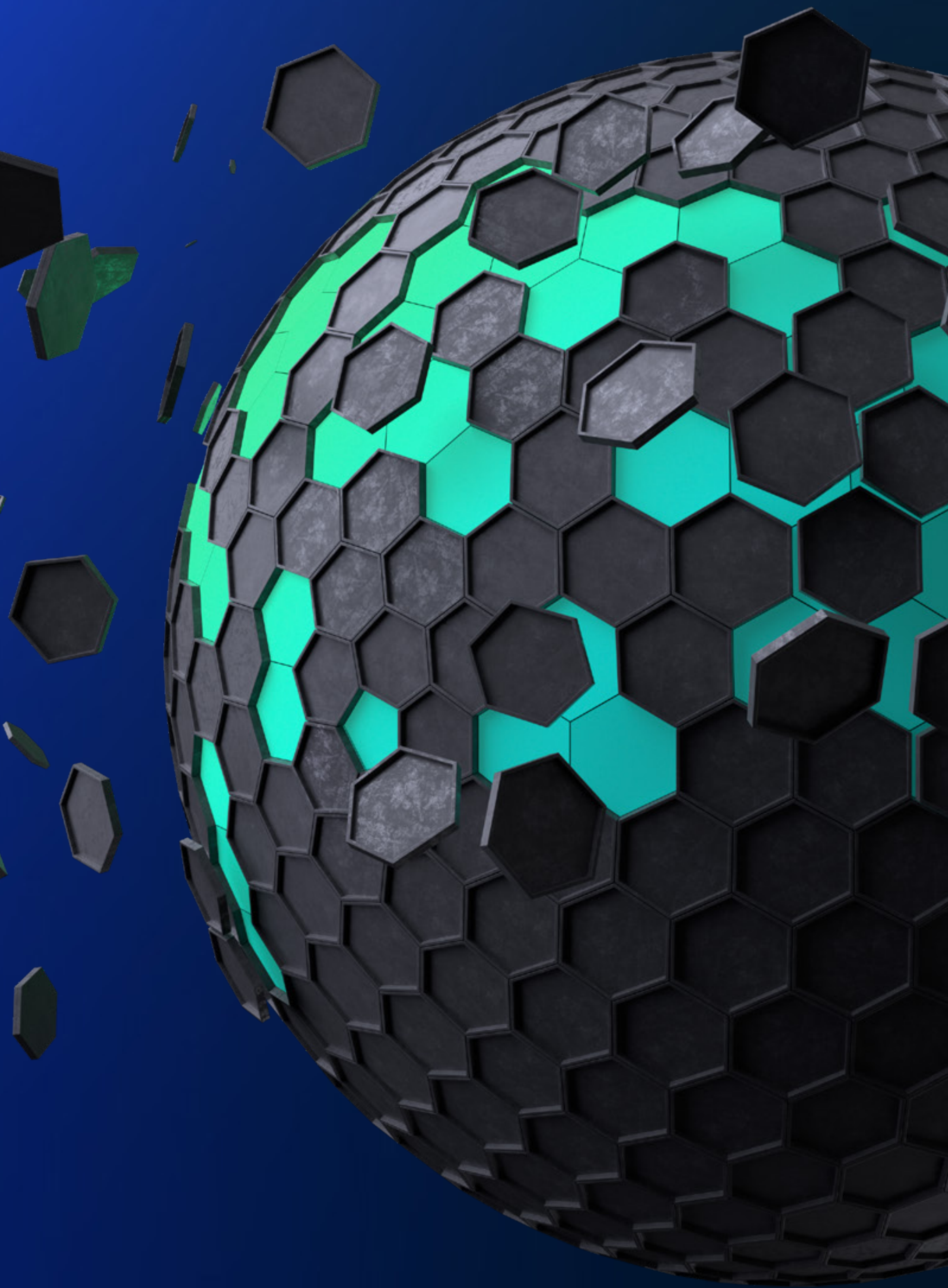
McKinsey Global Institute

The hard stuff

Navigating the physical realities of the energy transition



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Molten salt tower solar thermal
power station at sunset

At a glance

— **The energy transition is in its early stages, with about 10 percent of required deployment of low-emissions technologies by 2050 achieved in most areas.** Optimized over centuries, today's energy system has many advantages, but the production and consumption of energy account for more than 85 percent of global carbon dioxide (CO_2) emissions. Creating a low-emissions system, even while expanding energy access globally, would require deploying millions of new assets. Progress has occurred in some areas, but thus far has largely been in less difficult use cases.

— **Twenty-five interlinked physical challenges would need to be tackled to advance the transition.** They involve developing and deploying new low-emissions technologies, and entirely new supply chains and infrastructure to support them.

— **About half of energy-related CO_2 emissions reduction depends on addressing the most demanding physical challenges.** Examples are managing power systems with a large share of variable renewables, addressing range and payload challenges in electric trucks, finding alternative heat sources and feedstocks for producing industrial materials, and deploying hydrogen and carbon capture in these and other use cases.

— **The most demanding challenges share three features.** First, some use cases lack established low-emissions technologies that can deliver the same performance as high-emissions ones. Second, the most demanding challenges depend on addressing other difficult ones, calling for a systemic approach. Finally, the sheer scale of the deployment required is tough given constraints and the lack of a track record.

— **Understanding these physical challenges can enable CEOs and policy makers to navigate a successful transition.** They can determine where to play offense to capture viable opportunities today, where to anticipate and address bottlenecks, and how best to tackle the most demanding challenges through a blend of innovation and system reconfiguration.

Engineer inspecting a turbine in a nuclear power station.

Introduction

The global energy system is huge, complex, and fundamental to modern life. An average person consumes energy equivalent to 800 kilograms of crude oil a year.[1] In terms of physical labor, that is equivalent to 60 people working every day and night nonstop—and double or triple that in the richest economies. Access to abundant, cheap, and reliable energy has supported growth and prosperity for billions of people.

For all its benefits, however, the energy system is the source of more than 85 percent of carbon dioxide (CO_2) emissions.[2] It continues to be based mostly on fossil fuels, which account for more than 80 percent of all primary energy consumed.[3] The world has therefore embarked on an energy transition with the goal of reducing emissions and "holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels," according to the 2015 Paris Agreement.[4]

This energy transition is in its early stages. Thus far, deployment of low-emissions technologies is only at about 10 percent of the levels required by 2050 in most areas, and that has been in comparatively easy use cases. More demanding challenges are bound to emerge as the world confronts more difficult use cases across geographies.

Complicating the task of building a new low-emissions energy system is that it coincides with the need for it to continue to grow to expand access to energy for billions of people who still do not have it, thereby economically empowering them. This transition also needs to address rising concerns about energy affordability and security as well as the role of the energy system in ensuring industrial competitiveness.

Moreover, the aspiration is for a rapid energy transition. Today's energy system has been built and optimized over centuries. However, the energy transition is envisaged to take only a few decades, typically being associated with reaching net-zero emissions of CO_2 by 2050.[5]

That is a big ask. In the digital age, we have become accustomed to lightning-fast transformations. TikTok took nine months and ChatGPT only two months to gain 100 million users.[6] But an energy system is a physical entity, and historical energy transitions have taken many decades or even centuries. For example, the transition that created the current system was lengthy. In the 1800s, biomass accounted for 98 percent of energy used; over time, coal, oil, and gas gradually replaced it.[7] By the mid-2000s, the share of biomass in primary energy dropped below 10 percent.[8] After the Industrial Revolution, the transition of individual sectors to new forms of energy—from horses to cars in mobility and from biomass to gas boilers in buildings—took about 50 years on average.[9]

Given the multiple goals and ambitious expectations for the current energy transition, it is therefore important to understand what it would take.

Extensive research on the energy transition has been undertaken by McKinsey and many other organizations.[10] McKinsey has highlighted the importance of addressing other objectives of affordability, reliability, and competitiveness on the path to net zero.[11] It has also looked at the critical, interdependent building blocks that need to come together for an orderly transition, including physical building blocks like technology and new supply chains; economic and societal adjustments, including significant capital spending; effective governance and institutions, and robust commitments.[12]

This research builds on this vast body of literature, taking a closer look at the physical building blocks of the transition—the "hard stuff"—and doing so systematically across sectors while understanding their interdependencies. Specifically, it explores the barriers or complexities associated with substituting high-performing fossil-fuel-based assets or processes for low-emissions ones, and building the supply chains and infrastructure to support them. Metaphorically speaking, only by looking at the systems underlying the physical nuts and bolts of the engine of the energy system, and how they connect with one another, can a new, high-performance, low-emissions energy system that serves the needs of society be conceived.

The observation has widely been attributed to Albert Einstein that, given an hour to solve a problem, he would spend 55 minutes defining the problem and five thinking about solutions.[13] It is in that spirit that this research takes stock of the physical challenges of the energy transition, building on a large body of work on decarbonization pathways. Across seven domains of the energy system, we have identified 25 significant physical challenges. They have been classified into three levels that indicate both the extent of progress so far and how difficult they are to address. The implications for stakeholders, including for innovation and broader system reconfiguration, are explored. The first four chapters of this report give an overview of the findings. Chapters 5 to 11 are more detailed discussions of each of the seven domains and the challenges within them, and are coauthored with McKinsey experts.

The aspiration of this work is that viewing the energy transition from a physical perspective will contribute to a better design for a successful transition and to navigating an affordable, reliable, and competitive path to net zero.

Across seven domains of the energy system, we have identified 25 significant physical challenges.

Misty valley with electricity pylons

Executive summary

Today's energy system, encompassing both the production and consumption of energy resources, is massive and complex. The system has been optimized over centuries, is deeply embedded in the global economy, and serves billions of people, if not yet all of humanity.[14] And it is high-performing. Energy can be dispatched relatively easily where and when it is needed because current fuels are energy-dense and easily transportable. Supply can be ramped up and down quickly.

For all its advantages, today's system also has critical flaws. About two-thirds of energy is currently wasted.[15] And the system generates more than 85 percent of global emissions of carbon dioxide (CO_2).[16] Companies and countries are now engaged in an effort to transition the energy system and reduce those emissions. Real progress has been made, but the transition remains in its early stages.

Low-emissions technologies such as solar and wind power and electric vehicles (EVs) have advantageous properties and can be brought together to deliver high performance. But deploying them well and progressing the transition further requires understanding the physical realities and associated physical challenges of the energy transition—the "hard stuff."

Recognizing that the energy transition is first and foremost a physical transformation is a truth that can get lost in the abstraction of net-zero scenarios. But it is vital if the new energy system is to retain, or even improve on, the performance of the current one and secure an affordable, reliable, competitive path to net zero.[17]

Seven domains of the energy system would need to be transformed, and this effort is in its early stages

The energy transition involves the physical transformation of seven deeply interlinked domains. The first is the *power* domain, which needs to reduce its own emissions and to scale dramatically to provide low-emissions energy to the three large consuming domains: *mobility, industry*, and *buildings*. The final three domains are enablers of the energy transition: *raw materials*, especially critical minerals; new fuels, such as *hydrogen and other energy carriers*; and *carbon and energy reduction*.

This research primarily uses the 2023 McKinsey Achieved Commitments scenario, not as a forecast, but to understand the physical challenges to overcome.[18] Under this scenario, billions of low-emissions assets—for instance, about one billion EVs, over 1.5 billion heat pumps, and about 35 terawatts of low-emissions power generation capacity—would need to be deployed by 2050 alongside scaling supporting infrastructure such as the grid, EV charging stations, and supply chains.

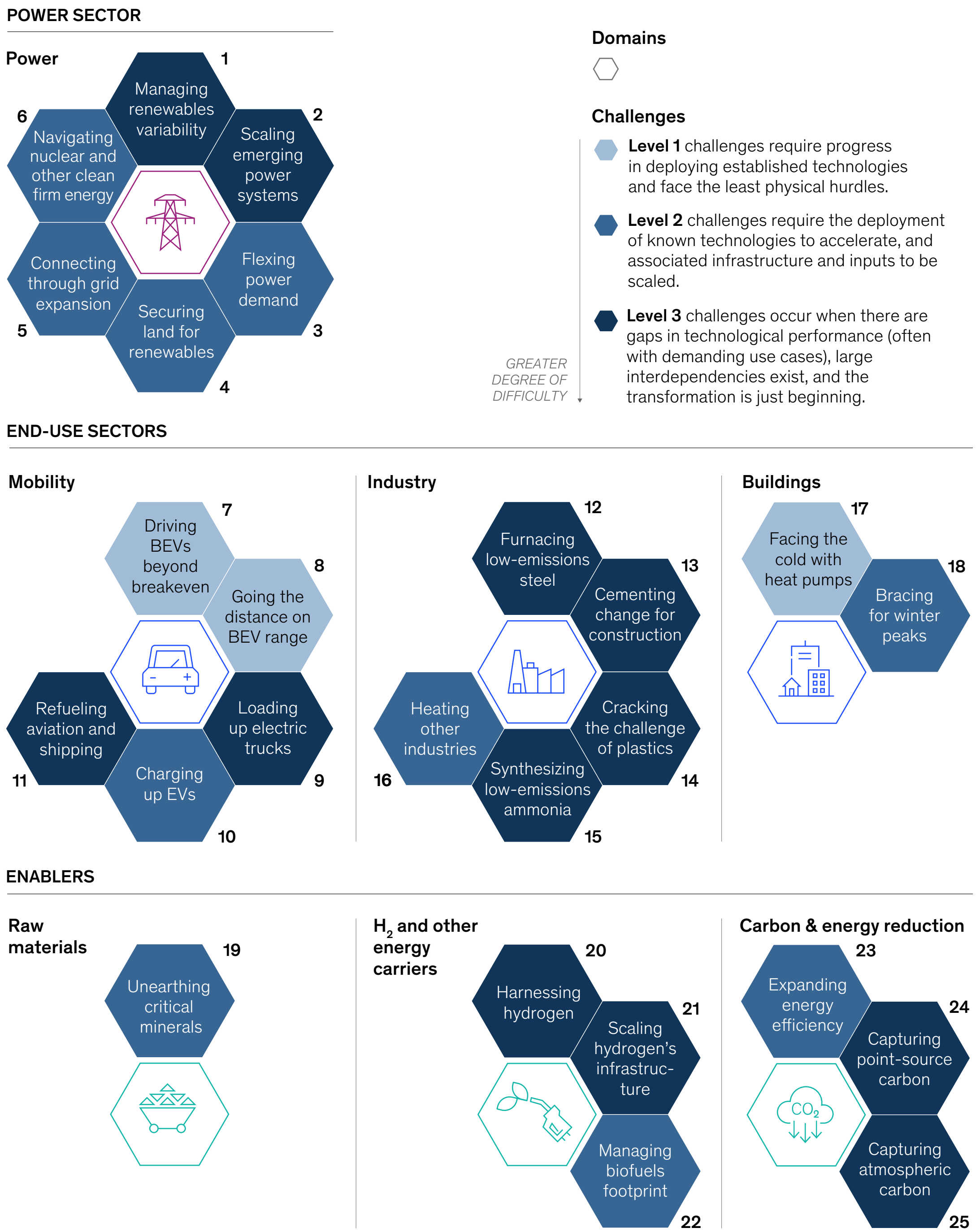
Recent years have seen momentum on many—but not all—fronts. For instance, about 90 percent of all battery EV sales and almost 60 percent of solar and wind power capacity added was in the past five years.[19] But overall, the transition is in its early stages. Deployment of low-emissions technologies is currently only about 10 percent of the levels required by 2050 in most areas—and largely in comparatively easy use cases. While some areas like solar have grown rapidly, others have not. In cases such as low-emissions hydrogen and carbon capture, less than 1 percent of required deployment by 2050 has been achieved thus far.

Abating about half of energy-related emissions depends on addressing the hardest of 25 physical challenges

To progress the transition further, 25 physical challenges—defined as barriers to switching from high-emissions physical assets and processes to low-emissions ones—across the seven domains would need to be addressed (Exhibit E1).

Exhibit E1

Twenty-five physical challenges would need to be addressed for the energy transition to succeed.



Note: The 25 challenges this analysis focuses on were prioritized based on the potential of related technologies to abate emissions. For more details, see the "Scope and methodology" sidebar.
Source: McKinsey Global Institute analysis

Some challenges are harder to address than others, and they have been categorized into three levels of difficulty based on technological performance, interdependencies across different challenges, and scaling needs:

— Three Level 1 challenges require progress in deploying established technologies and face the least physical hurdles.

— Ten Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled.

— Twelve Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning.

Eliminating between 40 and 60 percent of the energy system's CO_2 emissions depends on addressing Level 3 challenges.

Physical challenges appear in each of the seven domains: A summary

— *Power.* Overall, low-emissions power generation capacity would have to increase about ten times by 2050. There are two Level 3 challenges: managing variability in the power system as solar and wind generate a greater share of power, and doing so in emerging power systems that need to grow particularly rapidly. The flexible capacity that would be required to manage this variability, including backup generation, storage, and interconnections of grids in different regions, would need to grow two to seven times faster than power demand, but all face barriers.[20] Four other Level 2 challenges relate to securing enough land for renewables, investing in current transmission and distribution infrastructure and even expanding the grid, accelerating deployment of nuclear and other clean firm power, and increasing flexibility in power demand.

— *Mobility.* The number of EVs would need to surge from about 30 million on the road today to about one billion by 2050. Two challenges are Level 1: ensuring lifetime emissions savings from passenger battery EVs (BEVs) relative to internal combustion engine (ICE) vehicles, and ensuring that EVs have sufficient range for all needs.[21] For the latter, battery EVs already do so for roughly 70 percent of households. Scaling EV charging infrastructure and supply chains has further to go and is Level 2. Trucking, aviation, and shipping are harder to decarbonize, given that they require traveling long distances with heavy payloads, and are Level 3 challenges.

— *Industry.* Decarbonization of the "big four" industrial material pillars of modern civilization—steel, cement, plastics, and ammonia—poses four Level 3 challenges, where the transformation is just beginning. All rely heavily on fossil fuels as inputs and/or fuel for high-temperature heat.[22] A combination of more energy efficiency; different feedstocks, including hydrogen and recycled inputs; use of alternative materials; electrification; alternative fuels like biomass; and carbon capture would be needed. Other industries, such as general manufacturing, generally do not need high-temperature heat and tend not to use fossil fuels as feedstocks, but low-emissions processes to deliver heat would still need to be scaled and this constitutes a Level 2 challenge.

— *Buildings.* Heating accounts for the largest share of buildings-related emissions. Heat pumps are already established technologies and perform well, but still face two physical challenges.[23] Ensuring that they are efficient at cold temperatures is a Level 1 challenge, reflecting the fact that more than 95 percent of people live in places where existing heat-pump technologies do the job. More demanding, and therefore Level 2, is managing a potential doubling or tripling in peak power demand in some regions if heat pump use expands.[24]

— *Raw materials.* Demand for critical minerals, like lithium, cobalt, and rare earths, is expected to surge, but current supply is only about 10 to 35 percent of what would be needed by 2050. This is a Level 2 challenge, where supply would need to be accelerated, alongside managing demand for such minerals.

— *Hydrogen and other energy carriers.* New energy carriers would be needed to serve as alternative fuels and feedstocks for industrial processes. One option is hydrogen, which faces two Level 3 challenges. First, the hydrogen molecule goes through many steps and therefore energy losses before it can be used; these would need to be minimized and weighed against its advantageous properties. Second, hydrogen production and infrastructure would need to expand hugely. Few large-scale low-emissions hydrogen projects are currently operational.[25] Managing the growing land footprint of biofuels is Level 2.

— *Carbon and energy reduction.* Alongside measures to substitute high-emissions technologies for low-emissions ones, reducing the amount of energy consumed and the emissions of current technologies would also be needed. Expanding energy efficiency through established approaches, for example improving building insulation, is a Level 2 challenge. Carbon capture from new "point sources" such as cement could be three times harder—and costlier—than for less demanding current use cases, and removing carbon from the atmosphere through direct air capture could be even more costly. Both are Level 3.

Understanding the physical challenges can help CEOs and policy makers navigate the transition

Making progress on the transition requires understanding physical challenges. Innovation of technologies, such as improving the energy density of batteries, would need to continue. Broader system-level changes would also be needed—shifting the way technologies mesh together, for instance by expanding demand-side flexibility to reduce the variability of the power system. Even the way energy and materials are consumed could be adapted. For instance, alternative materials could replace industrial materials that are difficult to decarbonize.

CEOs and policy makers have a crucial role to play. For Level 1 challenges, they could consider how to quickly deploy fast-maturing technologies, and, for Level 2 challenges, how to address bottlenecks to unlock the next tranche of opportunities. For the difficult Level 3 challenges, they could consider in parallel how to make progress in the short term and how to unlock the system-level changes needed. As they do this, stakeholders need to consider how to ramp down the old system and ramp up the new one smoothly, and what investments could reduce emissions today while laying the groundwork for tackling future physical challenges.

Wind turbines and a coaster in the ocean and a coaster run on fuel oil

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1. The energy transition is a huge, nascent physical transformation

The energy system consists of the production, conversion, delivery, and consumption of energy resources across sectors as both fuels and feedstocks (that is, inputs for the production of different materials).[26] The system is a massive, interlocking physical entity that has been optimized over centuries. It has served billions of people—if not yet all of humanity—well. But in an era in which countries and companies around the world are aspiring to address climate change, the high emissions resulting from the current energy system are now firmly in focus. The world has duly embarked on a huge transformation, centered on switching from the high-emissions assets and processes on which the system is largely based to new low-emissions solutions.

