applied as early as possible.

In our illustrative scenario, changes in demand patterns would be required across five key areas to balance the equation by 2030 (Exhibit 7).

Exhibit 7

Across five key areas, the largest changes will likely be required in battery chemistry and the mix of electric-vehicle motors.

Demand of transition technologies and enablers in a potential technology trajectory, 2020 vs 2030, %



[1]For both EVs and stationary storage (BESS). [2]Nickel manganese cobalt. [3]Olivine LiMnxFe1–xPO4 is a cathode material for high-performance lithium-ion batteries. [4]Lithium manganese nickel oxide. [5]Lithium cobalt oxide and lithium ion manganese oxide. [6]Permanent-magnet synchronous motor. [7]Squirrel cage induction motor and electrically excited motor. [8]As there is zero hydrogen capacity today, announced projects for 2023 are shown. [9]Semiconductors are used in consumer electronics, appliances, and industrial machinery.

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Industry responses to supply challenges

Historically, the industry has been able to respond quickly to supply challenges and price volatility in three ways (exhibit).

Metal intensity reduction. In the expectation of cobalt supply shortages, there was a shift to nickel-manganese-cobalt (NMC) batteries with increasing nickel content and a lower cobalt intensity, leading to a reduction in cobalt consumption per battery unit from 2010 to 2020.

Materials substitution. High nickel prices caused a shift from 300- to 200- and 400-series stainless steel, with a reduction of 17 percentage points in 300-series stainless steel from 2000 to 2015.

Technology substitution. High nickel prices triggered a shift from NMC batteries, which are high in nickel content, to lithium-iron-phosphate (LFP) batteries, which do not require any nickel, effectively raising the share of LFP in global battery demand from 16 to 24 percent from 2018 to 2022.

Exhibit

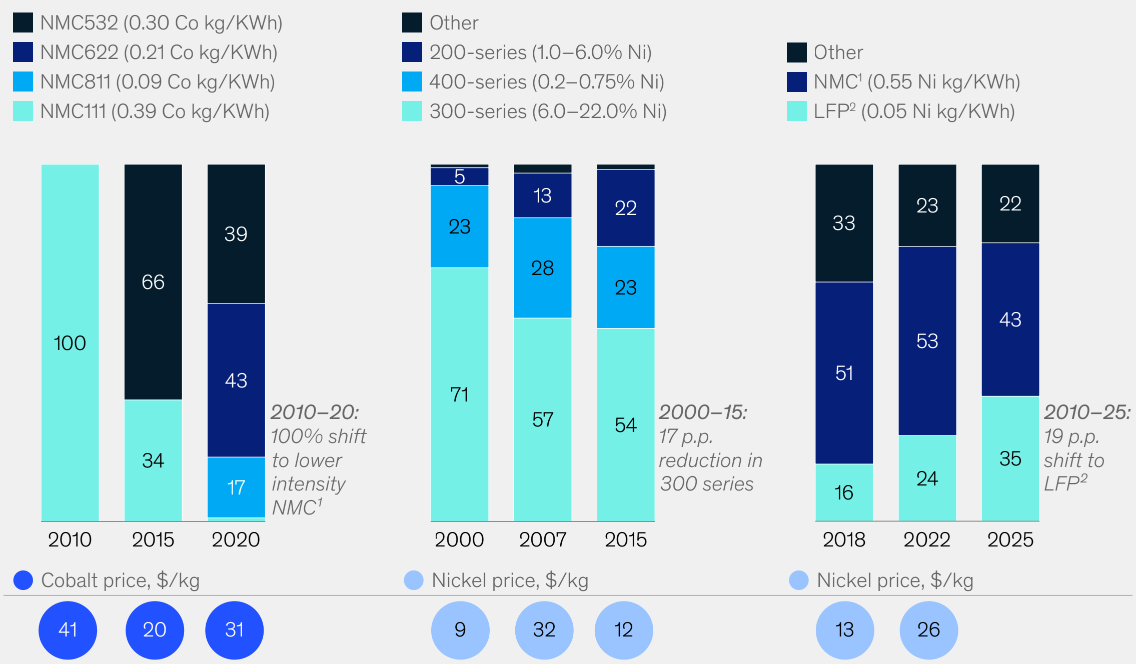
Historically, the materials industry has been able to respond quickly to supply challenges and price volatility.

Selected examples

Metal intensity reduction
Split between NMC[1] battery types
Expected cobalt (Co) supply shortages initiated a shift to NMC[1] batteries with a higher nickel but a lower cobalt intensity.

Material substitution
Stainless steel grade distribution
High nickel (Ni) prices caused a shift from 300- to 200- and 400-series stainless steel.

Technology substitution
Evolution of cathode type split
High Ni prices triggered a shift from NMC[1] batteries (high in Ni) to LFP[2] batteries (lower in Ni).