The key to success is recognizing that the energy system is physical, made up of millions of assets that work together to deliver specific functions, and that the transition is therefore first and foremost a physical transformation. The physical nature of the energy transition can get lost in the abstraction of net-zero scenarios, but understanding the physical realities and associated physical challenges of the transition—the "hard stuff"—is vital if effective solutions are to be designed and an affordable, reliable, competitive path to net zero delivered (see Sidebar 1, "Why understanding the physical realities of the transition matters").

The physical transformation is a shift on a massive scale of high-emissions assets to low-emissions ones, such as solar and wind power, electric vehicles (EVs), and myriad others, and doing so in a manner that continues to deliver performance. But this is not all—supporting infrastructure and supply chains would need to be developed. These would include critical minerals, manufactured goods, transmission and distribution infrastructure, and EV charging stations, to name a few.

Today's energy system is high-functioning but generates high emissions

The energy system is huge and complex. The world has well over 60,000 power plants, delivering electricity to more than six billion people.[27] The length of the global oil and gas pipeline network is about two million kilometers, equivalent to traveling from the Earth to the moon and back—twice.[28] The energy system enables the production of about seven billion tonnes (metric tons) of industrial materials every year, accounting for about 800 kilograms of steel, cement, plastics, and ammonia for every person annually.[29] And today, more than 1.5 billion vehicles are on the road, the vast majority of them powered by internal combustion engines (ICEs) that run on fossil fuels.[30]

Not only is the energy system extraordinarily large in scale, but it is high-performing. A number of crucial properties have enabled today's energy system to play its central role in society, making economic progress possible. It can move energy relatively easily to where it is needed because current fuels are both energy-dense and easily transportable. Just one average tanker carrying liquefied natural gas can power more than 40,000 homes in the United States for an entire year.[31]

The energy system can ramp the provision of energy up and down quickly, to dispatch energy to the right place at the right time. A gas turbine power plant can move from full shutdown to generating power at full capacity in less than ten minutes.[32] The current energy system also supports the manufacture of thousands of materials thanks to the chemical flexibility of fossil fuels, namely that they can be used as feedstocks for multiple materials, and the ability of fossil fuels to generate a wide range of temperatures needed for industrial processes. Natural gas alone can be a feedstock for a range of materials, such as fertilizers, plastics, and steel, and burns at temperatures close to 2,000°C, thereby providing the high-temperature heat needed for many industrial processes.[33]

Sidebar 1. Why understanding the physical realities of the transition matters

Understanding the physical realities of the energy transition—namely the physical properties of low-emissions solutions and the nature of the physical transformation—is critical to many aspects of designing a successful transition.

First, understanding the physical properties of low-emissions solutions can help design a new system that delivers performance on a par with the current system and does so reliably. This matters because the energy system is vital for driving economic growth and progress. As discussed later, this is not a trivial task and it requires a careful understanding of the performance and advantages of low-emissions technologies, innovation needs, and how such technologies can effectively be brought together in an interconnected system to deliver performance.

Second, looking at the nature and scale of the underlying physical transformation helps design a feasible transition. In an energy system made up of thousands or millions, and in some cases billions, of individual assets, the transformation that would be needed is monumental. With such a massive scale-up, bottlenecks in the build-out of supply chains could lead to shortages of critical minerals and manufactured goods. Installing or building new low-emissions assets at the scale and pace needed may be similarly difficult if not planned for well.

Third, and relatedly, applying a physical lens to different components of the energy system can highlight critical interdependencies, which similarly need to be factored into the design of a reliable and feasible energy transition.

Fourth, understanding the physical properties and maturity of different technologies, and the nature of the physical transformation, also helps to shed light on their costs and therefore on the affordability of the transition.[1] Prior McKinsey research has highlighted the large scale-up needed in low-emissions capital spending and various challenges associated with the affordability of the transition.[2] While costs associated with the transition are not the core focus of this research, appreciating the physical realities of the transition is crucial to better understand cost challenges. For example, in the case of carbon capture technologies, expanding their use to new use cases would require deploying them in processes where CO_2 makes up a small portion of the gases that are emitted (that is, is present in lower concentration in flue gases) and is therefore harder to capture. This could be about three times more expensive than the cost of capture of higher-concentration use cases deployed today.[3] The massive physical scale-up of the assets needed for a new system could also lead to shortages of raw materials and, as a result, contribute to price increases and create volatility. In 2022, prices of cobalt, lithium, and nickel surged, leading to an increase in the price of batteries of nearly 10 percent globally.[4] A sharp drop in prices quickly followed. This volatility generated uncertainty that contributed to the postponement of new mining projects.[5]

Thus, a physical lens brings focus on not just how to achieve emissions reduction feasibly but also to do so while ensuring affordability, maintaining the reliability of the energy system, and thus also securing the competitiveness of companies and economies—three other objectives that McKinsey research has identified as vital for a successful transition.[6]

1 It is also important to take a holistic view of the socioeconomic impacts of different transition pathways, and to use this to help inform decision making. See C*limate Transition Impact Framework: Essential elements for an equitable and inclusive transition*, McKinsey Sustainability, December 2023; and "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey Sustainability, October 27, 2021.

2 See, for example, *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022; *An affordable, reliable, competitive path to net zero*, McKinsey Sustainability, November 2023; and *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023.

3 See chapter 11, Challenge 24.

4 *Energy technology perspectives 2023*, International Energy Agency (IEA), January 2023; *IEA clean energy equipment price index, 2014–2023*, IEA, September 7, 2023; and *Trends in electric vehicle batteries*, IEA, April 2023.

5 Thomas Biesheuvel, "Battery metal price plunge is closing mines and killing deals," Bloomberg Law, January 9, 2024; and Aya Dufour, "Some minerals are 'critical' to the digital economy, but current prices don't reflect that," CBC News, March 4, 2024.

6 *An affordable, reliable, competitive path to net zero*, McKinsey Sustainability, November 2023.

This not to say that every component of the current energy system delivers equally high performance. For example, natural gas is much less energy dense than oil. Coal power plants cannot ramp up as quickly as natural gas ones. But, in combination, the component fuels and technologies are able to meet numerous use cases.

Moreover, over centuries, sectors that consume energy have coevolved to make the most of the properties of fossil fuels to optimize buildings, cars, and industries. For example, flights capable of long-range travel have emerged, making the most of the energy density afforded by fossil fuels.

Industrial processes have developed to use the high temperatures generated by the burning of coal or gas. And these changes have shaped our broader economic and social lives. Coupled with hundreds of years of industrial learning and accumulated investment, this coevolution has delivered cheap, reliable, convenient, and resilient ways to produce and consume energy.

Nevertheless, for all the advantages of the current energy system, it has significant flaws.[34] About two-thirds of energy consumed today is wasted, mostly due to low energy efficiency in the conversion and use of fossil fuels.[35] But perhaps most notably, today's energy system leads to high emissions of greenhouse gases. Today's energy system is responsible for more than 85 percent of global emissions of carbon dioxide (CO_2).[36] To take one instance, more than two kilograms of CO_2 are released for every liter of gasoline burned. An average tree would take about 40 days to absorb that volume.[37]

Overall, then, today's energy system is a conundrum, offering a mix of positive and negative attributes. At the heart of the transition is an aspiration to retain—and even improve on—the performance advantages offered by the current energy system while addressing many major downsides, especially high emissions.

This effort is further complicated in two ways. First, as noted, the current aspiration is to achieve the energy transition in a short time frame in comparison with transitions of the past.[38] Second, the energy system of today does not meet the needs of a large share of the world's people—it still needs to grow.[39] The average person lives with less than 55 gigajoules of energy each year. That is about the level of Thailand but only about half the energy each person in Germany consumes.[40] In 2022, 760 million people, mostly in sub-Saharan Africa and South Asia, had no access to electricity.[41] Transforming the vast and complex energy system in a short time, even while growing to serve the needs of more of the world's population, would be no mean feat.

Transforming the energy system would require considering how best to deliver performance

Standards of living across the world would depend on a new energy system being able to deliver the same or better performance in comparison with the existing one.

A superficial glance at today's energy system might suggest that fossil-fuel-based technologies deliver performance superior to that of low-emissions alternatives across the board (Exhibit 1). Today, fuels such as diesel have about 50 times higher gravimetric energy density (or per unit weight) than the batteries used in electric cars.[42] Electricity and many low-emissions energy carriers such as hydrogen are harder and more costly to transport over long distances than fossil fuels. Solar and wind power output is variable and not dispatchable, unlike gas or coal power plants' output.

But a closer look reveals that advantageous physical properties are not universally the purview of fossil fuels. Low-emissions technologies can often match or even exceed the performance of fossil-fuel-based ones.[43] For instance, batteries can provide quicker dispatchability than even gas-fired peaking plants.[44] Nuclear plants often have higher capacity factors than gas plants. Hydrogen has higher gravimetric energy density and burns at higher temperatures than natural gas. Electric technologies such as electric cars and heat pumps often have double the efficiency of fossil-fuel combustion-based assets, or even more. A new energy system built using low-emissions technologies could potentially replicate the properties of the current one and even improve on them, depending on how these technologies are deployed and combined.

Low-emissions technologies are also improving as innovation advances. For instance, the capacity factors of wind power in the United States have almost doubled in the past 20 years (meaning that they generate electricity more consistently), and the energy density of batteries has been growing at about 3 percent a year (meaning that the same weight of battery carries more energy).[45]

Exhibit 1

Today's energy system has beneficial properties but produces high emissions.

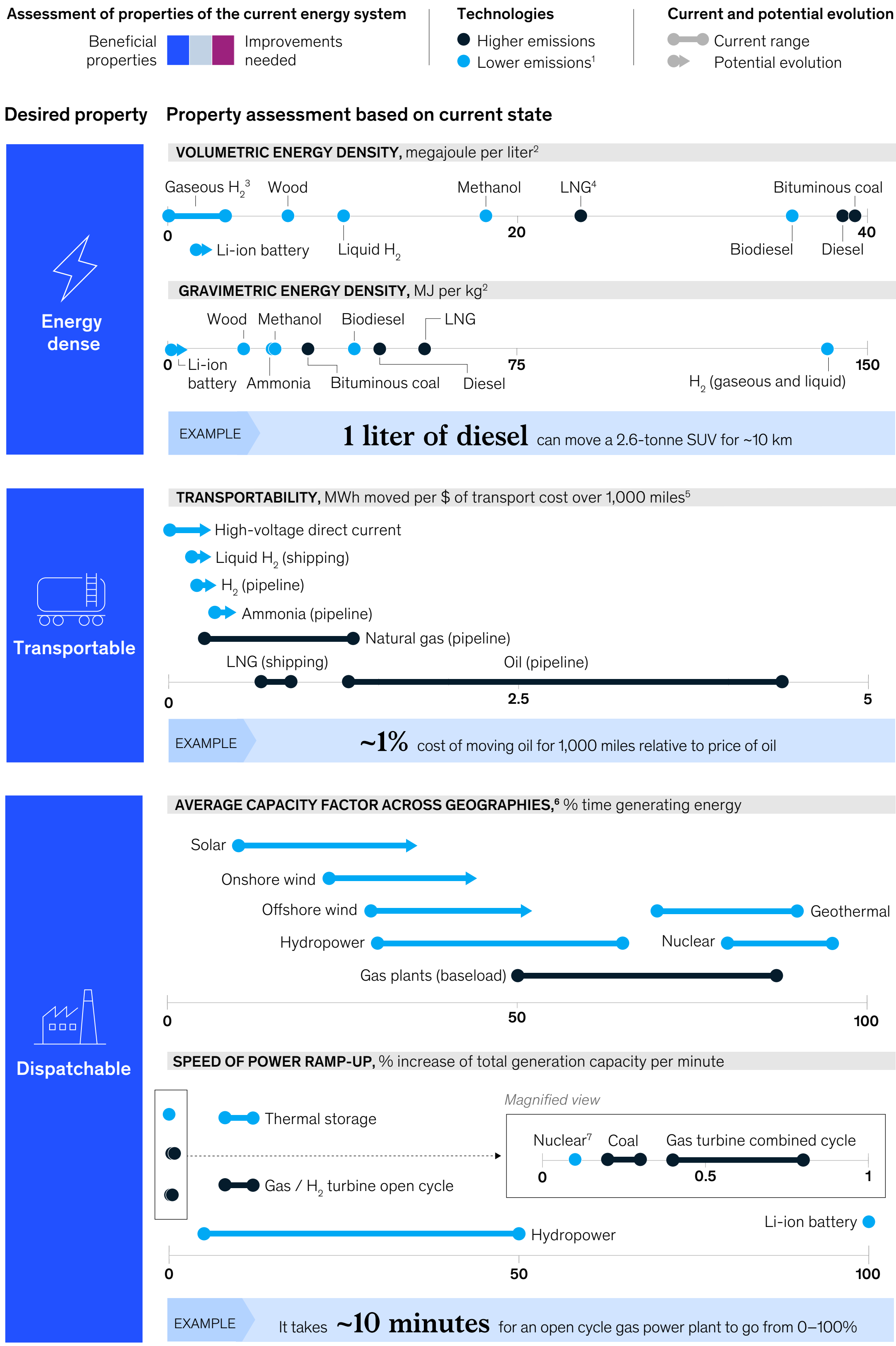
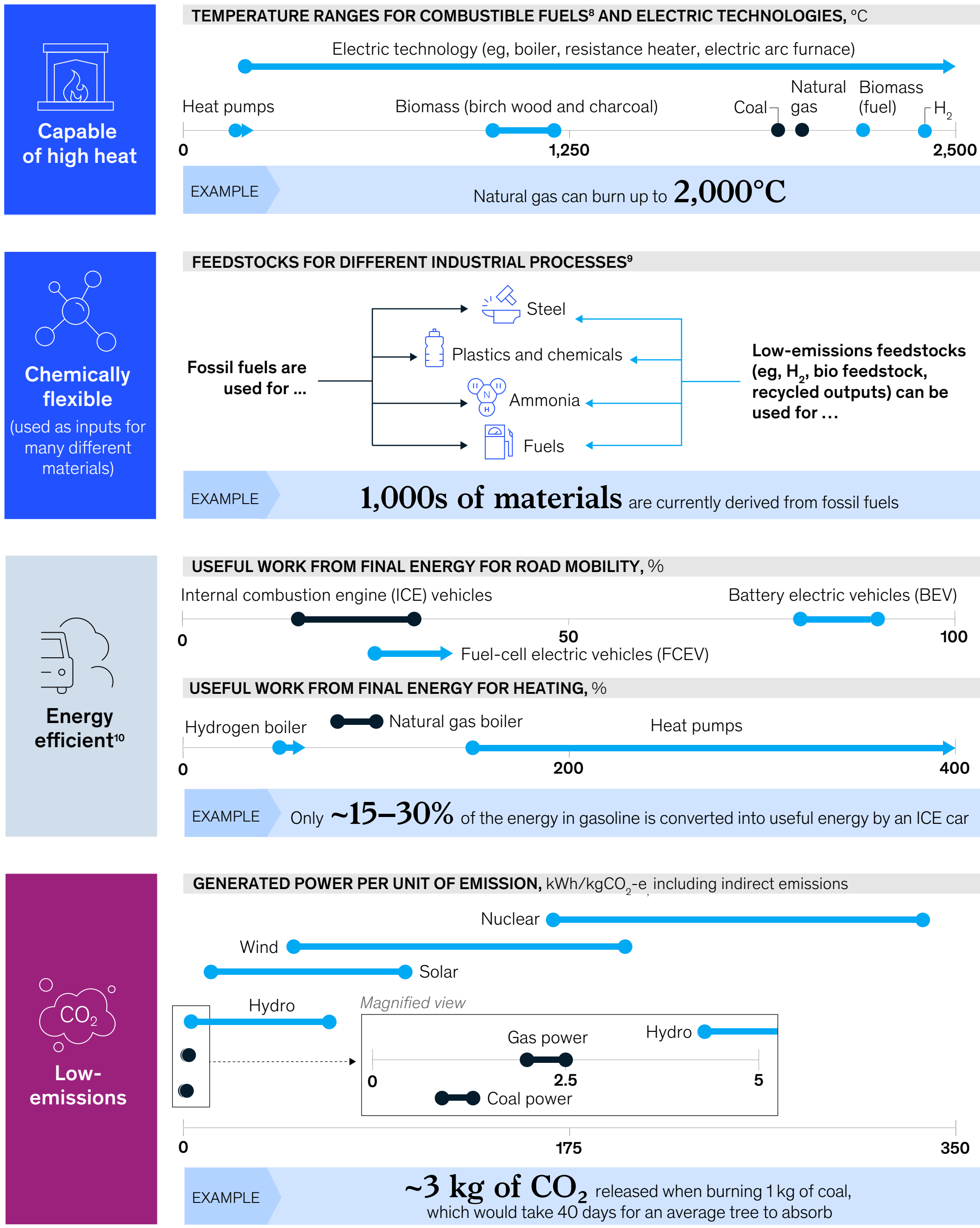


Exhibit 1 (continued)

Desired property **Property assessment based on current state**



Note: This exhibit assesses the current state of critical properties of individual technologies to outline the potential building blocks of a new system. In practice, a new system would not consist of one-to-one substitutions, so performance at the system level depends not just on individual technology performance but on how the system is wired together. Technologies are illustrative and not exhaustive.
[1]Some of the options classified as "lower emissions" can entail a range of different potential emissions profiles depending on how they are produced (for example, ammonia). [2]Higher heating value. [3]Ranged across different pressures, from 1 to 350 bar. [4]LNG = liquefied natural gas. [5]Transmission costs include total operating costs and amortized capital cost for new line construction. Cost comparisons of transported energy have important limitations, including the fact they exclude upstream and downstream losses in generating and using that energy. [6]Excludes assets used only to provide power flexibility. [7]For large-scale nuclear fission. [8]Flame temperature that these fuels can burn at; actual temperatures may be lower due to energy losses. [9]For instance, coal in steelmaking; natural gas in the production of ammonia, chemicals, plastics, and steel, and in fuels; oil in fuels and in the production of chemicals and plastics. Low-emissions feedstocks such as hydrogen and biobased feedstocks can be used to make ammonia, chemicals, plastics, and steel. [10]Starting from electricity for H_2, heat pumps and BEVs, and from fossil fuels for boilers and ICEs: includes local uses, excludes long-haul transport of hydrogen.
Source: US Department of Energy; National Renewable Energy Laboratory; International Energy Agency; World Nuclear Association; International Renewable Energy Agency; US Energy Information Administration; European Energy Research Alliance; Energy Transitions Commission; Hydrogen Council; Hydrogen Science Coalition; GTK; Agora Industry; Ambienta; DeSantis et al. (2021); Galimova et al. (2023); The Oxford Institute for Energy Studies; US Environmental Protection Agency; European Environment Agency; McKinsey Global Institute analysis

Furthermore, there is considerable scope to combine individual low-emissions technologies to create entirely new configurations to deliver on performance, even if those individual technologies have less favorable physical properties than fossil-fuel ones. This is not limited to energy supply but applies across sectors that both produce and consume energy. Indeed, just as the current energy system was shaped by the co-evolution of energy-producing and -consuming sectors, so too can a new system. One such reconfiguration is coupling industrial electrification with thermal energy storage (TES), which stores heat and therefore creates a much more flexible demand profile for electricity from industry. This can help manage the variable supply from some renewable sources of electricity like sunshine and wind. In a nutshell, electrified industrial processes can produce and store some of the heat they need in advance during times when such renewable electricity is plentiful and cheap due to lots of generation (for example, during the day when the sun is shining). They can draw on that stored heat later in order to reduce the demand on the grid at times when generation is lower, thus helping manage the fact that many generation technologies that would be part of a new energy system are not dispatchable.[46] (Other examples of such reconfigurations are discussed in chapter 4).

Put together, this discussion underscores the importance of understanding the physical properties of low-emissions technologies and how they can be brought together to ensure a high-functioning low-emissions energy system.

Seven interlinked domains of the energy system would need to be physically transformed

Seven domains would need to be physically transformed as part of the energy transition.

The first of these is the power sector, which is at the heart of the transition. It would need to transform to reduce its own emissions. In an interlinked energy system, it also needs to scale up dramatically to provide low-emissions energy to the three key consuming sectors: mobility (road vehicles and other forms of transportation to move people and things); industry (which manufactures a broad range of materials and goods like steel and cement); and buildings (facilities that consume energy for lighting, heating, and more). The final three domains explored are crucial enablers of the energy system transformation: raw materials, with a key focus on the critical minerals needed for many low-emissions technologies like batteries and electrolyzers (devices that split water molecules into hydrogen and oxygen); new energy carriers, such as hydrogen; and carbon and energy reduction approaches that include carbon capture and energy reduction (Exhibit 2).[47] Addressing issues in other sectors, like agriculture, forestry, and other land use, is of course critical to achieving net-zero emissions, but the focus of this research is energy supply and demand and therefore does not consider these aspects of the transition.

These seven domains are deeply interlinked. All of the low-emissions physical assets that would make up the new energy system are interdependent, making the transition a complex undertaking. For example, decarbonizing mobility, buildings, and industry would require a larger, lower-emissions power system to feed ever-growing demand for electricity from new technologies ranging from EVs to heat pumps. New energy carriers, such as hydrogen, also would need a great deal of power. These carriers, in turn, could propel adoption of applications in mobility and in industry, such as low-emissions steelmaking. Hydrogen and other low-emissions fuels can also be used as sources of backup power for power systems with large shares of variable renewable energy sources. All domains would rely on the availability of raw materials, and the power system, mobility, and hydrogen applications would be particularly voracious consumers of critical minerals. As such, a modular approach to the energy transition would not work. A system view is needed.

Exhibit 2

Seven interlinked physical domains would need to be transformed for the energy transition.

Note: This research focuses only on the energy transition and therefore on energy supply and demand. Sectors such as agriculture, forestry, and waste are not included.
[1]Displayed linkages across domains are not exhaustive. For example, electrolyzers for H_2 need some critical minerals (eg, platinum, cobalt); hydrogen is also being considered as a potential source of fuel for boilers in buildings; decarbonizing construction of buildings would require low-emissions industrial materials.
Source: McKinsey Global Institute analysis

Progress has been made, but the transformation is at an early stage, and the next phases will be different

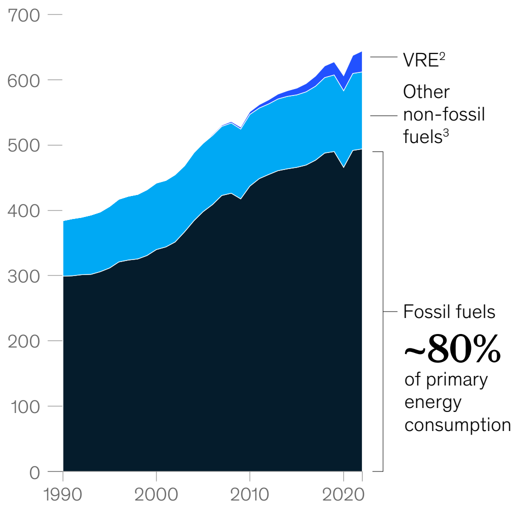
While real progress has been made, the energy transition is in its early stages. Although the intensity of emissions per unit of primary energy consumed has declined by about 7 percent over the past decade, CO_2 emissions are still growing globally—albeit at a slowing rate and not everywhere.[48] Fossil fuels still account for about 80 percent of global primary energy demand, only about four percentage points lower than 20 years ago (Exhibit 3).[49] The world has been electrifying, but slowly. Between 2005 and 2022, the share of electricity in total final energy consumption grew by fewer than five percentage points, from about 16 percent to 20 percent.[50] While sales and deployment of low-emissions technologies have been rising, stocks take time to turn over.

Exhibit 3

The energy transition is at an early stage.

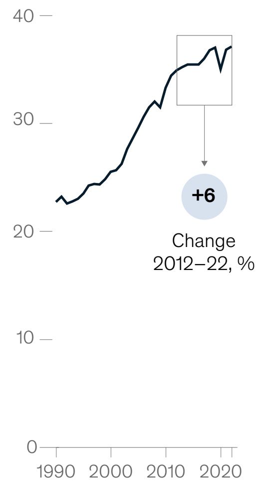
Fossil fuels account for about 80% of primary energy consumption

Primary energy[1] consumption by source, exajoules

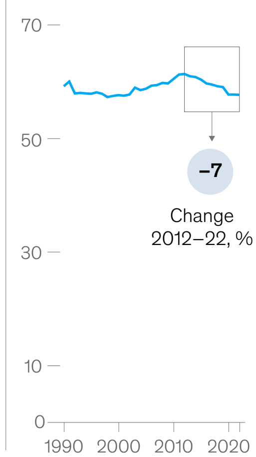


Emissions have not started to decline

Energy-related CO_2 emissions
Billion tonnes CO_2



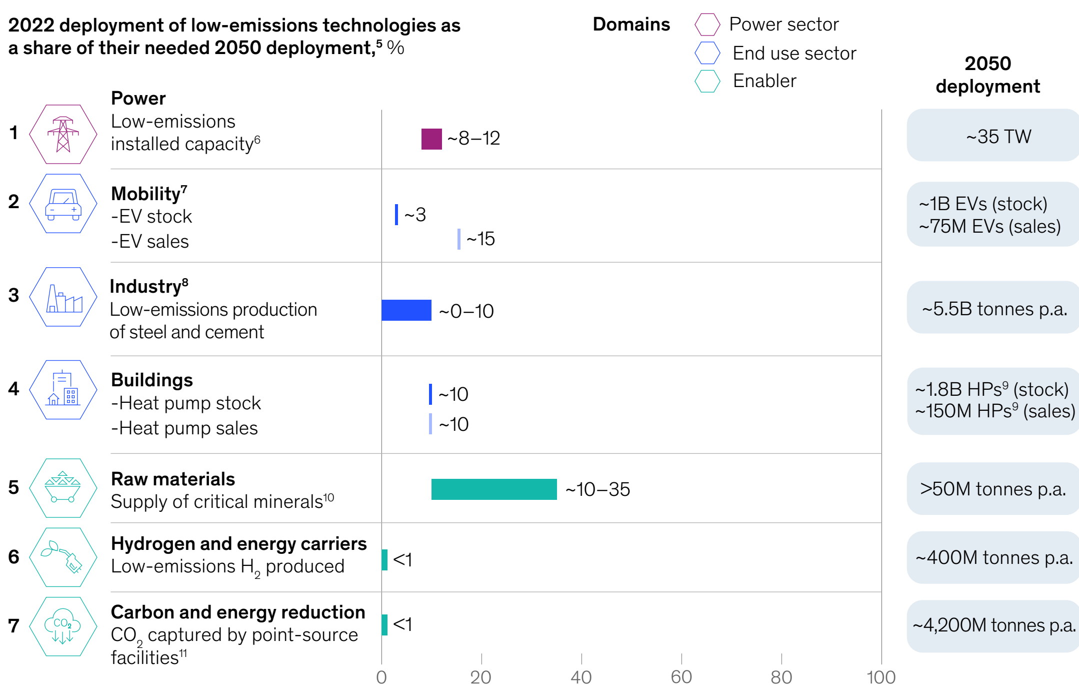
Emissions intensity
Million tonnes CO_2/exajoules of primary energy consumption



Deployment of key decarbonization approaches is at an early stage in most domains

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO[4]

2022 deployment of low-emissions technologies as a share of their needed 2050 deployment,[5] %



[1]Total energy available from natural sources before any losses occur in the energy conversion process, using substitution method. Primary energy is used here because it is a widely available global metric that gives a rough indication of current contributions of different energy sources to the energy system. But there are limitations to comparisons of primary energy contributions from fossil fuels and other energy sources, given that most energy contained in fossil fuels is lost in conversions. During the energy transition, therefore, not all primary energy supply would need to be replaced one-for-one. [2]Variable renewable energy, including solar and wind. [3]Other non-fossil fuels include nuclear, hydropower, biomass, biofuels, and other renewables. [4]Scenario in which most countries that have committed to net zero (some by 2050, some later) meet those commitments. [5]Estimated ranges of current deployment compared with 2050 deployment needs, based on parameters detailed below. [6]Low end only includes VRE, while high end includes all low-emissions power. [7]For mobility specifically, we consider 2023 deployment (as a share of needed 2050 deployment). Figures are for BEVs and FCEVs, excluding two- and three-wheelers, which are more electrified today. [8]Average of steel and cement. Low end only includes low-emissions primary production, while high end includes all low-emissions production including secondary supply for steel. [9]HPs = Heat pumps. [10]Across eight minerals. For each, today's production is assessed relative to 2050 demand. The low end refers to the minimum value of this across minerals, while the high end refers to the average value across minerals. [11]Includes only point-source capture, excludes direct-air capture.
Source: Energy Institute; International Energy Agency; McKinsey MineSpans; *Global energy perspective 2023*, McKinsey; McKinsey Global Institute analysis

Overall, in most domains, deployment of low-emissions technologies is only at about 10 percent of the levels required by 2050 under the energy transition.[51]

Particularly in recent years, there has been momentum on many—but not all—fronts. For instance, around 90 percent of all battery EV sales and almost 60 percent of solar and wind power capacity added occurred in the past five years.[52] In this period, battery EV sales grew by more than 45 percent a year, and solar and wind power capacity added grew at a rate of more than 25 percent annually. In these cases, sustaining such growth rates would be compatible with the envisaged energy transition by 2050.

However, the sheer scale of what would still be needed cannot be underestimated. Sustaining rapid growth is not guaranteed. Most of the progress to date has been in relatively easy use cases, such as the deployment of passenger EVs, rather than in the more challenging case of long-haul heavy-duty trucking, which involves longer trips and greater payloads. And while rapid growth has been seen in some areas like solar, this has not yet been true across the board. In some cases, such as the low-emissions primary production (excluding recycling) of large industrial materials; hydrogen; and carbon capture, less than 1 percent of required deployment by 2050 has been achieved thus far.

In each of the seven domains, much would need to change. In order to understand and size the degree to which each domain would have to be transformed, this research primarily uses the 2023 McKinsey Achieved Commitments scenario.[53] This scenario (and, in some cases, other similar scenarios) is not meant to be a forecast of the pace and manner in which the energy transition will play out. Rather, it is used to shed light on the underlying physical transformation economies would need to undertake if they are to meet their stated commitments related to the energy transition, and therefore the nature and magnitude of physical challenges which will need to be overcome.[54] This research considers periods 2030 and 2050, both typical milestones associated with the energy transition.[55]

— *Power.* The power system would need to both decarbonize and grow as more people gain access to electricity and more parts of the energy system, such as mobility, industry, and buildings, are electrified. Overall, the power system would quintuple in size (generation capacity installed) between now and 2050. At the same time, the share of power that is generated from low-emissions sources would need to more than double to over 90 percent.[56] More low-emissions sources of power would be needed, including variable renewable energy (VRE) such as solar and wind, and clean firm power, such as nuclear.[57] All in all, low-emissions assets have only been deployed at about 10 percent of levels needed by 2050. There are also new and rapidly growing sources of power demand that could impact the scale of the transformation needed in the near term. For example, in 2022, approximately 450 terawatt-hours—around 2 percent of total global power demand—were attributed to data centers, including artificial intelligence and other applications.[58] By some estimates, this demand could more than double to over 1,000 terawatt-hours as soon as 2026.[59] Furthermore, most of the deployment of low-emissions assets today has been in comparatively easier use cases. As VRE penetration increases, managing the power system would become progressively harder because the intermittency of these assets would require a much more "flexible" power system than today; that is, one with more forms of backup power, storage, and interconnections of grids in different regions. Larger and faster deployment of these flexibility solutions would also need to occur in markets that have less developed power systems today. Nonetheless, progress has been accelerating across the world. China, for instance, has deployed more energy storage than any other economy in the world in recent years.[60]

— *Mobility.* Decarbonization of mobility would require significant ramp-up of low-emissions assets, with both demonstrated and evolving technologies. In the case of road mobility, modal shifts to rely more on public and other means of transportation are being considered, as well as the use of hybrid vehicle technologies, but electrification to replace ICE vehicles with EVs is expected to be a critical lever to decarbonize the sector. Current deployment of EVs is only 3 percent of what would be required to decarbonize road mobility by 2050.[61] Consider that while one billion EVs would be on the road by 2050, only about 30 million are on the road today. To achieve the required scale-up, the share of sales of EVs would have to grow from about 15 percent of new vehicles today to over 75 percent in 2030 and almost 100 percent by 2050. Today, EV deployment is concentrated in segments that are comparatively easier to tackle, including lower-range passenger vehicles in dense urban environments. China and the European Union accounted for about 80 percent of electric passenger cars sales in 2023.[62] As the transition progresses, harder use cases would need to be addressed. As yet, for example, there are very few electric medium- and heavy-duty trucks on the road. Under the transition scenario examined here, this would need to rise to more than 40 million in 2050.[63] The decarbonization of aviation and shipping is at an even earlier stage—less than 1 percent of energy consumption in these sectors comes from low-emissions sources, such as electricity, biofuels, and synthetic fuels.[64]

— *Industry.* Decarbonizing industries would require deploying new technologies to abate both process emissions and heat emissions generated by the use of fossil fuels. The four big industrial materials—steel, cement, plastics, and ammonia—would be especially hard to decarbonize because they rely on fossil fuels both as feedstocks and/or as sources of high-temperature heat. In 2022, less than 10 percent of the seven billion tonnes of these four materials that was produced was done with low-emissions processes.[65] In the International Energy Agency Net Zero scenario, that would need to rise to between 90 and 95 percent by 2050.[66] Furthermore, almost all progress thus far has been in secondary production through recycling; virtually no primary production is a low-emissions process today, and this would be particularly hard because it would require new processes (such as carbon capture) and changes to the inputs required (for instance, use of biomass or hydrogen). The transformation is especially challenging in parts of the world, such as India and China, where high-emissions assets are still relatively new. Other industries beyond the big four may be somewhat easier to decarbonize because they require relatively lower-temperature heat that can be provided by low-emissions options that are commercially mature today and generally require less retrofitting. Nevertheless, a massive deployment of low-emissions heat sources would be needed.

— *Buildings.* Heating and cooling make up the lion's share of building-related emissions, and abating them would require deploying low-emissions technologies, notably heat pumps and district heating systems (among a few other options). Overall, deployment of heat pumps is only at about 10 percent of the levels required by 2050.[67] Although high deployment is already occurring in colder climates in Europe, reaching the necessary deployment levels by 2050 would nonetheless require solving the most demanding use cases related to the use of heat pumps in the most extreme temperatures and addressing implications of large-scale electrification of heat for the power system.

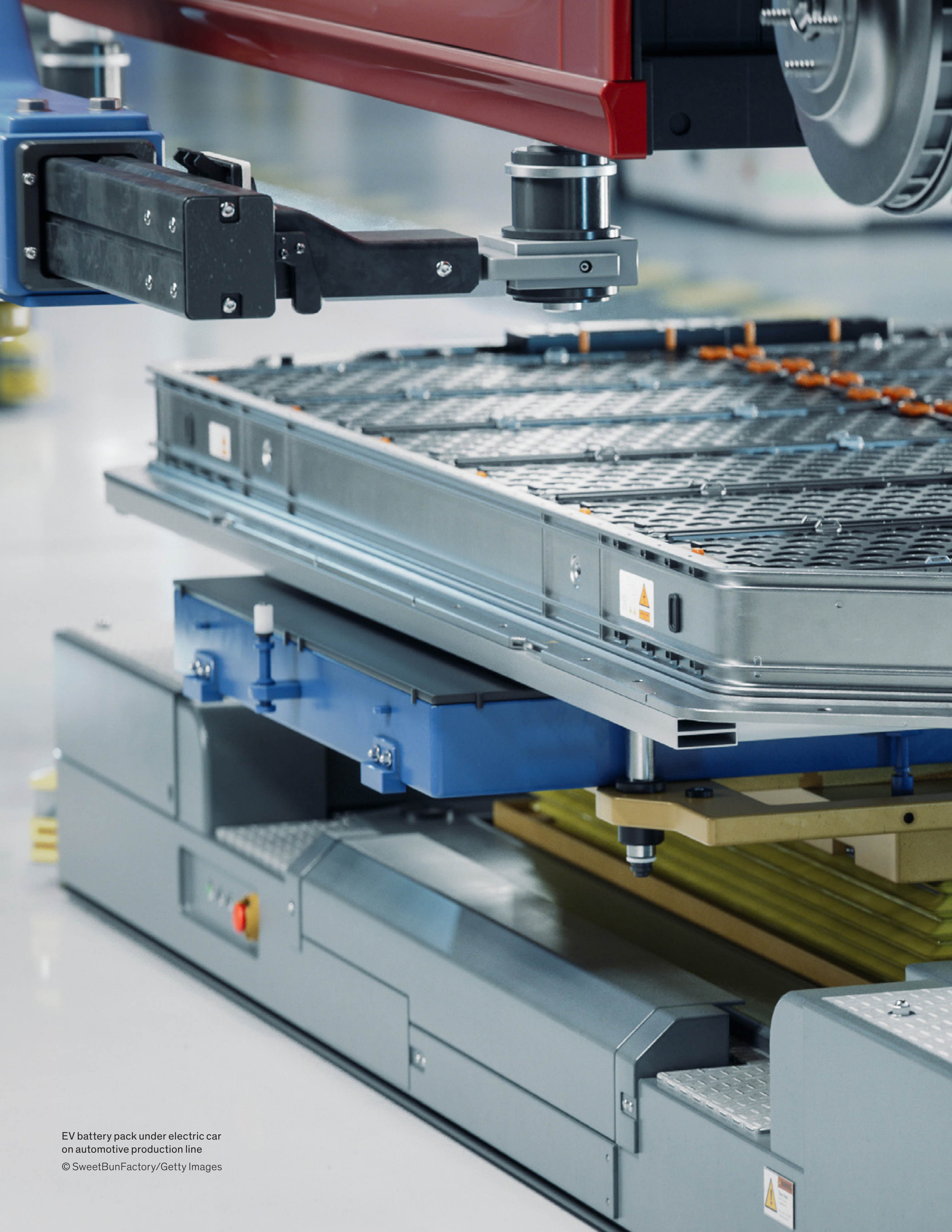
— *Raw materials.* The energy transition would require many raw materials, none more significant than the critical minerals needed for low-emissions technologies, such as batteries, wind turbines, electric motors, and electrolyzers. Current supply is only about 10 to 35 percent (depending on the specific critical mineral) of what would be needed by 2050.[68] Potentially complicating addressing this challenge is the fact that the supply and refining of the most critical minerals is concentrated in only a few countries.[69] To ensure sufficient supply of critical minerals would require expanding supply by accelerating the development of new mines and refining plants. At the same time, demand would need to be managed through new technologies that are less mineral intensive, such as new battery chemistries or new types of electric motors.

— *Hydrogen and other energy carriers.* The energy transition would require new low-emissions energy carriers to assume some of the role currently played by fossil fuels. Hydrogen is a key one being considered (alongside other low-emissions fuels such as biofuels). Less than 1 percent of the 90 million tonnes of hydrogen produced today comes from low-emissions processes, and demand could rise significantly under the transition by as much as four to five times by 2050.[70] Moreover, increasing the use of hydrogen would depend on tackling challenges related to the production and transport of hydrogen. It would also involve substantially more demanding use cases, expanding beyond the way that hydrogen is used today (such as in refining or in the production of ammonia) to areas where its use is nascent, including, for instance, steelmaking and dispatchable power generation and storage.

— *Carbon and energy reduction.* Alongside deploying low-emissions assets, ways of reducing the overall emissions footprint of current assets would need to be identified. One way to reduce the overall emissions of current assets is to increase energy efficiency (using less energy for a given process or use). The Intergovernmental Panel on Climate Change (IPPC) finds that energy efficiency mitigation options could contribute more than five gigatonnes of CO_2 equivalent to net emissions reduction by 2030.[71] Another possibility is capturing CO_2 either at the point of emissions or from the atmosphere. In 2022, only about 40 million tonnes of CO_2 were captured through carbon capture, utilization, and storage (CCUS), and mostly in comparatively easier use cases.[72] Under the transition, the role played by carbon capture from point sources could be at least 100 times larger by 2050, with about 4,200 million tonnes of CO_2 capture capacity potentially required. This ramp-up in the use of CCUS would require addressing the current difficulty (and cost) faced in capturing CO_2 in low concentrations in flue gases as well as developing storage solutions and new use cases for captured carbon. Capturing atmospheric CO_2 would be even more demanding.

This discussion offers a guide to what might be needed for the world to achieve its aspirations for decarbonization. Overall, the transition remains in its earlier stages with more difficult challenges ahead.

Deployment of low-emissions technologies is only at about 10 percent of the levels required by 2050.



EV battery pack under electric car
on automotive production line

2. Twenty-five physical challenges would need to be addressed

Across the seven domains of the energy system, this research has identified 25 physical challenges that would need to be addressed to progress the transition (Exhibit 4). This chapter summarizes all 25. For more detail, see chapters 5 to 11.

A physical challenge is defined in this research as a barrier to switching the high-emissions physical assets and processes of the current energy system for low-emissions ones. Challenges cover issues related to developing new low-emissions technologies and scaling them as well as the inputs, supply chains, and infrastructure needed to operate them.

Overcoming these physical challenges would be especially complex because the energy system and the domains within it are deeply interlinked. It may not always be possible to address challenges in isolation because tackling one would often depend on making progress on another. This research looks not only at individual challenges but also at these interdependencies.

Challenges fall into three levels of difficulty

All 25 challenges would need to be addressed in some way for decarbonization to be successful (see Sidebar 2, "Scope and methodology"). But they are different. This analysis categorizes them into three levels of difficulty, reflecting both the progress made to date in addressing them and the nature of the hurdles to overcome.

The starting point of this analysis is considering three specific features that make challenges difficult: (1) technological performance (assessed at a use case level); (2) gnarly interdependencies between challenges; and (3) degree of, and constraints on, scaling the deployment of low-emissions technologies, and also scaling required inputs, supply chains, and infrastructure. Each of the 25 challenges is considered against these features and categorized into Level 1, Level 2, or Level 3.