Note: Figures may not sum to 100%, because of rounding.
[1]Nickel manganese cobalt.
[2]Lithium iron phosphate.
Source: World Bank; McKinsey Battery Insights

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1. *EV and stationary batteries (affecting battery materials such as lithium, cobalt, nickel, and manganese).* Battery chemistries have seen drastic changes in recent years, including a reduction in cobalt intensity and the adoption of LFP batteries in BEVs given their lower cost compared to NMC batteries (albeit at a lower energy density and recyclability). Shifting toward NMC batteries with a high nickel content could alleviate the pressure on lithium supply chains; the lithium intensity for these batteries is lower compared to low-nickel NMC batteries. A partial shift toward sodium-ion batteries, a nascent technology with initial commercial-scale production announced for 2024, could further alleviate pressure. Because these batteries have a lower energy density, it is expected that stationary storage applications would shift first because there are fewer constraints on physical volume.

2. *EV powertrain system (affecting magnet materials dysprosium and terbium, and neodymium and praseodymium).* Most BEVs have a permanent-magnet synchronous motor that requires approximately 1 kilogram of rare-earth materials for every 100 kilowatts of power output. However, a few automotive OEMs have launched vehicles running on either squirrel cage induction motors or electrically excited motors that do not require any rare-earth materials. An accelerated shift toward rare-earth-free electric motors, as recently alluded to by Tesla in its Master Plan,[19] could resolve the gap for all rare-earth elements while also diversifying supply chains in a context in which more than 80 percent of permanent magnets are currently produced in China.

3. *Hydrogen electrolyzers (affecting iridium).* Given the small size of the low-carbon hydrogen market, there is no clear trend yet on preferred electrolyzer technologies. Furthermore, only 12 percent of currently announced hydrogen projects have disclosed their preferred electrolyzer technology. As a result, there could still be flexibility to resolve any potential shortage in iridium by shifting from polymer electrolyte membrane (PEM) technology toward alkaline-water electrolysis or other nascent technologies, such as solid-oxide electrolyzer cells.

4. *Electric wiring (affecting copper and aluminum):* Copper is often the material of choice in electrical wiring given its high electrical conductivity. However, there are certain applications for which other materials, notably aluminum, have a better cost performance. For example, most overhead transmission lines are made from aluminum instead of copper because its lower weight allows a larger distance between pylons and, consequently, a lower systems cost. Therefore, it's possible to rebalance the copper market by further shifting from copper to aluminum in electric wiring as the difference between copper and aluminum prices increases.[20]

5. *Semiconductor packaging (affecting tin).* There are several microelectronics packaging methods, including flip chip and wire bonding, and advanced methods such as 2.5-D and 3-D stacking. Because tin intensity is higher in flip chip packaging, which represented about 35 percent of the integrated-circuit (IC) packaging market in 2020, a shift toward wire bonding or

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[19] *Master Plan Part 3: Sustainable energy for all of Earth*, Tesla, April 5, 2023.
[20] Historically, there has been a strong correlation between the spread and copper substitution rate (as reported by the International Copper Association).

advanced packaging methods (which use less tin solder) could resolve the market imbalance for tin.

Sulfur shortages may still be resolved by increasing supply, although this would require a partial shift from sweet to sour oil or natural-gas production. Alternatively, the gap could be resolved on the demand side through, for example, substituting hydrochloric acid or nitrophosphate for sulfuric acid in fertilizer production or shifting from high-pressure acid leaching to rotary kiln electric furnaces in nickel processing.

Several of these technology shifts would require a higher investment versus a business-as-usual scenario and therefore may not be the desired path for industrials, given the risk of losing competitiveness. At the same time, delaying the shift to these alternative technologies could lead to short-term and midterm price spikes for current technologies, primarily driven by rising materials prices as the market becomes tighter, which could eventually lead to an even costlier transition.

Therefore, companies will need to reflect on the optimal timing of the shift from an economic perspective. They will also need to consider the relative emissions intensity of alternative technologies and the cost of decarbonization. If not, shifting may mitigate exposure to commodity price volatility but increase exposure to carbon taxes.

Conclusion

As the world accelerates the deployment of climate technologies in support of the net-zero transition, there is a risk that materials supply might not scale at the required speed. Our research has shown that energy and materials are strongly interconnected and that the world will also have to go through a materials transition to deliver on its net-zero ambitions.

While several uncertainties remain about how the materials transition will play out—such as the speed of decarbonization, development of trade policies, speed of innovation and time to market for breakthrough technologies, and permitting timelines for new projects, among others—governments and companies can plan strategic actions that are resilient across a broad range of outcomes.

As a first step toward mitigating risks and tapping into the vast opportunities presented by the materials transition, it is critical for governments and companies to maintain or strengthen their understanding of changing global materials supply chain dynamics with a long-term perspective. For governments, doing so could help shine a light on security of supply and safeguarding long-term competitiveness of local industries. And similar to the actions and results of frontrunners in the energy transition, companies can gain insight on decisive actions that are more likely to position them as industry leaders in the years to come.

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