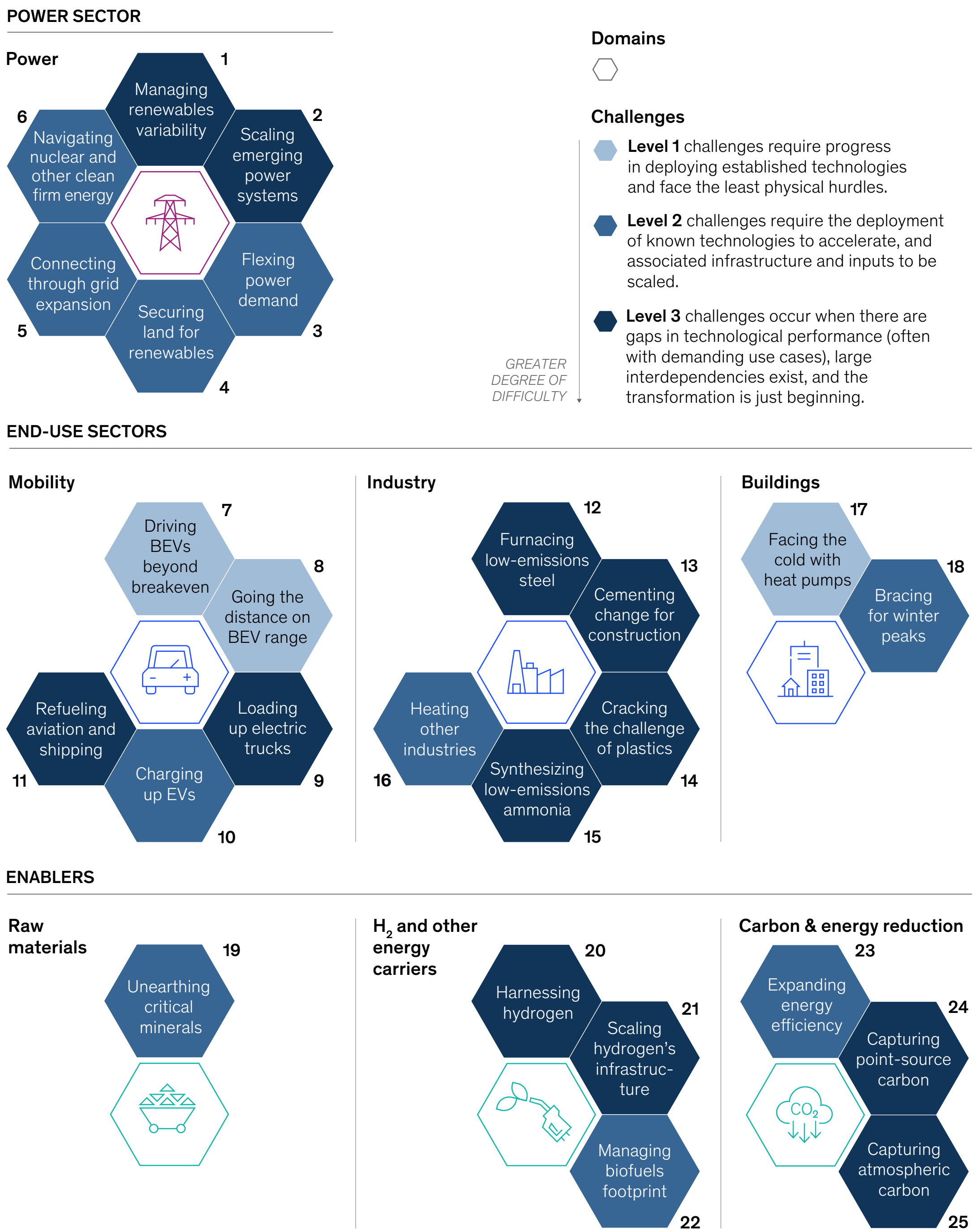
As an illustration, consider how the challenges in the mobility domain fall into three levels, as follows:

— *Level 1 challenges require progress in deploying established technologies and face the least physical hurdles.* For such challenges, technological performance needed from low-emissions technologies has been addressed for a large portion of use cases, and progress on bridging performance gaps in any remaining use cases has been robust. Some interdependencies may exist with other challenges, but they are not critical bottlenecks for most use cases. In addition, where applicable, scaling is progressing roughly on pace with the needs of the energy transition.

  In mobility, ensuring that passenger battery electric vehicles (BEVs) reach the range drivers need is a Level 1 challenge. BEVs can go shorter distances than internal combustion engine vehicles, or ICEs, before they need to refuel; an average passenger BEV currently has a reported range of about 400 kilometers, in comparison with about 650 kilometers for an ICE. Moreover, charging a BEV takes at least 25 to 50 times longer than filling up an ICE vehicle.[73] However, even with a safety margin for range deteriorating due to extreme weather conditions, today's average BEV is estimated to meet the daily needs of 70 percent of households.[74] Overall, therefore, a substantial portion of use cases is already addressed by today's levels of technological performance. In addition, substantial progress has been made in addressing remaining use cases where performance still lags. For example, the energy density of batteries is increasing by about 3 percent a year, and the average range of a BEV has risen by about 200 kilometers in the past decade.[75]

Exhibit 4

Twenty-five physical challenges would need to be addressed for the energy transition to succeed.



Note: The 25 challenges this analysis focuses on were prioritized based on the potential of related technologies to abate emissions. For more details, see the "Scope and methodology" sidebar.
Source: McKinsey Global Institute analysis

— *Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled.* For these challenges, mature technological options are available. Their deployment or the scaling of important inputs and infrastructure faces constraints, however, and this sometimes also creates interdependencies with other challenges. Further acceleration would be needed to address these challenges.

Building more extensive charging infrastructure and supply chains for BEVs and fuel-cell EVs (FCEVs) is a Level 2 challenge. In McKinsey's 2023 Achieved Commitments scenario, global public charging infrastructure would need to grow by 24 percent per year between 2022 and 2030, from 2.8 million charging points to about 16 million.[76] In the case of hydrogen refueling stations, the scale-up would be from a very low base.[77] Manufacturing capacity for batteries used in mobility would need to grow tenfold, to about 5,800 gigawatt-hours by 2030.[78] The concomitant scale-up of critical minerals supply that would be needed for batteries also creates an interdependency with challenges in the raw materials domain.

— *Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning.* For these challenges, technological performance gaps can exist for a large portion of use cases, which often have more demanding needs. Substantial progress is needed toward bridging these gaps. Moreover, such challenges often have critical interdependencies with other Level 3 challenges, and the transformation is just beginning.

Some low-emissions technologies in mobility do not yet offer the performance that would be needed by more demanding cases. Trucking, for instance, is difficult to decarbonize because it entails carrying heavy payloads over long distances, and this is particularly challenging for battery-powered vehicles with current levels of battery energy density. That density does not matter as much for passenger EVs because they tend to travel shorter distances with lighter payloads. However, even the best heavy-duty battery electric trucks available today could fail to meet roughly 20 to 45 percent of current long-haul trucking use cases with a single charge if weight regulations are not changed.[79] Moreover, the transformation is just getting started—fewer than 1 percent of trucks on the road today are electric, and almost none of those run on long-haul routes.[80] A new transformation would need to be kick-started to get electric trucks on the road in greater numbers.

Each of the 25 challenges is summarized and categorized into a level in this chapter. Chapter 3 discusses in more detail the three features that make challenges difficult and what this implies for the hardest Level 3 challenges.

Fewer than 1 percent of trucks on the road today are electric.

Sidebar 2. Scope and methodology

This research focuses on understanding the physical challenges of the energy transition. Important methodological choices were made to do this.

The focus is the energy system, encompassing both production and use (including the current use of fossil fuels as feedstock for industrial processes). The system accounts for more than 85 percent of current CO_2 emissions.[1] Sources of emissions outside the energy system, including in agriculture, forestry, and other land use, are not included. Other important sustainability topics, including the preservation of natural capital and the impact of pollution beyond greenhouse gas emissions, are also not within scope.

In each domain of the energy system, the analysis explores what physical asset and process transformations would be required when switching from high-emissions assets to low-emissions alternatives. Examples include switches from fossil-fuel-based power generation, such as coal power plants, to low-emissions sources like variable renewable energy in the form of solar and wind, and clean firm power like nuclear or hydropower in the power domain; from ICE vehicles to EVs in the mobility domain; and from gas boilers to low-emissions heat sources in industry or buildings. The associated infrastructure and supply chains that would need to be built to support these switches are also analyzed.

Based on these transformations, the research then identifies 25 physical challenges that must be addressed for the CO_2 emissions of the energy system to be reduced. These challenges were identified in consultation with more than 50 industry experts and academics within and outside McKinsey alongside an extensive literature review of analysis of the energy system.[2]

The 25 challenges are prioritized based on the potential of new, low-emissions technologies to abate emissions. Some exclusions help bound the scope of the work.

First, challenges that are expected to affect only a small portion of total emissions are not included. Second, incremental improvements to existing assets that do not involve major switches in technologies are not directly discussed as individual challenges; two examples are improved ICE fuel efficiency and insulation in buildings. Nevertheless, their collective impact is recognized in Challenge 23. Third, as noted, the challenges focus only on the energy system; those related to the transition of agriculture and other land use are not discussed directly, although the role of land as a physical challenge is discussed as part of the power domain challenges. Fourth, the focus is on challenges of a physical nature; any challenges that are purely related to market adoption or policies are excluded. Fifth, this research does not explicitly cover challenges related to labor. Finally, since this work focuses on analyzing the physical realities of the transition, costs are not the main focus, although, as noted, physical realities can help shed light on cost challenges.

The choice and precise boundaries of the 25 challenges are subjective to a degree, and some challenges are broader in scope than others. Different taxonomies, granularity, or segmentation of some challenges would certainly be possible. For example, circularity and recycling are important cross-cutting challenges that are discussed in the context of individual materials, such as plastics and critical minerals, but they could be deemed challenges in themselves. The list of 25 is neither collectively exhaustive (as noted, a prioritization lens has been used) nor mutually exclusive (many challenges share interdependencies).

The challenges are categorized into three levels, reflecting both the progress made to date in addressing them and the nature of the hurdles to overcome. Three features of difficulty, discussed further in chapter 3, are considered to do this: technological performance; gnarly interdependencies with other challenges; and degree of, and constraints on, scaling.

In examining the 25 challenges, this research builds on existing analyses of the transition in three ways. First, the examination of the performance of individual technologies is done in the context of specific use cases rather than their technological maturity in general. Second, this analysis goes beyond assessing technological maturity to consider other physical challenges, such as the required scale-up of supply of critical minerals. Finally, it considers how the system as a whole interacts—including how a particular individual technology relies on others—and the implications of that interaction.

Of course, the precise boundaries between the levels of challenges can be debated, and the classification into levels can vary by region. Parts of a Level 3 challenge could be categorized as Level 1 or 2. For instance, overall, decarbonizing cement is a Level 3 challenge that requires substantial technological innovation, but some decarbonization approaches, such as using biomass for heating or deploying clinker substitutes, are already widespread in some markets.

A global view of challenges is taken, but deployment of different technologies varies

1 Global CO_2 emissions from energy combustion and industrial processes total about 37 gigatonnes, with about five gigatonnes in agriculture, forestry, and other land use. In the case of methane, more than 35 percent of global emissions arise from the energy system, from combustion and industrial processes, with the remainder split between agriculture at about 40 percent and waste and other sectors at about 25 percent; McKinsey EMIT database, 2023.

2 This includes reviews of the level of progress in clean technologies and associated challenges by McKinsey and others. Among other research, see, for instance, Hauke Engel, Mekala Krishnan, Hamid Samandari, Humayun Tai, Daniel Pacthod, Simran Khural, and Mackenzie Murphy, *A sector progress tracker for the net-zero transition*, McKinsey Sustainability, November 2023; *Energy technology perspectives 2023*, IEA, January 2023; *Tracking clean energy progress 2023*, IEA, July 2023; *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; *World energy transitions outlook 2023*, International Renewable Energy Agency, 2023; Systems Change Lab data dashboard, accessed May 2024; *Climate change 2022: Impacts, adaptation, and vulnerability*, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2022; *ETP Clean energy technology guide*, IEA, updated September 14, 2023; *The state of clean technology manufacturing*, IEA, May 2023; *New energy outlook 2023*, BloombergNEF, 2023; *Global critical minerals outlook 2024*, IEA, May 2024; *The state of clean technology manufacturing*, IEA, May 2023; *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023; and *Better, faster, cleaner: Securing clean energy technology supply chains*, Energy Transitions Commission, June 2023.

Sidebar 2. Scope and methodology (continued)

among regions. Some challenges may be more or less important—and more or less difficult—depending on the region.

Across challenges, the research looks at the required deployment of low-emissions assets in 2050, comparing it with today's levels using McKinsey's 2023 Achieved Commitments scenario.[3] Other net-zero scenarios may have slightly different combinations of technologies and rates of deployment, but the broad trends and themes described in this research would still apply. In some instances, this research also uses insights from other external scenarios for reasons of data availability.

Among the external sources of data that were used in this report, we acknowledge the use of publicly available data from the International Energy Agency (Paris). We relied on IEA sources including *Energy technology perspectives 2023, IEA, January 2023, https://www.iea.org/reports/energy-technology-perspectives-2023*; and *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach 2023 update, IEA, September 2023, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach*. All are license CC BY 4.0. We note that some analysis in this research was derived from IEA material, and MGI is solely liable and responsible for it; it is not endorsed by the IEA in any manner. This holds true for all providers of the data that went into our analysis. We gratefully acknowledge their input, but the conclusions and any errors are our own.

This chapter discusses all 25 challenges briefly, and chapters 5 to 11 explore 20 of the 25 in more detail. These 20 were chosen to illustrate the broad dynamics associated with the physical transformation of the energy system and to illuminate the path of the energy transition. The five not discussed in depth are refueling aviation and shipping; synthesizing ammonia production; managing biofuels footprint; expanding energy efficiency; and capturing atmospheric carbon.

3 This research uses the 2023 McKinsey Achieved Commitments scenario because it provides detail across different economies and types of assets about the deployment levels that would be required for those economies to meet the climate commitments they have made. The scenario assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and that warming reaches 1.6°C relative to preindustrial levels by 2100. *See Global energy perspective 2023*, McKinsey, October 2023.

Reducing about half of energy-system CO_2 emissions hinges on solving Level 3 challenges

Eliminating between 40 and 60 percent of the energy system's CO_2 emissions depends on addressing the most demanding—Level 3—challenges (Exhibit 5).[81]

The power and industrial domains are the biggest contributors to the emissions tied to Level 3 challenges, together accounting for almost 80 percent of these emissions. In the case of power, the emissions tied to Level 3 challenges include those that would require increased deployment of variable renewable energy sources to the point at which they make up a large share of total capacity; as well as, to a smaller extent, carbon capture in the power system.[82] In the case of industry, the emissions tied to Level 3 challenges relate to the ones generated by the production of steel, cement, plastics, and ammonia.[83] The remaining emissions tied to Level 3 challenges arise mostly in the mobility domain, related to trucking, aviation, and shipping, which account for about half of current mobility emissions.[84]

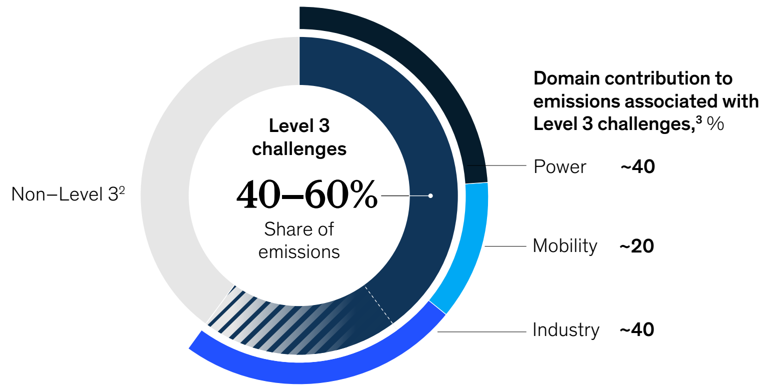
Quantification of the emissions associated with Level 3 challenges drew on the analysis in this report of what makes those challenges difficult to address. The potential of a given technology to contribute to abating emissions was assessed with consideration of its technological performance and maturity in the context of specific use cases, as well as any interdependencies with other technologies and the supply chains and infrastructure that they would require.[85]

As an illustration, consider solar and wind power. Despite these technologies typically being considered to be commercially mature, this analysis finds that their total potential to abate emissions depends on being able to solve interdependencies with a broader set of technologies with different degrees of maturity.[86] This is because once solar and wind scale to provide a large share of all generation, the output of the power system becomes highly variable.[87] As a result, for

Exhibit 5

Level 3 challenges are associated with 40 to 60 percent of the emissions of the energy system.

Energy system emissions directly or indirectly associated with Level 3 challenges,[1] $GtCO_2$, 2022, %



[1]Share of CO_2 emissions related to the energy system only (ie, excludes agriculture, forestry, and other land use).
[2]The remaining emissions are classified as non–Level 3 (eg, power has some non–Level 3 emissions).
[3]Other challenges not displayed given they account for less than 5 percent of the total.
Source: McKinsey Platform for Climate Technologies; *Global energy perspective 2023*, McKinsey; McKinsey Global Institute analysis

these technologies to reach high shares of total generation, much larger amounts of assets that deliver flexibility, such as novel long-duration storage, interconnections, or backup forms of power generation, would need to be deployed. Therefore, in the context of use cases that involve large solar and wind penetration, the physical challenge of variability and the development of both larger and newer sources of flexibility would need to be addressed: a Level 3 challenge.

In estimating the emissions associated with L3 challenges, we also considered interdependencies across challenges. Examples of interdependencies include passenger vehicles and heat pumps. Both are mature, but realizing their full abatement potential would require clean grids to power them. This, in turn, would again rely on addressing the Level 3 challenges in the power domain.[88]

Of course, the amount of emissions associated with Level 3 challenges could vary depending on the specifics of the decarbonization pathway being considered. However, the broad conclusions from this analysis would still hold. First, a great deal of progress on abatement is possible by addressing Level 1 and Level 2 challenges. Second, and crucial for the success of the transition, is that ultimately Level 3 challenges need to be tackled to achieve net-zero emissions.

The 25 physical challenges—a summary

Power

Addressing physical challenges in power is fundamental to the entire transition because abating emissions in the huge energy-consuming sectors—mobility, industry, and buildings—requires sweeping electrification under typical decarbonization scenarios. Two difficult challenges arise: managing the variability of renewables such as solar and wind, as they grow their share of total generation; and doing so specifically for emerging power systems that need to grow, often more rapidly and by more than advanced power systems. These two are classified as Level 3 because addressing variability challenges would require the use of novel technologies that have not yet been deployed commercially and face other substantial barriers. Four other challenges, classified as

Level 2, relate to constraints on scaling more established technologies, inputs, and infrastructure, where accelerated progress would be needed for the transition.

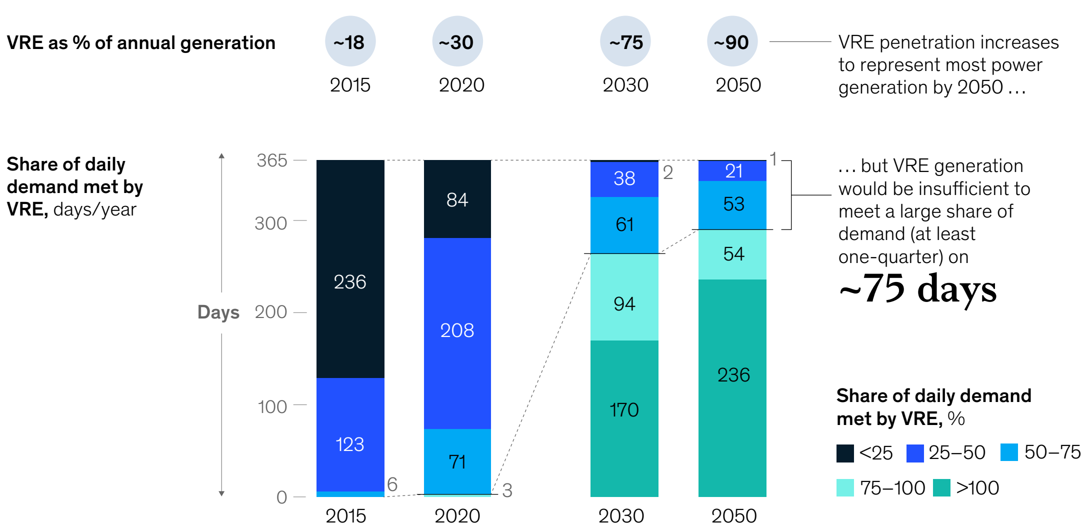
— *Challenge 1: Managing renewables variability (Level 3).* With the energy transition, VRE sources, such as solar and wind, would be required to grow and reach a relatively high share of total generation. As this happens, the output of power systems would become progressively more variable, exceeding demand on some days but falling substantially short on others. Consider Germany. VRE could potentially account for 90 percent of all power generation by 2050, in the McKinsey 2023 Achieved Commitments scenario. Nonetheless, there could still be about 75 days a year when VRE generation would be insufficient to meet a large share of demand (meaning that at least one-quarter of demand would have to be met by other sources) (Exhibit 6). VRE-heavy power systems would therefore require much more supply-side flexibility.[89] This could come from storage (both power and heat), backup generation capacity (including thermal generation like gas power and beyond), and interconnections. Such flexibility solutions may need to scale by as much as two to seven times faster than overall power demand globally in the next three decades.[90] However, these forms of flexibility in turn face significant barriers relating, for example, to critical inputs (for some forms of energy storage) and other factors such as market design mechanisms (for backup generation). Most critically, some of the technologies that would be crucial for providing flexibility to the power system over the course of seasons, including novel long-duration energy storage (LDES) and hydrogen-based generation, would need to scale hundreds of times by 2050 from a negligible base today.

Exhibit 6

When variable renewable energy makes up a large share of annual electricity generation, backup power would be needed for much of the year.

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO | GERMANY ILLUSTRATION

Evolution of Germany's variable renewable energy (VRE) generation,[1] 2015–50



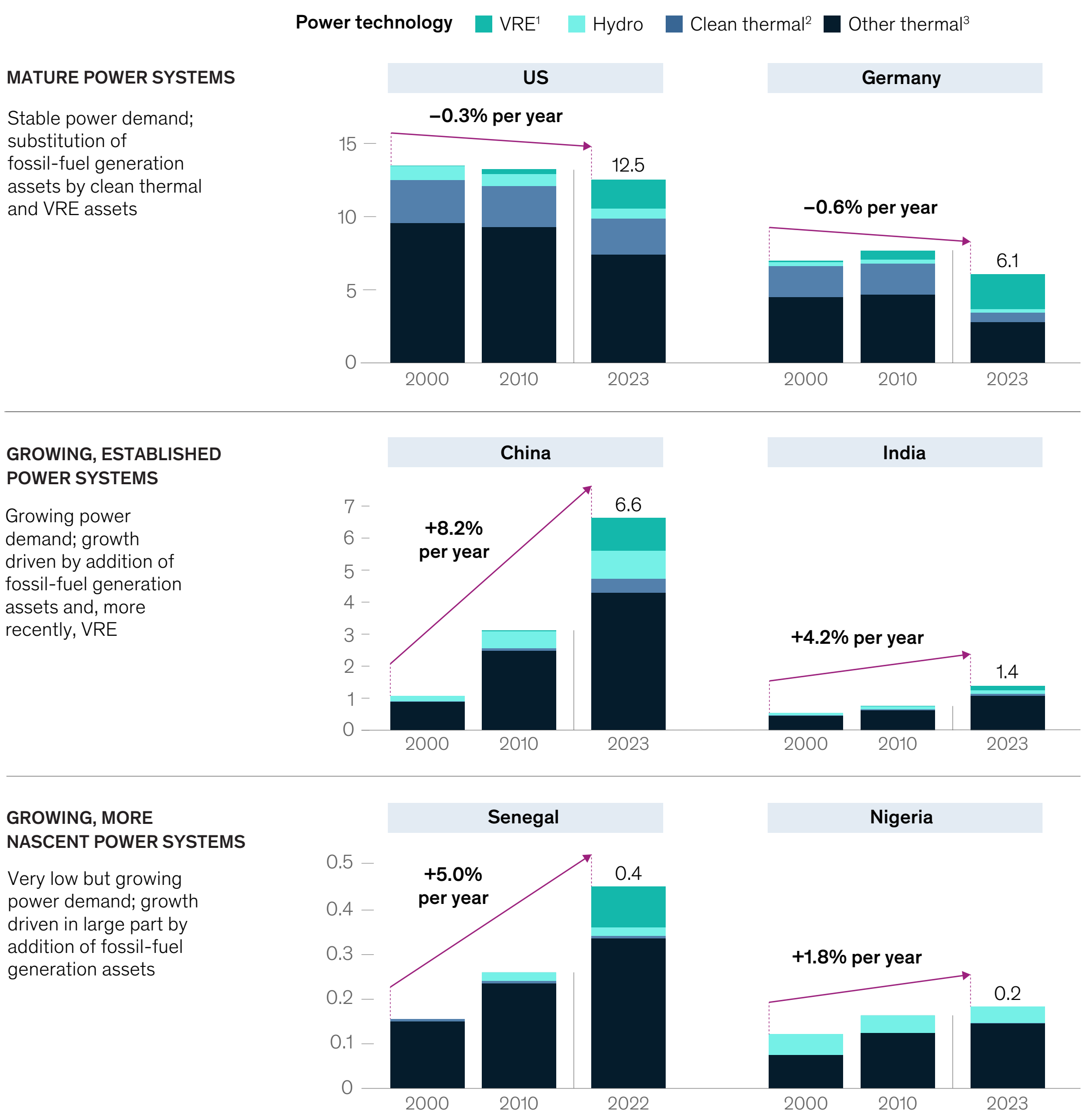
[1]Germany data for 2015–22; 2030 and 2050 projections from the McKinsey Power Model.
Source: Fraunhofer Institute for Solar Energy Systems; McKinsey Power Model; McKinsey Global Institute analysis

— *Challenge 2: Scaling emerging power systems (Level 3).* Many countries, especially those that are lower-income, need faster and more significant growth in their power systems to increase access to electricity. Historically, power systems have grown by adding firm power sources such as coal, gas, and hydropower, which can deliver power consistently when needed. Firm power accounted for 80 percent of the increase in per capita power generation in China and India between 2000 and 2023, often in the form of high-emissions assets such as coal plants (Exhibit 7). But this trend has started to shift, and in the last 5 years VRE made up around 30 to

Exhibit 7

Power systems are at different stages of development.

Per capita electricity generation, MWh



[1]Variable renewable energy, includes solar and wind power.
[2]Includes biofuels, geothermal, nuclear, and waste.
[3]Includes coal, natural gas, and oil.
Source: Ember; Energy Institute; Our World in Data; McKinsey Global Institute analysis

40 percent of growth in generation in these two markets.[91] As emerging power systems aspire to grow at the same time as reducing emissions, VRE is expected to play a larger role. The challenge is that these power systems tend to have much less existing flexibility to accommodate VRE than mature power systems, given their relatively smaller size today. For example, relative to power demand in 2030 in McKinsey's 2023 Achieved Commitments scenario, the existing flexible capacity of emerging power systems is only about one-third that of mature power systems.[92] This largely reflects the fact that their thermal generation asset base, which could be called upon to provide backup flexible capacity, is smaller than that of mature power systems. More flexibility could come, as discussed in Challenge 1, in the form of thermal generation assets (such as gas), more interconnections, and more storage. And as in Challenge 1, novel technologies would be needed, but in this case to potentially deliver an even larger increase in flexibility.

— *Challenge 3: Flexing power demand (Level 2).* Alongside supply-side flexibility, there may be more opportunity for demand-side flexibility in power as the world electrifies. This kind of flexibility could provide as much as 25 percent of the total amount needed to accommodate VRE in 2050, in the IEA's Net Zero scenario.[93] Possibilities include smart charging in EVs to switch demand to off-peak hours and even enabling EVs to flow power back to the grid through vehicle-to-grid technologies. Industrial loads could become more flexible by coupling electrification with dual-source heating systems or with ways to store heat for future use (so-called thermal energy storage or TES). Some emerging markets could build more demand-side flexibility from the start through more flexible manufacturing processes, for instance. Most of the demand-side technologies required are already mature today and being installed, but expanding their use faces hurdles, such as accelerating deployment of hardware and software infrastructure; requiring asset integration; behavioral changes, such as accepting the need to shift consumers' use of energy-intensive assets like EV charging and washing machines to different times of the day; and implementing system control measures to ensure the optimization and stability of the grid.[94]

— *Challenge 4: Securing land for renewables (Level 2).* For the power system to quintuple its capacity even while decarbonizing, more land would be needed. VREs, in particular, have a comparatively large land footprint for each unit of electricity generated (accounting for both direct and indirect use of land). However, there is nuance in this challenge. On the one hand, while they need more land, estimates suggest that only 2.5 percent of technically available land could be required globally for VRE.[95] On the other, various factors such as suitability (for instance, the incline of the land), regulatory restrictions (for example, distance to settlements), and competing uses could hugely limit the amount of available land for VRE in many economies, creating bottlenecks. Managing these bottlenecks would require measures to address land constraints and manage the amount of land needed, such as higher VRE efficiency, co-location with other uses, and deploying other energy sources that require less land.

— *Challenge 5: Connecting through grid expansion (Level 2).* With the growth of the power system and the addition of more geographically dispersed energy sources such as VRE, grids would need to become larger and more distributed, interconnected, and resilient. They may need to more than double in size by 2050, growing 40 to 50 percent faster than they are currently.[96] However, lead times for the permitting and construction of transmission lines are long, especially in mature markets such as the EU and the United States, where they have tended to be between five and 15 years.[97] Among other initiatives, accelerating permitting with new streamlined processes could facilitate the expansion of grids.[98]

— *Challenge 6: Navigating nuclear and other clean firm energy (Level 2).* Increased deployment of clean firm power, such as nuclear, geothermal, and low-emissions thermal plants (for example, hydrogen, biogas, and natural gas with CCUS), could reduce the challenges of variability, land use, and grid expansion. Nuclear is an example of a clean firm technology that is mature and gaining momentum. At COP28, for example, a group of economies announced commitments to triple nuclear capacity by 2050.[99] Nonetheless, increasing the deployment of nuclear requires managing complex engineering, supply chain, skills, and siting issues as well as safety considerations. In combination, these issues could result in long lead times, frequent delays, and cost overruns. Addressing these would require, for instance, standardizing the design of nuclear plants and building multiple plants using the same designs to leverage shared learning, training workforces in the skills they need, and developing necessary supply chains.[100]

Mobility

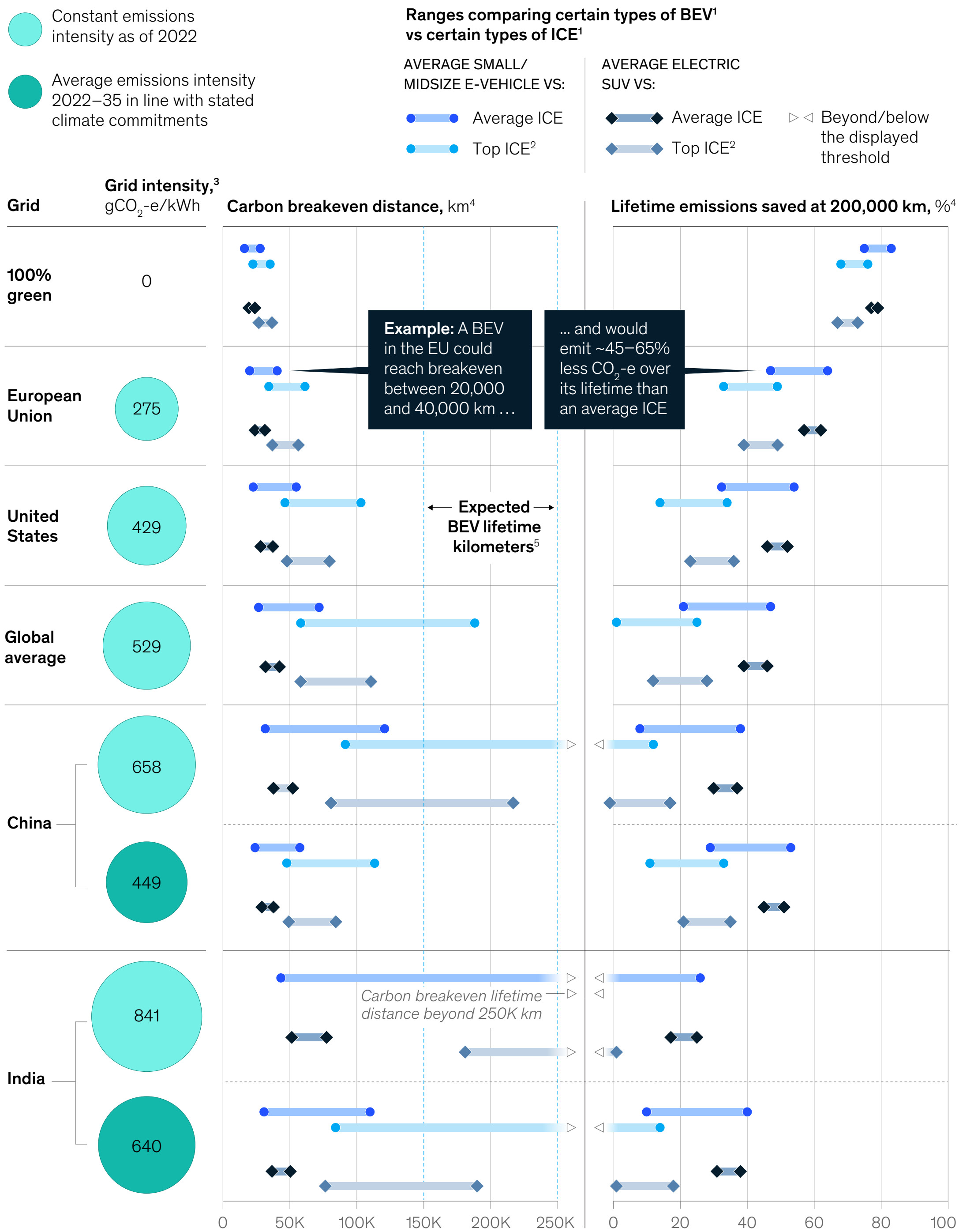
The energy transition requires decarbonizing different forms of transportation, including cars, trucks, aviation, and shipping. Relatively straightforward and broadly on track—and therefore classified as Level 1—are two challenges that relate to ensuring that passenger BEVs save on emissions overall in comparison with ICEs and have sufficient range.[101] Scaling charging infrastructure and supply chains for road vehicles is somewhat more constrained, and therefore Level 2. Most demanding of all are two challenges relating to decarbonizing longer-range forms of mobility, including trucking, aviation, and shipping, where more fundamental performance gaps remain; these are classified as Level 3.

— *Challenge 7: Driving BEVs beyond breakeven (Level 1).* While passenger BEVs have no direct tailpipe emissions, they still lead to CO_2 emissions during their manufacture and when electricity is produced to power them. For BEVs to contribute to decarbonization, they would need to be driven beyond their carbon breakeven point—the point at which their life-cycle emissions fall below those of a comparable ICE. This breakeven point depends on (1) the amount of emissions embedded in the manufacture of BEVs (for instance, larger and heavier batteries lead to higher manufacturing emissions); and (2) the relative running emissions of the vehicles, including the emissions intensity of the power grid on which BEVs rely and the efficiency of the ICEs they displace. Where grids have relatively low emissions, as they tend to in the EU, for instance, life-cycle emissions of small and midsize passenger BEVs are already substantially below those of comparable ICEs. Here, BEVs would save 45 to 65 percent of emissions, compared with average ICEs over their lifetime even if the grid did not decarbonize further.[102] At the global average intensity of grids, an average BEV could already lead to savings of about 20 to about 50 percent over its lifecycle. In countries with high-emissions grids, such as China and India, emissions savings tend to be lower. And if grids do not decarbonize quickly enough, there could be close to no savings in those countries for BEVs in comparison with relatively efficient ICEs (Exhibit 8). Ensuring that BEVs reach their carbon breakeven point and save emissions across all regions and vehicle types would require decarbonizing the grids that power them and introducing new manufacturing practices, including recycling, to reduce those emissions. Both of these are happening. For instance, the emissions intensity of grids in G-20 countries has dropped by about 8 percent over the past five years.[103] Global battery recycling capacity could grow by five times by 2030 based on announced projects.[104]

At the global average intensity of grids, an average BEV could already lead to savings of about 20 to about 50 percent over its lifecycle.

Exhibit 8

Grid emissions intensity has a large impact on the carbon breakeven point and lifetime emissions savings of battery electric vehicles.



[1]BEV = battery electric vehicle; ICE = internal combustion engine. Small/mid-size vehicles include sedans, coupes, and hatchbacks.
[2]Top-performing vehicles in fuel efficiency (95th percentile).
[3]This includes upstream emissions related to power generation, encompassing emissions from extraction, processing, and transportation of fuels.
[4]Range in the exhibit is driven by spread of values for the emissions performance of average BEVs and electric SUVs against average and top ICEs, due to specifics of the cars driven, different emissions estimates across different regions, and other factors.
[5]Based on the first and third quartiles in the distribution of odometer readings of cars 12 years old (average lifespan of vehicles) or more in the United States in 2017.
Source: European Environment Agency; US Environmental Protection Agency; GREET model (Argonne National Laboratory); Climate Transparency; McKinsey Center for Future Mobility; McKinsey Global Institute analysis

- *Challenge 8: Going the distance on BEV range (Level 1).* Passenger BEVs drive shorter distances (with an average range of about 400 kilometers) than ICEs (with an average range of about 650 kilometers) before they need to refuel, and refueling BEVs takes at least 25 to 50 times longer than for ICEs.[105] Other factors, such as performance in different terrain (like steep inclines), weather conditions (such as cold weather), and higher driving speeds, can mean that the actual range of BEVs could fall by about 20 to 30 percent.[106] Even factoring this in, however, in the United States where people tend to drive longer distances than in most other economies, the average BEV would enable about 70 percent of US households to complete almost all of their longest journeys without stopping to recharge—they would have to do so on fewer than five days a year. In the case of top-performing BEVs more than 90 percent of US households could have their range needs met.[107] Continued increases in the energy density of batteries and the development of fast-charging infrastructure can help to serve the most demanding range use cases. Battery energy density is rising at about 3 percent a year, and the average range of a BEV has increased by about 200 kilometers over the past decade.[108] Of course, other options to mitigate range issues could also be used. One example is hybrid vehicles, which combine internal combustion and electric engines and display higher ranges—although there are implications for emissions from using them.

- *Challenge 9: Loading up electric trucks (Level 3).* Battery electric trucks may struggle to serve the trickiest long-haul heavy-duty use cases. For such trucks to have longer ranges, they need heavier batteries, but limits on how heavy trucks can be mean that this additional weight lowers the payload they can carry. Even the best-performing battery electric trucks available today may be unable to meet roughly 20 to 45 percent of current long-haul trucking use cases with a single charge under current regulations on truck weights.[109] Furthermore, the transformation is just getting started. Fewer than 1 percent of the electric trucks that would be required by 2050 in McKinsey's 2023 Achieved Commitments scenario are on the road today, and almost none in the case of the longest-range vehicles. Improved battery energy density, adjusting regulation and road infrastructure to enable trucks to carry more weight, and operational shifts such as route reconfigurations to align any mandatory breaks to when batteries need to be recharged could be options. Other low-emissions technologies, such as hydrogen-powered fuel-cell electric trucks, face less of a constraint on their payloads, but deployment of those technologies has been very limited. Scaling deployment would require a rollout of associated refueling infrastructure, from a low base today, as well as solving associated Level 3 challenges in the hydrogen domain.

- *Challenge 10: Charging up EVs (Level 2).* For more low-emissions vehicles to be deployed, supply chains would need to be built out, and the associated charging infrastructure to operate them would need to be in place. Battery manufacturing supply chains would need to increase by about tenfold by 2030 under McKinsey's 2023 Achieved Commitments scenario.[110] This also creates a substantial interdependency with the challenge of securing the critical minerals these batteries need—another Level 2 challenge. Moreover, refueling would require the number of public charging points for BEVs to increase six times globally between 2022 and 2030. In some areas, progress has been fast. China, for instance, has about three million public charging points as of 2024, more than the rest of the world combined.[111] In the case of fuel-cell vehicles, scaling both manufacturing capacity and refueling infrastructure could be particularly tricky since they would need to grow from minimal deployment today. Only about 1,000 hydrogen refueling stations operate globally today.[112] This would also require solving associated challenges in the hydrogen domain.

- *Challenge 11: Refueling aviation and shipping (Level 3).* Less than 1 percent of current aviation and shipping energy consumption comes from low-emissions sources.[113] It is difficult to decarbonize these modes of transportation because carrying heavy loads over long distances requires high-density energy, and these modes would therefore need a large scale-up in the supply of new low-emissions fuels (such as synthetic fuels, biofuels, and hydrogen or its derivatives) under typical decarbonization scenarios. This would depend on the ability of developers of such fuels to secure long-term purchasing commitments from aviation and shipping buyers to create incentives to produce the fuels, as well as the availability of sufficient feedstock and low-emissions electricity to produce synthetic fuels. Supply of those fuels could be constrained given that they would also be required for other uses in, for instance, the power and industry domains. Furthermore, even with an adequate supply, airplanes and ships would need to be compatible with sustainable fuels. In aviation, up to 50 percent of sustainable aviation fuel can already be blended into the fuel of conventional jets. Future aircraft engines are expected to be capable of running on 100 percent sustainable aviation fuel.[114] In shipping, there is some uncertainty about the fuel mix that would prevail in the future. Because specific fuels would require different ship engine designs, shipping fleet decisions could be delayed by the uncertainty about the relative merits and availability of different sustainable fuels—and therefore how new ships would be fueled over the next two to three decades.[115] Other technologies are expected to play a role alongside sustainable fuels, but there is uncertainty about the range of use cases they can meet. For instance, trials of batteries for short-distance aircraft and coastal vessels are under way, but the batteries may not yet have the energy density to support longer distances.[116]

Industry

Decarbonization of many industries is hard. Fossil fuels are used as feedstocks (inputs) and/or as a fuel for high-temperature heat in many processes, most notably in the manufacture of the four big material pillars of modern civilization: steel, cement, plastics, and ammonia.[117] Decarbonization of each of these four poses Level 3 challenges.[118] Decarbonization of other industries would not be as difficult, because processes tend to require lower temperatures and do not generally use fossil fuels as feedstocks, and the required technologies are broadly commercially mature. Nonetheless, decarbonizing these other industries is a Level 2 challenge because doing so would require retrofitting existing industrial sites to accommodate low-emissions technologies, and this would constitute a large transformation.

— *Challenge 12: Furnacing low-emissions steel (Level 3).* Making primary steel currently relies on fossil fuels, mostly coking coal, both for the high-temperature heat required and as a reductant for the production of pig iron from iron ore.[119] Decarbonization could require multiple technological pathways, each with trade-offs. Some of the required technologies and processes have not yet been deployed at scale, including direct iron reduction (DRI) with hydrogen, use of premelters, and carbon capture at blast furnaces, and their performance has limitations. For example, DRI processes are less flexible in terms of the input iron ore that they can accommodate, requiring higher grades. Reconfiguration of the assets, inputs, and value chains that support steel production would also be needed. In some economies, including China and India, the relatively young age and limited size of current steel assets could make such reconfigurations particularly onerous because the assets would not be due for relining or decommissioning—a natural point at which to deploy substitute technologies. Use of secondary (recycled) steel using scrap is mature and low emissions, but limits on the amount of scrap available restrict how much it can be scaled.

— *Challenge 13: Cementing change for construction (Level 3).* Making cement produces emissions in two ways, and both would need to be addressed. First, the “clinkerization” process releases CO_2 from the chemical conversion of limestone into lime. Second, fossil fuels are burned to produce the high-temperature heat needed for cement production in both the clinkerization step and the subsequent calcination step. Clinkerization accounts for about 10 percent of energy used and requires temperatures up to 1,500°C. Calcination, which accounts for most of the remaining, requires 900°C. Abating emissions in both steps would require the deployment of multiple technologies, as well as substantial asset reconfigurations. Some technologies have not yet been deployed at scale. They include the electrification of heat to replace fossil fuels, and carbon capture approaches, which would require processes to be redesigned to produce purer CO_2 than in traditional cement production. Other approaches are already commercially mature, including alternative fuels such as biomass, the use of clinker substitutes or even alternatives to cement such as cross-laminated timber. Many such materials are mature and proven ways to abate some emissions in the shorter term, but the use cases in which they can be deployed have some limits, and other pathways would therefore also be needed to decarbonize cement production.

— *Challenge 14: Cracking the challenge of plastics (Level 3).* Plastics are largely produced from fossil-fuels feedstock, and decarbonizing them would require addressing the entire plastics life cycle with new feedstock options, such as bio or synthetic carbon sources; alternative low-emissions heat sources, including electrification or low-emissions fuels; use of carbon capture; or advanced chemical recycling approaches. Most of these technologies and processes have been trialed, but not been deployed in industrial settings. They would require scaling new inputs such as biomass and low-emissions hydrogen, and substantial reconfiguration of existing assets, such as replacing gas furnaces with electric crackers. In the shorter term, using alternative materials like biodegradable bioplastics instead of plastics or mechanical recycling could contribute to decarbonizing plastics production, but scaling their deployment would not be suitable across some use cases.[120]

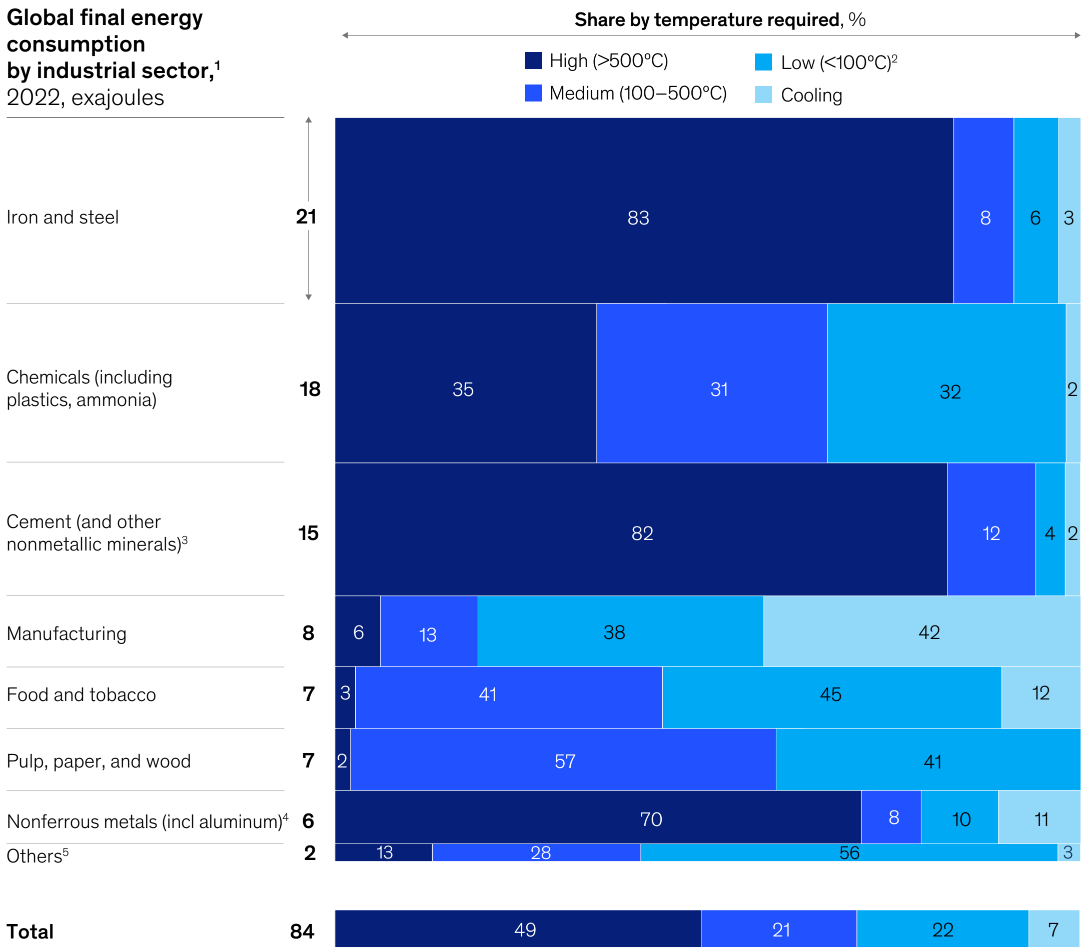
— *Challenge 15: Synthesizing low-emissions ammonia (Level 3).* The main source of emissions in making ammonia is the production of hydrogen, which is a necessary input. More than 99 percent of hydrogen is currently produced in high-emissions processes using fossil fuels, such as steam-methane reforming.[121] Decarbonizing ammonia would therefore require scaling production of low-emissions hydrogen, either by capturing CO_2 emissions from fossil-fuel reforming operations or by replacing fossil-based hydrogen with hydrogen derived from low-emissions processes, like the electrolysis of water. In both cases, these approaches would rely on addressing other Level 3 challenges in the carbon capture and hydrogen domains. Another option is the electrochemical synthesis of ammonia, which involves converting nitrates to ammonia, but this approach is still technologically nascent and has so far only been trialed as small prototypes.[122]

— *Challenge 16: Heating other industries (Level 2).* Other industries beyond the big four would be comparatively easier to decarbonize. Industries such as food production and paper, wood, and pulp production require only low- to medium-temperature heat for roughly 90 percent of their heating needs (Exhibit 9).[123] Mature and proven technologies can decarbonize the heat needed. Options include electrification or other low-emission heat sources such as nuclear, geothermal, and concentrated solar power. Thermal energy storage technologies can also help. However, these technologies would need large-scale asset deployment, which would require retrofitting millions of individual industrial sites around the world.

Other industries beyond the big four would be comparatively easier to decarbonize.

Exhibit 9

Most high-temperature heat in industry is required by steel, chemicals, and cement.



[1]Excludes ~18 EJ of final energy consumption with insufficient reporting; excludes agriculture and forestry (~5 EJ). Across all industries, industrial energy consumption is categorized by the temperature requirements for both thermal and mechanical energy. High-temperature heat supports processes like smelting and chemical reactions, medium-temperature heat is used in drying and other moderate-temperature processes and often for mechanical energy demands, and low-temperature heat is applied for pre-heating or maintaining specific conditions. Mechanical energy demands, such as compression work, are typically met by steam turbines or electric motors.
[2]Includes hot water and space heating.
[3]Also includes ceramics and glass.
[4]The production of aluminum requires temperatures of over 1,000°C. However, unlike the big four industrial materials, most of this high-temperature energy demand is already delivered through electricity.
[5]Includes oil and gas, construction, mining, and fishing industries.
Source: McKinsey Energy Solutions and McKinsey Global Institute analysis

Buildings

Heating accounts for the largest share of emissions from buildings.[124] Heat pumps could provide the majority of the heat required by buildings by 2050, according to the McKinsey 2023 Achieved Commitments scenario. While heat pumps are already commercially mature with dozens of millions installed throughout the world, deploying them in more than a billion homes and commercial buildings would require addressing two physical challenges. The first, relatively straightforward and therefore a Level 1 challenge, would be ensuring that heat pumps perform sufficiently to meet the tail end of use cases where temperatures are coldest and where heat pump efficiency declines. The second relates to managing the impact on peak demand for power from the electrification of heat in buildings, a more difficult, Level 2 challenge.[125]

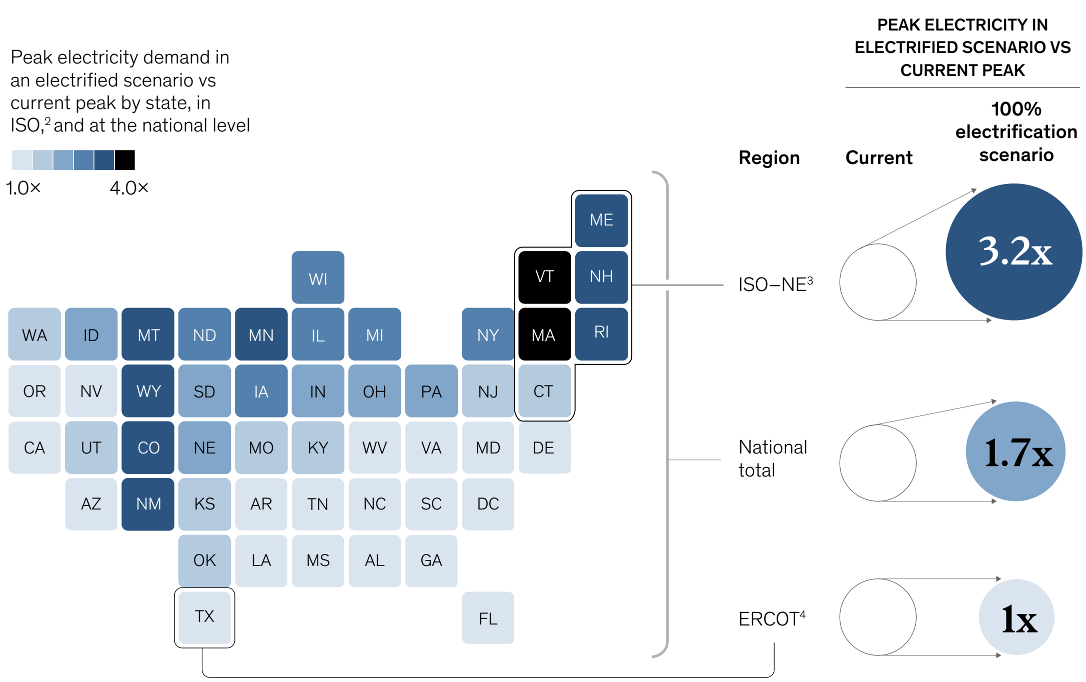
— *Challenge 17: Facing the cold with heat pumps (Level 1).* Demand for heating increases when and where temperatures are lower, and the heating capacity and efficiency of heat pumps in these situations also decrease. For example, when temperatures drop from 5°C to minus 10°C, the coefficient of performance of standard heat pumps almost halves.[126] In general, research finds that, at temperatures of between minus 10°C and minus 15°C, the performance of many standard air source heat pumps drops substantially—in some cases, the amount of heat pumps can deliver (heating capacity) may even fall below needed levels.[127] Specialized heat pumps designed for cold climates could offer an alternative up to a range of minus 20°C to minus 25°C. Overall, however, most people—some 95 percent of the population—live in regions with minimum temperatures above such thresholds, leaving only a relatively small number of unmet use cases.[128] Moreover, heat pump efficiency is improving, and this is set to continue. Together with more deployment of ground and dual-source heat pumps, which can perform better in cold temperatures, this could address the tail end of use cases.

— *Challenge 18: Bracing for winter peaks (Level 2).* As heating in buildings electrifies, demand for electricity will increase, especially during the coldest hours of the coldest days of the year. More pronounced peaks in demand for power—typically occurring in the winter—would result, which could necessitate building an oversize power system. In the United States, for instance, research estimates that if all heating of buildings were to be electrified, peak power demand could almost double, and it could even triple in colder regions such as the Northeast (Exhibit 10).[129]

Exhibit 10

As heating electrifies, peak electricity demand could triple in some US states if not managed.

Projected peak electricity demand in 100% electrified heat scenario in the United States vs current, without additional demand management measures[1]



[1]Based on analysis by Waite and Modi (2020) comparing current electricity demand to a scenario with 100% electrification of current building heat demand in the US. Assumes top-performing heat pump (90th percentile) is used. This analysis does not consider the potential growth of energy demand and electrification in other domains, such as mobility and industry. Peak loads refer to noncoincidental loads. Alaska and Hawaii not included in analysis.
[2]In the United States, independent system operators (ISOs) are split into different regions, such as ISO-NE and ERCOT.
[3]ISO-New England (NE) serves Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont.
[4]Electric Reliability Council of Texas (ERCOT) serves most, but not all, of Texas.
Source: Waite and Modi (2020); McKinsey Global Institute analysis

These accentuated peaks could necessitate building an oversize power system, but there are ways to minimize the extent to which this is needed, including improved efficiency of heat pumps; use of additional heating technologies, such as dual-fuel systems and district heating, which could deliver heat without relying on the power system; and shifting demand for power to other parts of the day by, for instance, combining heat pumps with TES. Improving energy efficiency, for instance through better insulation, could also contribute to reducing demand overall.

Raw materials

Deploying the low-emissions technologies required to decarbonize other domains would necessitate a range of raw materials to be available in sufficient quantities in a timely manner. Particularly important are the critical minerals needed for low-emissions technologies.[130] Ensuring that the supply of these critical minerals is scaled up quickly enough to meet demand during the transition is a Level 2 challenge.

— *Challenge 19: Unearthing critical minerals (Level 2).* Many low-emissions technologies rely on critical minerals, from lithium for batteries to rare earths for wind turbines and electric vehicles. As the energy transition advances, demand could grow by as much as sevenfold, depending on the mineral, in the period to 2030 under McKinsey's 2023 Achieved Commitments scenario (Exhibit 11).[131] There are sufficient reserves to meet expected demand, but additional supply often takes many years—sometimes decades—to come online. Current projections of supply based on announced projects would not be sufficient to meet surging demand, particularly in the period to 2030.[132] Potential supply-demand imbalances could arise.[133]

Exhibit 11

Demand for critical minerals is expected to grow by up to seven times, with a risk of demand-supply imbalances.

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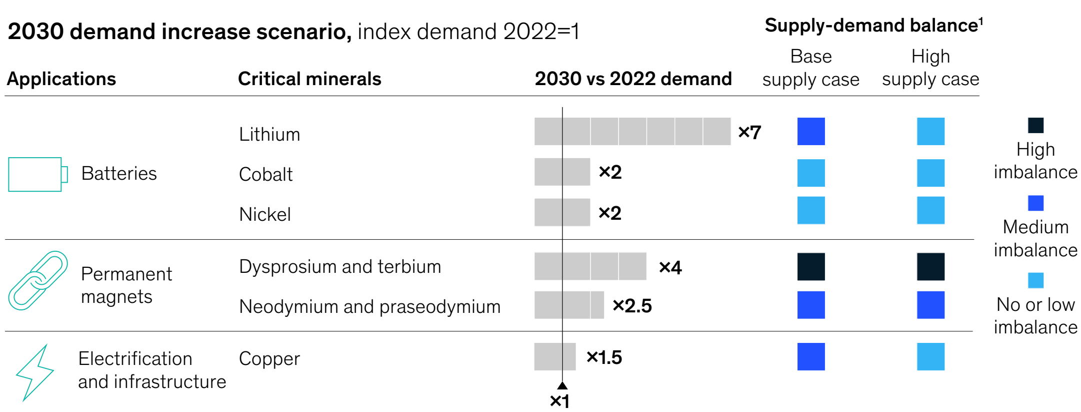


[1]McKinsey MineSpans' base-case of supply includes all operating mines (corrected for depletion and expected closure where relevant), and a selection of projects currently under construction or at the feasibility stage, and in most cases with financing confirmed. The high-case of supply includes, for example, some projects in feasibility stage and no financing confirmed, with adjustments for potential delays. Note that reaching this high-case of supply is by no means guaranteed, and would rely on many conditions being met, including the required financing and concurrent execution of multiple projects in parallel, which has not historically always been the case. Potential imbalances between required demand and projected supply are classified into three categories. "High imbalance" corresponds to cases in which demand is more than 50% higher than projected supply. "Medium imbalance" corresponds to cases where demand is more than 10% higher than supply, but less than 50%. "No or low imbalance" corresponds to cases where demand is less than 10% higher or even lower than supply.
Source: McKinsey MineSpans; International Energy Agency; Energy Transitions Commission; McKinsey Global Institute analysis

Meeting surging demand is even more complex when the source and processing of a mineral are geographically concentrated in a limited number of economies. Many of the critical minerals required for the energy transition, including cobalt, lithium, natural graphite, nickel, and rare-earth elements, rely on the three largest supplying economies for more than 50 percent of their extraction—and over 80 percent in some cases.[134] Refining is even more concentrated.[135] To address imbalances would require supply to increase more quickly. In some cases, this is happening already. In 2023 alone, production of lithium and cobalt rose by 23 and 17 percent, respectively.[136] Recent developments in new extraction technologies, surveying approaches, and modular construction could accelerate lead times. In addition, increased recycling rates could expand secondary supply. Even then, managing demand for critical minerals would likely be needed through, for instance, improved efficiency in the use of materials, substitution, and new technologies such as sodium-ion batteries and rare-earth-free motors. Some of these are beginning to be deployed, but the process is still at a relatively early stage, and there could be performance trade-offs, such as lower energy density in some battery chemistries.

Hydrogen and other energy carriers

New energy carriers, notably hydrogen and biofuels, would also be needed to decarbonize the domains by acting both as a source of fuel and as feedstocks for industrial processes.

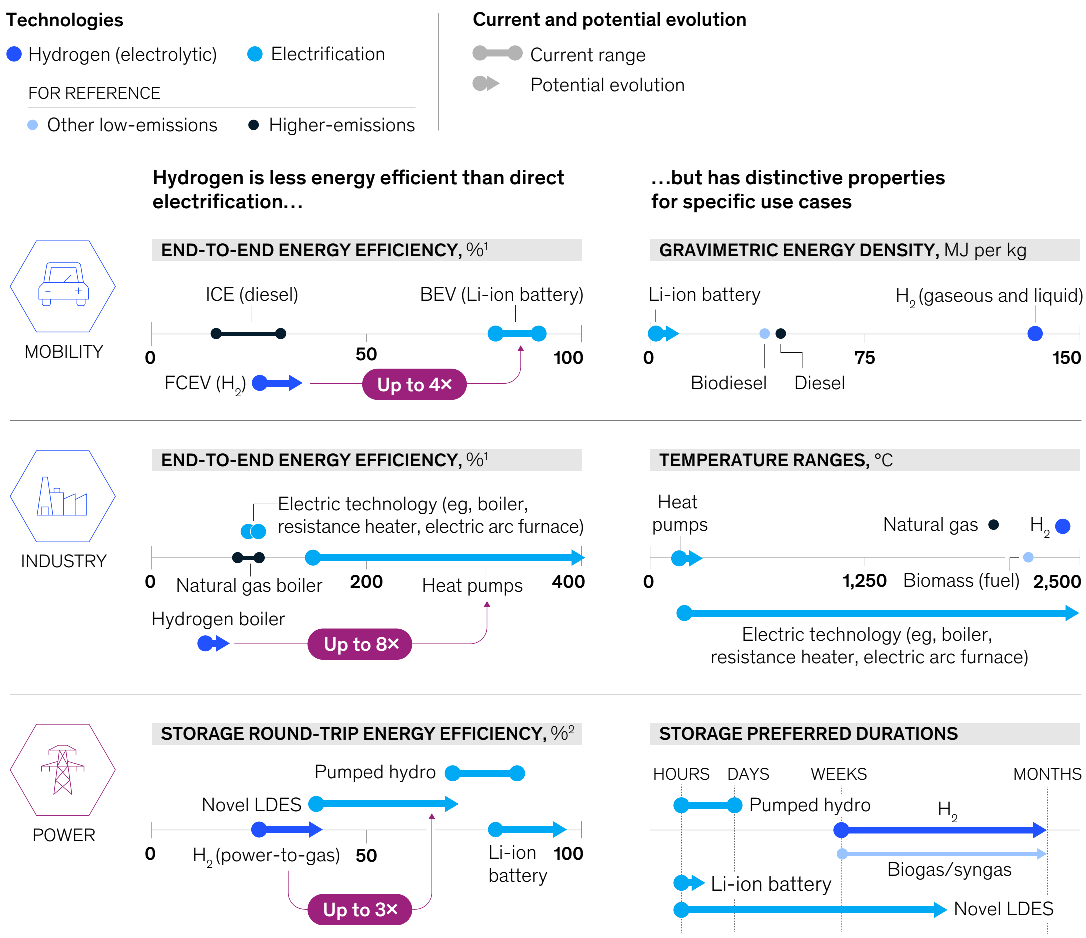
Hydrogen's physical properties could make it a flexible energy carrier that could potentially play a role in many different use cases in a low-emissions energy system. It has high (gravimetric) energy density (per unit of weight), which could be important for long-range transportation or long-duration energy storage. It can be used as a feedstock for many industrial processes, including in the manufacture of steel and chemicals. And burning hydrogen generates high-temperature heat. However, using hydrogen to a greater extent in the energy transition depends on addressing two particularly hard Level 3 challenges: harnessing hydrogen in new use cases while handling a range of tricky physical properties including energy losses; and building the infrastructure needed to enable use of hydrogen to scale from a very small base today.

The third challenge in this domain relates to other energy carriers—biofuels—and specifically how much land use their scaling could entail. This challenge is classified as Level 2.

— *Challenge 20: Harnessing hydrogen (Level 3).* Hydrogen's unique physical properties can make it a valuable tool for many use cases across domains, but they also make hydrogen particularly tricky to use. Hydrogen has low density per unit of volume when it is in its gaseous form, it can easily leak, and it is flammable. Furthermore, the hydrogen molecule goes through many steps before it can be used, and each stage involves energy losses. These energy losses matter since electricity costs can make up half or more of the levelized cost of hydrogen production in some regions.[137] During production, a large amount of energy is needed to convert water into hydrogen, and more than 20 percent of that energy is lost in the process.[138] To be transported and stored, hydrogen often needs to be compressed or transformed into other molecules. This, too, consumes energy, leading to as much as 5 to 35 percent of losses. Finally, energy is lost—ranging from 20 to 60 percent—when hydrogen is used, for instance to generate heat or power. Overall, as much as 40 to 75 percent of energy can be lost when hydrogen is used in power, industrial heat, or mobility applications. Where direct electrification options are available, they may often have energy efficiencies that are higher—for example when considering local use-cases.[139] To scale the use of hydrogen, energy losses would need to be minimized through, for instance, innovation of new electrolyzer models and new configurations of production and transportation (such as the transportation of intermediates). Furthermore, hydrogen use could be prioritized for cases that can leverage its beneficial properties and where other low-emissions alternatives are less feasible. Examples include using hydrogen as an industrial feedstock or as very long (seasonal) power storage (Exhibit 12).

Exhibit 12

Despite being less efficient than direct electrification, hydrogen has distinctive features for a set of specific use cases.



Note: Efficiency calculations assume electrolytic hydrogen produced from alkaline water electrolysis/proton exchange membrane electrolysis, and transported only for a short distance—the most common scenario. Efficiencies displayed start from the point of final energy—in the case of hydrogen, from the power used to produce it. In that way, efficiencies between hydrogen and electric use cases are directly comparable since they have the same starting point (electricity). Other cases—fossil fuels or biomass—entail other forms of final energy and, as such, are not directly comparable and shown only for reference.
[1]In mobility and industry, all hydrogen and electrification cases consider efficiency from electricity to the fulfillment of useful work (movement and heat, respectively).
[2]Efficiency from storing power and converting it back into power.
Source: Long Duration Energy Storage (LDES) Council; Fraunhofer ISI; US Department of Energy; National Renewable Energy Laboratory; International Energy Agency; Energy Transitions Commission; Hydrogen Council; International Council on Clean Transportation; Hydrogen Science Coalition; Agora Industry; Paschchenko (2024); McKinsey Global Institute analysis

— *Challenge 21: Scaling hydrogen's infrastructure (Level 3).* Many projects for the production of hydrogen have been announced, but actual production remains limited. Few large-scale projects are operating and about 5 percent of announced low-emissions capacity globally has gone past the final investment decision stage.[140] Scaling up the use of hydrogen would require a large expansion of its associated infrastructure. In the McKinsey 2023 Achieved Commitments scenario, for instance, electrolyzer capacity may need to be scaled thousands of times by 2050.[141] And powering hydrogen production could account for as much as 20 percent of total electricity consumption by 2050. As well as production capacity, specialized infrastructure would be needed to store and transport hydrogen if it is to realize its full potential as an energy carrier. For short-distance transportation, the length of hydrogen pipelines may need to grow by more than 40 times in the IEA's Net Zero scenario.[142] This would include retrofitting existing gas pipelines to accommodate hydrogen. For long-distance transportation, where relevant, shipping capacity could have to grow by over ten times in McKinsey's 2023 Achieved Commitments scenario.[143] Some innovation in transportation approaches like liquid organic hydrogen carriers and ammonia cracking could also be needed.

— *Challenge 22: Managing biofuels footprint (Level 2).* Biofuels can substitute for fossil fuels in some use cases, including aviation and heavy industry. They are particularly important in cases where electrification is challenging. The energy transition would require an acceleration of the use of biofuels and other forms of modern bioenergy (i.e., excluding traditional biomass use), which would grow by about 8 percent a year between 2022 and 2030 in the IEA's Net Zero scenario—more than double the rate at which use is currently increasing.[144] Continuing to scale production of biofuels would require managing competition for the land they would need. Developing new, more efficient biofuels could help, as would increasing the use of biomass sources such as waste, which does not increase competition for land.

Carbon and energy reduction

Substituting high-emissions technologies with alternative low-emissions technologies would be vital for a successful energy transition, but so would reducing the total amount of energy required and therefore CO_2 emitted—and capturing that CO_2. These efforts could be crucial across domains. For instance, carbon capture could support the decarbonization of the power system through clean firm power generation, play a role in decarbonizing the big four industrial materials, and support the production of low-emissions hydrogen. But there are physical challenges. Two of the three identified in this domain have performance gaps with demanding use cases and where the transformation is just beginning, and, therefore, are Level 3 challenges: CO_2 capture and carbon removal from the atmosphere, both of which would require technological progress and large scale-up of technologies that, in some cases, begin from a negligible starting point. The third challenge is improving energy efficiency. This is classified as Level 2 because the technologies are mature, but a large transformation would be needed to retrofit many millions of assets such as industrial sites and buildings.

— *Challenge 23: Expanding energy efficiency (Level 2).* Energy efficiency could help reduce emissions with solutions that use mature technologies, such as more efficient lighting and equipment, improved vehicle fuel efficiency, and industrial process improvements. The Intergovernmental Panel on Climate Change finds that energy efficiency mitigation options could contribute more than five gigatonnes of CO_2 equivalent to net emissions reduction by 2030.[145] But a step change in energy efficiency would require a large transformation by retrofitting or replacing millions or billions of individual assets, which would take time and effort and would come with deployment challenges and up-front costs. A potential complication is that any realized efficiency gains could result in rebound effects whereby higher efficiency does not lead to a proportional drop in demand.[146]

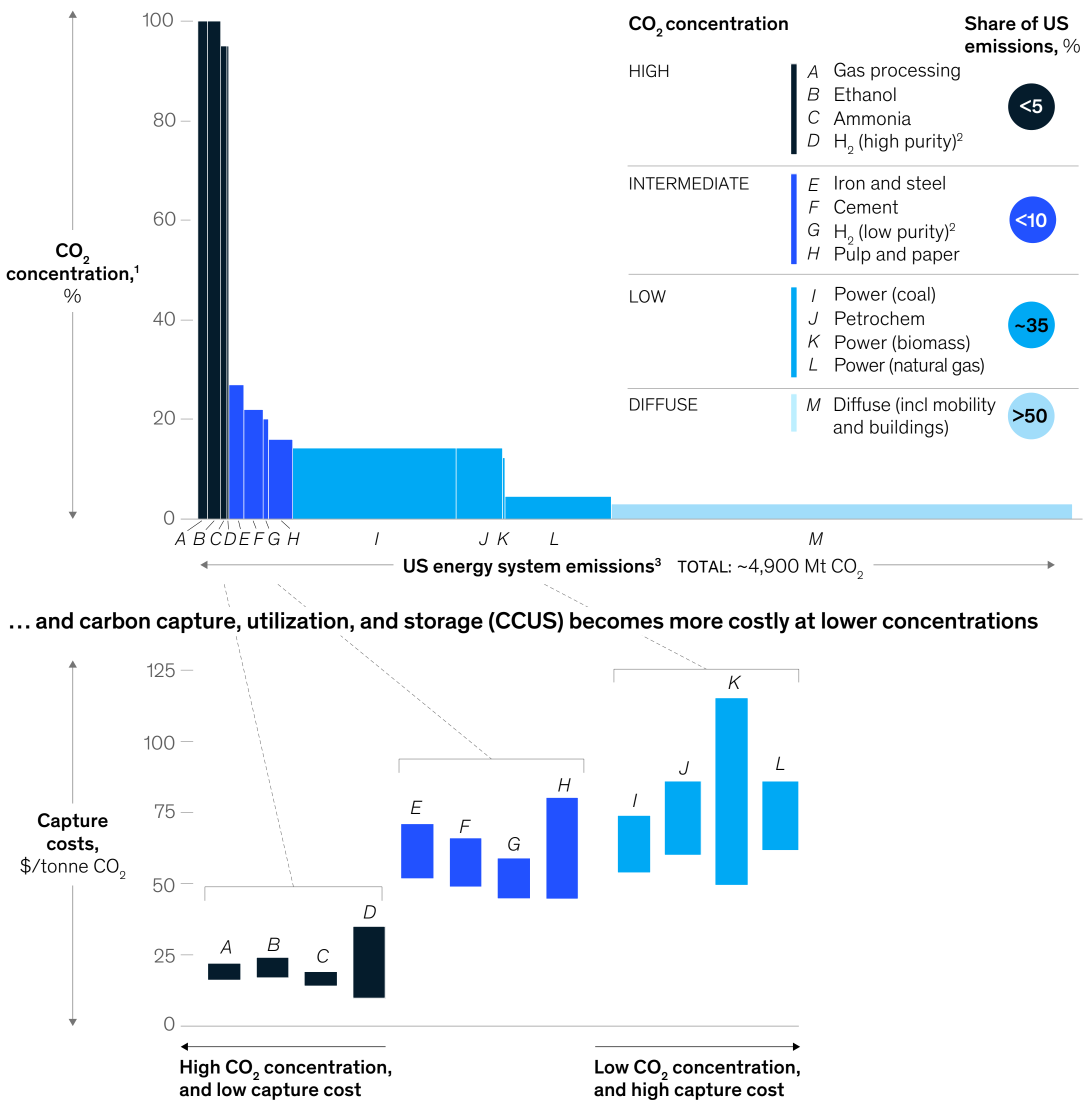
— *Challenge 24: Capturing point-source carbon (Level 3).* Carbon capture, utilization, and storage (CCUS) refers to a group of technologies that, as the name suggests, capture CO_2 from different processes to prevent it from entering the atmosphere (known as point-source capture), and then utilize or store it. These technologies have been used for decades but are mostly deployed on a relatively small scale and in high-concentration CO_2 streams such as natural gas processing. In the McKinsey 2023 Achieved Commitments scenario, carbon capture would scale by more than 100 times by 2050. For CCUS to play a more significant role in decarbonization, it would have to be deployed in lower-concentration processes, such as in cement production or natural gas power plants. Thus far, little of this has happened because employing CCUS in such use cases could be three to four times more costly than it is in current use cases (Exhibit 13). This reflects the fact that more energy and equipment is required, and that new technologies would be needed to capture CO_2 effectively at low concentrations. New innovation in CCUS technologies and processes would be needed to lead to more effective capture processes at lower costs.[147] Once captured, a massive amount of CO_2 would need to be transported and used or stored. Expanded storage capacity would be required, and new use cases for captured CO_2 would need to become commercially feasible, including, for instance, the production of synthetic fuels.

Exhibit 13

Most emissions arise from processes with low CO_2 concentration, where carbon capture, utilization, and storage is harder and more costly to deploy.

A large share of emissions arises from processes with lower CO_2 concentrations …

… and carbon capture, utilization, and storage (CCUS) becomes more costly at lower concentrations



[1] CO_2 concentration refers to the degree of concentration of CO_2 in the flue gas, also associated with the level of purity, with high purity referring to high CO_2 concentration. Note that all values denote averages for the US only.
[2] Hydrogen emissions can range from isolated high-purity streams (lower cost) to lower-purity combined streams (higher cost).
[3] Globally the emissions mix differs from that of the US.
Source: US Environmental Protection Agency; Global CCS Institute; National Petroleum Council; Santos et al. (2021); Lagnholtz et al. (2020); National Energy Technology Laboratory; US Energy Information Administration; McKinsey Global Institute analysis

— *Challenge 25: Capturing atmospheric carbon (Level 3).* Direct air capture (DAC) removes CO_2 directly from the atmosphere. DAC can play a role alongside nature-based carbon-removal options.[148] This carbon removal technology operates at lower inlet concentrations of CO_2 than point-source carbon capture, which means that it consumes a great deal of energy. DAC currently captures only about 0.01 million tonnes of CO_2.[149] Under the IEA's Net Zero scenario, the scale-up would need to be tremendous, to as much as 1,000 million tonnes by 2050.[150] Overall, DAC is a nascent technology with only a few dozen facilities operating and none yet on a large scale; their high energy intensity makes their use challenging.[151]

Steelworker starting molten steel pour in steelworks

3. What makes this so hard

Level 3 challenges are currently more demanding and further from being addressed than those in Level 1 or 2. But, over time, finding ways to tackle Level 3 challenges would be essential for cutting about half or more of the energy system's CO_2 emissions. The issue is that specific features make this difficult to do. Understanding them is critical to finding a path forward.

All challenges vary in three key features that determine how and why they are hard to address

The physical challenges vary in how hard they are to tackle because of three key features (Exhibit 14), as follows:

— *Technological performance gaps.* A new energy system would need to deliver the performance required by a wide range of use cases. But in some instances, low-emissions technologies have performance gaps in comparison with current technologies. These gaps especially matter in use cases that demand a high degree of performance. Consider long-haul heavy-duty trucking. Here, the use case currently demands accommodating heavy payloads and long driving ranges, which low-emissions battery electric trucks cannot yet sufficiently do on some routes.

— *Gnarly interdependencies.* In an interlocking system, attempts to implement solutions in one area may not be possible because of constraints in other areas. Often, then, multiple physical challenges would have to be tackled simultaneously. One example where such interdependencies manifest is in decarbonizing low-emissions steel, whose production would in turn require scaling a combination of hydrogen and carbon capture technologies.

— *Degree of, and constraints on, scaling.* The sheer amount of scaling needed for low-emissions technologies compared with today can itself make the energy transition difficult. For some challenges, staying on the current course is sufficient, but for others the physical transformation has barely begun. Two broad issues could make scaling difficult. One is constraints on the supply of raw materials, manufacturing capacity, land, supporting infrastructure, and other inputs. The second is that significant scaling up from a low base could be hard in the absence of a track record of effectively deploying the new technologies at the core of the transition. Trying to deploy nascent technologies, even if they have been proven in experimental settings, could create execution challenges.

Detailed analysis of 20 out of the 25 challenges in chapters 5 to 11 of this report explores how each stacks up on these three features and what this implies about how progress could be made.

Finding ways to tackle Level 3 challenges would be essential for cutting about half or more of the energy system's CO_2 emissions.

Exhibit 14

Three features determine the difficulty of addressing the 25 challenges and inform what level they are.

Difficulty Minor constraint or not applicable | Moderate constraint | Critical constraint

Level	#	Challenge	Domain	Technological performance gaps	Gnarly interdependencies	Degree of, and constraints on, scaling
1	17	Facing the cold with heat pumps	*Buildings*	Minor constraint or not applicable	Minor constraint or not applicable	Minor constraint or not applicable
1	7	Driving BEVs beyond breakeven	*Mobility*	Minor constraint or not applicable	Moderate constraint	Minor constraint or not applicable
1	8	Going the distance on BEV range	*Mobility*	Minor constraint or not applicable	Moderate constraint	Minor constraint or not applicable
2	3	Flexing power demand	*Power*	Minor constraint or not applicable	Minor constraint or not applicable	Moderate constraint
2	4	Securing land for renewables	*Power*	Minor constraint or not applicable	Minor constraint or not applicable	Moderate constraint
2	5	Connecting through grid expansion	*Power*	Minor constraint or not applicable	Minor constraint or not applicable	Moderate constraint
2	22	Managing biofuels footprint	*Hydrogen and other energy carriers*	Minor constraint or not applicable	Minor constraint or not applicable	Moderate constraint
2	23	Expanding energy efficiency	*Carbon and energy reduction*	Minor constraint or not applicable	Minor constraint or not applicable	Moderate constraint
2	10	Charging up EVs	*Mobility*	Minor constraint or not applicable	Moderate constraint	Moderate constraint
2	18	Bracing for winter peaks	*Buildings*	Minor constraint or not applicable	Moderate constraint	Moderate constraint
2	6	Navigating nuclear and other clean firm energy	*Power*	Minor constraint or not applicable	Moderate constraint	Moderate constraint
2	19	Unearthing critical minerals	*Raw materials*	Moderate constraint	Minor constraint or not applicable	Moderate constraint
2	16	Heating other industries	*Industry*	Moderate constraint	Moderate constraint	Moderate constraint
3	24	Capturing point-source carbon	*Carbon and energy reduction*	Critical constraint	Moderate constraint	Critical constraint
3	25	Capturing atmospheric carbon	*Carbon and energy reduction*	Critical constraint	Moderate constraint	Critical constraint
3	9	Loading up electric trucks	*Mobility*	Critical constraint	Critical constraint	Critical constraint
3	1	Managing renewables variability	*Power*	Critical constraint	Critical constraint	Critical constraint
3	2	Scaling emerging power systems	*Power*	Critical constraint	Critical constraint	Critical constraint
3	11	Refueling aviation and shipping	*Mobility*	Critical constraint	Critical constraint	Critical constraint
3	12	Furnacing low-emissions steel	*Industry*	Critical constraint	Critical constraint	Critical constraint
3	13	Cementing change for construction	*Industry*	Critical constraint	Critical constraint	Critical constraint
3	14	Cracking the challenge of plastics	*Industry*	Critical constraint	Critical constraint	Critical constraint
3	15	Synthesizing low-emissions ammonia	*Industry*	Critical constraint	Critical constraint	Critical constraint
3	20	Harnessing hydrogen	*Hydrogen and other energy carriers*	Critical constraint	Critical constraint	Critical constraint
3	21	Scaling hydrogen's infrastructure	*Hydrogen and other energy carriers*	Critical constraint	Critical constraint	Critical constraint

Note: Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning.
Source: McKinsey Global Institute analysis

Level 1 and 2 challenges face the least hurdles, but more scaling would be needed

In the three challenges characterized as Level 1, mature and established low-emissions technologies can already meet the performance requirements of most use cases. Where relevant, deployment is progressing at the required speed, and the relative degree of necessary scale-up and transformation is not as large as for other challenges. Nonetheless, continued deployment is needed, and additional innovation is often required to tackle the tail end of more demanding use cases.

As an illustration, consider the Level 1 challenge of ensuring that heat pumps are effective in cold climates. Heat pumps are technologically mature and are already able to heat homes efficiently in many settings and climates. Some best-in-class air source heat pumps even provide uninterrupted heat at below minus 25°C—and less than 5 percent of the world's population experiences minimum daily temperatures like this even once a year.[152] For typical heat pumps operating in these coldest temperatures, further innovation could help improve their efficiency and serve the coldest temperature use cases. And progress is already being made—the efficiency of heat pumps has been improving at a rate of about 2 percent a year.[153]

In ten Level 2 challenges, required low-emissions technologies are also mature and proven. However, scaling the deployment of these technologies and of the infrastructure and inputs they need often faces physical bottlenecks, including long lead times and competing uses for the inputs needed. Such constraints would need to be overcome to achieve the required acceleration in the pace of deployment.

For example, in the case of expanding nuclear fission power, a source of clean firm power, the technologies required are mature, but a number of physical factors stand in the way of greater and speedier deployment. These factors include complexity in design and engineering, inefficient planning and construction, and the need for specialized supply chains. Addressing these constraints would require multiple and simultaneous approaches, including more visibility on upstream supply shortages, adjustments to make permitting faster and smoother, and increased use of modular construction and repeat deployment. Several Asian economies, for instance, have cut lead times by building identical nuclear plants in succession to avoid reinventing the wheel for each.[154]

In some Level 2 challenges, such as ensuring that sufficient critical minerals are available to support the deployment of low-emissions technologies, scaling supply is not likely to be enough. Measures to manage demand are likely to be needed, too, including scaling recycling and innovating to reduce the need for critical minerals in components, such as using alternative battery chemistries or rare-earth-free motors.[155]

Level 3 challenges face broader hurdles, and new approaches will be needed to tackle them

The three features that make challenges hard are all more prominent in Level 3 challenges. Gaps in technological performance often exist, and coincide with demanding use cases. Many Level 3 challenges rely on solving other Level 3 challenges and require massive scaling, with the transformation just beginning and a lack of a track record of deployment. All these factors make addressing Level 3 challenges particularly tricky. Doing so would likely require innovation in individual technologies to be paired with changes in how the energy system works.

Level 3 challenges would require navigating larger performance gaps associated with more-demanding use cases

In Level 3 challenges, the low-emissions technologies that would be required still often face performance gaps where the technology cannot yet fully replicate at least one critical property of the current energy system. Dispatchability and transportability are two examples. In power, the lack of dispatchability can be a more significant issue in systems with large shares of VRE. In the case of new energy carriers, hydrogen and some of its derivatives are harder and more expensive to transport than fossil fuels.

Such performance gaps may also be present in Level 1 and 2 challenges, but Level 3 challenges stand out because those gaps typically occur where the use case is also more demanding.

Decarbonization of each of the big four industrial materials presents a Level 3 challenge that illustrates this feature. Steel, cement, plastics, and ammonia production currently rely on fossil fuels as sources of high-temperature heat and/or as feedstocks. In cement production, for example, the high-temperature heat required for clinkerization has thus far proven to be hard to replicate with electrification (although pilots have emerged that attempt to do this).[156] In steelmaking, replacing blast furnaces that use coking coal as a feedstock for the reduction process is hard because, among other factors, alternative processes such as hydrogen-based DRI are less flexible in the type of iron ore input that they can accommodate. In the case of plastics, fossil fuels are currently the feedstocks that provide the molecules that are the building blocks of these materials. By contrast, a range of other industries such as food manufacturing do not use fossil fuels as feedstocks, and their heating needs can easily be electrified because they need relatively lower temperatures where electrification is more straightforward, making decarbonization of other industries a Level 2 challenge.

The same collision between performance gaps and demanding use cases appears in other domains, too. In mobility, gaps in the energy density of batteries affect long-haul trucking, a Level 3 challenge, more than passenger vehicles. Carbon capture technologies do not yet perform well enough where CO_2 is present in low concentrations in flue gas streams.

In most Level 3 challenges, this combination of performance gaps and demanding use cases also creates uncertainty about which, if any, combination of low-emissions technologies could replicate the performance of the current energy system. While multiple technological options appear promising and are being explored, if this uncertainty persists over time, it can make focusing investment and deployment efforts effectively more difficult.

Addressing performance gaps would require more innovation and commercial scaling of promising new approaches. New electrification approaches in industry currently being tested could produce the high temperatures required by cement and plastics, for example, but have not yet been deployed commercially on an industrial scale. In the case of steel, new processes using premelters could enable DRI-based approaches to accommodate lower grades of iron ore. But innovation of individual technologies may not be sufficient to fully match current performance levels in all cases. For example, advances in battery technologies such as solid-state batteries could double energy density and enable longer ranges, but even these batteries would be about 20 times less (gravimetric or per unit weight) energy dense than diesel.[157] In other cases, the performance profiles of low-emissions technologies are inherently different. For example, while solar and wind innovations have improved capacity factors, these technologies are intrinsically variable in their output.

The implication is not that a new energy system can never serve the most demanding use cases, but that achieving that goal would necessitate innovation of individual technologies and, in some cases, reconfiguration at the system level—changing the way low- and high-emissions technologies mesh together to deliver higher performance. In the case of solar and wind technologies, this could mean reconfiguring the power system to deliver more flexible supply through storage, backup power sources, and more interconnections, or making demand more flexible. In a nutshell, the new energy system would need to evolve to make the most of the performance profile of low-emissions technologies and the way they work together (this is described in more detail in chapter 4).

Level 3 challenges face gnarly interdependencies that would require systemic interventions
Addressing Level 3 challenges often tends to depend on tackling other Level 3 challenges, compounding the difficulty of making progress and arguing for the need to consider the entire system as the transition unfolds. Deploying low-emissions trucks and decarbonizing steel illustrate these gnarly interdependencies (Exhibit 15).

In some cases, of course, solving Level 3 challenges is dependent on addressing relatively less demanding challenges. Consider the example of low-emissions trucks, a Level 3 challenge. In the case of battery-powered trucks, two Level 2 challenges would need to be tackled: unearthing minerals (required for the production of batteries) and expanding charging networks. But in the case of fuel-cell electric trucks, multiple Level 3 challenges come into play. Fuel-cell electric trucks require low-emissions hydrogen, and securing it would require solving Level 3 challenges in that domain. In turn, hydrogen would require a great degree of low-emissions power, creating an interdependency with the Level 3 challenge of managing renewables variability. And this interdependency cuts both ways: balancing the intermittency of renewables may require hydrogen as a clean backup source of power at times when VRE generation is lower.

Exhibit 15

Level 3 challenges can have gnarly interdependencies with one another.

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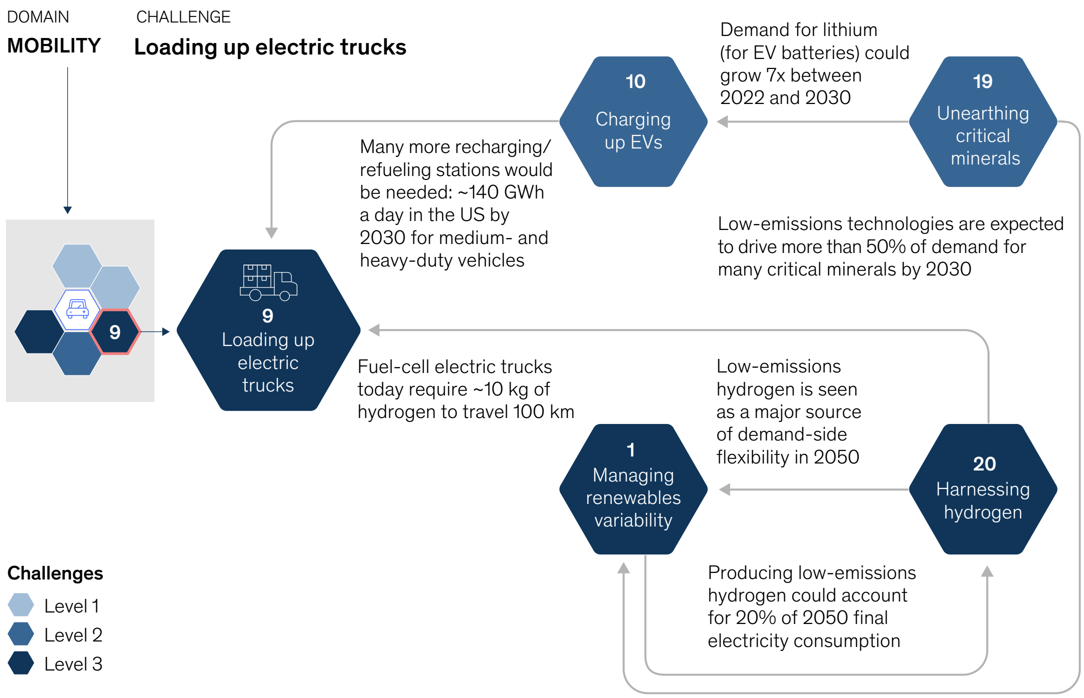
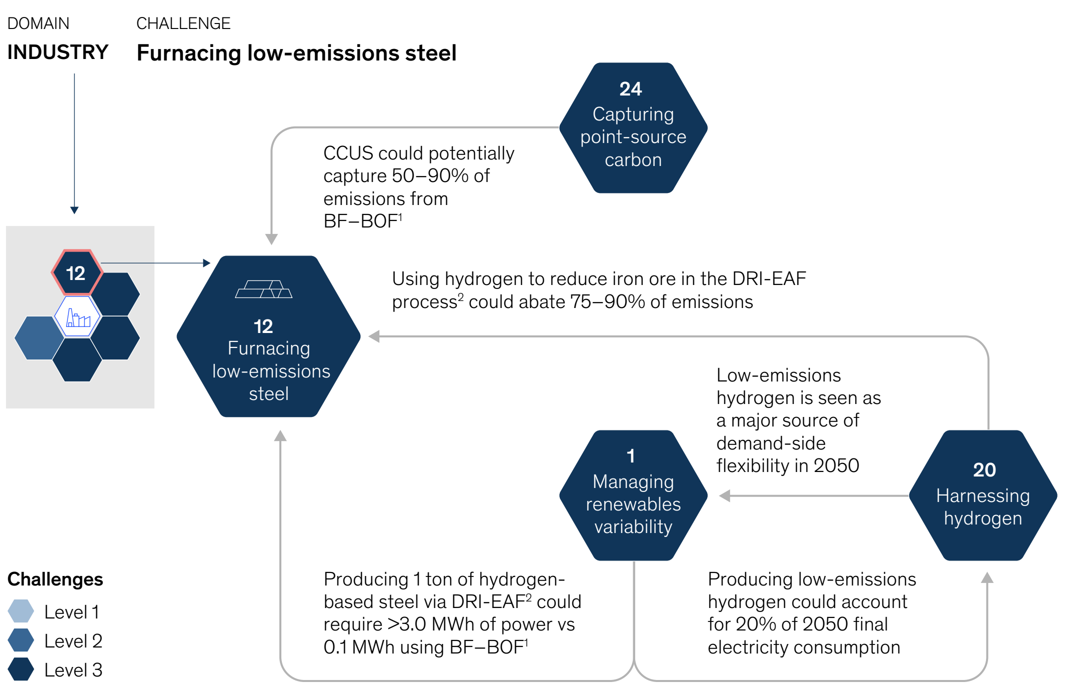
Example 1



Example 2



Note: Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning.
[1]Blast furnace–basic oxygen furnace (conventional steelmaking).
[2]Direct reduced iron-electric arc furnace.
Source: International Council on Clean Transportation; European Commission; McKinsey MineSpans; *Global energy perspective 2023*, McKinsey; McKinsey Global Institute analysis

Several Level 3 challenges are linked in efforts to develop low-emissions steel, too. As discussed in chapter 2, DRI is a key technology for the decarbonization of steel, but its deployment would require solving Level 3 challenges related to hydrogen and power. Another option being considered is retrofitting blast furnaces with carbon capture technologies, creating an interdependency with another Level 3 challenge.

These interdependencies could well influence how multiple challenges are addressed. For instance, decisions on how best to produce low-emissions steel could depend on whether it is easier—or faster—to deploy hydrogen or carbon capture. This could, in turn, vary among regions.

Multiple actors in different sectors would likely need to coordinate to create solutions or projects that address multiple challenges simultaneously. One example of this in action is the HYBRIT project in Sweden, which aims to create low-emissions steel through hydrogen-based DRI technologies and involves a collaboration among companies in the mining, energy, and steelmaking sectors.[158]

Level 3 challenges require kick-starting entirely new transformations

In Level 3 challenges, the transformation is just beginning, and large scale-ups lie ahead—sometimes by hundreds of times or more in novel LDES, and new use cases for carbon capture and hydrogen electrolyzers, for example. The sheer scale of substituting thousands and sometimes millions of assets from scratch is hard given that there is little or no execution track record in Level 3 challenges and therefore a good chance of more "unknown unknowns" emerging.

Moreover, if and when deployment accelerates, putting in place the necessary accompanying infrastructure and securing required inputs could run up against bottlenecks. This has not happened to any great degree yet, because addressing Level 3 challenges is at such an early stage. As the energy transition advances, bottlenecks would likely become more material, as they already are in Level 2 challenges.

Anticipating and addressing potential bottlenecks is crucial for Level 3 challenges, as are the broader types of measures discussed previously for Level 2 challenges. In some places, this is happening. In the case of low-emissions steel, for instance, many mining companies have anticipated that the supply of high-grade iron ore would be a bottleneck, and they have been focusing on developing new projects for the extraction of higher-grade iron ore that is more suitable for DRI.[159]

Another way to mitigate the difficulty of handling large transformations would be to try to trim its scale. An option would be increasing the use of established alternative technologies, thereby reducing the need for more nascent ones. For instance, deploying mature clean firm power technologies, such as nuclear, where possible and where deployment challenges of its own could be addressed, would reduce variability of the power system and therefore the need for more nascent forms of supply-side flexibility. If use of energy-efficiency technologies were to increase, this could help to reduce the size of the required scale-up of low-emissions assets.

But there are limits to the extent to which such substitutions could be deployed. For example, utilizing secondary steel—an established technology—is not suitable for many use cases, and modal shifts in mobility (for example, to rely more on public transportation or to use rail rather than low-emissions trucks for long-haul transportation) are often not possible for logistical reasons. Efforts to trim the size of the required transformation where feasible would be useful, but they would not obviate the need to execute transformations effectively for the transition to succeed.

Biodiesel industry plant

4. Concluding thoughts

The path of the energy transition will not be straightforward, and stark trade-offs and consequences lie ahead. Taking time for the transition to play out, as in many physical transformations of the past, could allow for the physical realities of the transformation to be confronted more gradually with time to innovate and scale new low-emissions technologies, address bottlenecks, and reconfigure the system. While this may make navigating the physical challenges easier, such a path would almost certainly involve compromising on the climate goals that countries and companies across the world have agreed to, with consequences for rising physical risks.[160] However, driving the transition forward without confronting physical realities would most likely compromise the performance of the energy system—and as a result challenge energy access, growth, prosperity, and support for the transition itself.

Alternatively, stakeholders could confront difficult physical challenges head-on—in fact, they could use an understanding of physical realities to guide the way forward to an affordable, reliable, competitive path to net zero. While many open questions remain on what precise path would enable the physical challenges to be addressed, this analysis sheds light on some crucial ingredients that would have to be present in a successful energy transition.

More innovation would be needed, along with changing the way the energy system works

Across the domains examined, the transformation required would be both deep and broad (Exhibit 16). In particular, to address the most demanding challenges, large performance gaps remain to be addressed. Detailed examination of individual challenges suggests avenues for stakeholders to consider (for further discussion, see chapters 5 to 11). These avenues include the following:

— *Continue to drive technological innovation.* Continued technological innovation and scaling is critical for progress on the path to building a new energy system. It could come in the form of higher energy density of batteries, more efficient hydrogen electrolyzers, and new electrified high-heat industrial processes, such as e-cracking. Yet despite the progress that innovation of individual technologies can offer, it may prove insufficient for building a new energy system that fully mirrors the performance of the current energy system. For example, even new batteries being conceived today have only a fraction of the energy density of oil. Innovation would therefore need to go hand in hand with other approaches to building a high-performing energy system.

— *Change how technologies mesh together to produce and consume energy resources.* Beyond innovation, bringing individual technologies together in new configurations could raise the performance of the entire energy system. One approach would be to reconsider how the supply of energy comes together with demand for it. This is not a new concept and has been in place for decades, but opportunities to do so would multiply during the energy transition. For instance, the potential increased variability of low-emissions power supply could be balanced by increasing the flexibility of demand, thereby managing the need for large-scale energy storage technologies. Options include making demand for heat of different industries flexible using thermal energy storage or even using electric vehicles to send power back to the grid when it is most needed.

  A second approach could entail changing how forms of energy production, energy transportation, and energy uses interact. For example, energy losses in long-distance transportation could be minimized by transporting energy embedded in goods (for example, hot briquetted iron) instead of transporting energy carriers such as hydrogen, which would need to undergo multiple conversions to make it suitable for transportation.

Exhibit 16

The energy transition would require fundamental reconfigurations to overcome physical challenges.

ILLUSTRATIVE, NOT EXHAUSTIVE

DOMAINS	ASSOCIATED CHALLENGES	DRIVE TECHNOLOGICAL INNOVATION	CHANGE HOW TECHNOLOGIES MESH TOGETHER	ADAPT USE CASES
Power	1 **Managing renewables variability** 2 **Scaling emerging power systems**	▪ Improve and scale long-duration energy storage ▪ Develop hydrogen-ready turbines	▪ Expand demand-side flexibility (eg, smart charging, vehicle-to-grid)	▪ Redesign manufacturing processes for variability
Mobility	9 **Loading up electric trucks**	▪ Increase energy density of batteries ▪ Develop fuel-cell electric trucks	▪ Substitute and/or complement long-haul trucking with rail where feasible	▪ Reconfigure trucking routes to manage lower battery density
Industry	12 **Furnacing low-emissions steel** 13 **Cementing change for construction** 14 **Cracking the challenge of plastics**	▪ Develop premelters ▪ Achieve higher temperatures in electrified heating systems (eg, kilns) ▪ Develop new low-emissions fuels and feedstock (eg, hydrogen) ▪ Explore chemical recycling for plastics instead of mechanical recycling	▪ Carefully choose CCUS or hydrogen in steelmaking depending on location and availability	▪ Expand use of secondary steel for some use cases ▪ Explore alternatives to cement in construction (eg, cross-laminated timber) ▪ Use plastics substitutes (eg, bioplastics)
Buildings	18 **Bracing for winter peaks**	▪ Improve performance of heat pumps in cold climates	▪ Reuse waste heat for district heating ▪ Deploy dual-source heating systems ▪ Develop thermal energy storage to smooth demand	▪ Make buildings more energy efficient
Raw materials	19 **Unearthing critical minerals**	▪ Explore new extraction technologies (eg, direct lithium extraction) ▪ Innovate new battery chemistries (eg, sodium-ion) ▪ Develop rare-earth-element-free motors	▪ Supplement primary supply with circular value chains (eg, battery recycling)	▪ Match less minerals-intensive technologies to easier use cases (eg, lithium iron phosphate batteries for shorter-range BEVs)
Hydrogen and other energy carriers	20 **Harnessing hydrogen** 21 **Scaling hydrogen's infrastructure**	▪ Develop more efficient electrolyzers (eg, solid oxide electrolysis cells)	▪ Produce hydrogen to store otherwise unused or excess renewable power ▪ Develop transport intermediates instead of energy carriers (eg, hot-briquetted iron rather than hydrogen transportation)	▪ Consider retrofitting of existing assets to be able to run with hydrogen (eg, gas pipelines, turbines)
Carbon and energy reduction	24 **Capturing point-source carbon**	▪ Innovate new carbon capture approaches for low-concentration streams (eg, oxy-fueling)	▪ Use CCUS to convert high-emissions assets into low-emissions assets	▪ Share common infrastructure between emitters and CCUS services providers

Note: Examples are illustrative and their viability would have to be assessed carefully before they are implemented.
Source: McKinsey Global Institute analysis

A third approach, albeit one with some consequences for emissions, would be reconsidering how low- and high-emissions systems could be coupled together to address performance gaps for the most difficult use cases, at least in the short term. For example, natural gas could increasingly become a source of flexibility.[161] Gas peaker plants can act as backup systems for variable renewables. Gas boilers in homes and industries could be used in the context of dual-source (hybrid) heating systems that can switch between electric and fossil-fuel heating sources according to the needs—and economics—of the grid over time, helping to manage peaks in demand. Some of these solutions could be temporary, and the use of fossil fuels in these systems could potentially be replaced with low-emissions energy carriers or abated using other means like carbon capture.

— *Adapt use cases.* The very use cases associated with how energy and materials are consumed could also be adapted. For instance, the lower energy density of batteries means that battery electric trucks cannot drive the same distance as diesel ones without stopping to recharge, but there are ways around this. Truck drivers often have to stop for mandatory breaks at given intervals. If routes were reconfigured and the location of depots adjusted, the trucks could charge during those breaks. Mature technologies could also be deployed where effective—so, for instance, more rail travel could substitute for electric trucks.[162] Similarly, decarbonizing some industrial materials is challenging, and it may make sense to explore the feasibility of using alternative materials. Cross-laminated timber could, it has been estimated, be applied to more than 10 percent of the use cases that currently use cement, and potentially many times more than that.[163]

Which of these three broad approaches is most suitable will vary by domain and among regions, and more work is needed to identify the details of a viable approach in different contexts. What is clear, however, is that innovation and such reconfigurations of the energy system would involve profound changes to how the current energy system works. Implementing them would require action by many different stakeholders.

Understanding the physical realities can help CEOs and policy makers navigate the energy transition

Innovation and system reconfigurations are important, and executing on them would require Herculean effort from both the private and public sectors.

CEOs could start by understanding how physical challenges could affect their pathway to net zero and impact their products and services. They could assess the full potential value at stake for their organizations from tackling physical challenges in their operations, in their supply chains, and through the products and services they can offer. Based on this, they can decide how to play offense to capture opportunities and create value for their organizations.[164]

Policy makers, too, have a crucial role in ensuring a holistic and coherent approach to tackling physical challenges. They would need to ensure that companies have the right incentives and enabling environment to factor emissions into their decision making, collaborate with each other, and engage in the hard task of transforming today's high-functioning energy system.

As physical challenges for the transition are tackled, it would also be important to consider how best to run two energy systems—the old and the new—in parallel in the near term, and to ensure that the ramp-down of the current high-emissions system and ramp-up of a low-emissions one is smooth.[165] Some investments in the current energy system like transmission and distribution are often needed in any case, and can both improve today's energy system, and make it easier to solve future physical challenges. Some investments can smooth the ramp-down and ramp-up; energy efficiency is an example. Finally, investing in "hybrid" technologies could be an opportunity to explore; such approaches would not eliminate emissions entirely of course, but could be options to consider that enable some near-term progress on emissions as broader physical challenges are resolved. Examples include hybrid passenger cars which could address vehicle range issues, and using hybrid heating boilers (that alternate between electricity or other fuels) in industry that can enable flexibility of energy sources and even cost savings.

Plans for the way forward could be calibrated by carefully considering challenges across the three levels. This can help inform what challenges to address, how, and in what sequence. Key questions to consider include the following:

— *For Level 1 challenges, how can near-term opportunities from the deployment of fast-maturing technologies be captured?* Such challenges correspond to areas in which technologies are mature today, minimal interdependencies exist, and scaling is well under way. They offer potential opportunities for near-term value creation for organizations. Companies could explore areas in which they have a strategic advantage and the geographies that offer the most attractive prospects to play offense and create value. Doing so would also require understanding both the current and potential future costs of low-emissions technologies relative to high-emissions ones. Policy makers similarly need to understand what it would take to drive deployment in these areas in their regions as well as how to best unleash the potential of the private sector to capture these opportunities, for example via incentives and sending appropriate demand signals.

— *For Level 2 challenges, what bottlenecks need to be addressed today to unlock the next tranche of opportunities?* These challenges entail deploying mature technologies, but they face immediate or short-term constraints. The key is identifying and anticipating which bottlenecks are particularly important and the options to address them. For companies, this might mean actions toward securing the supply of critical inputs through collaborations with suppliers, building capabilities in supply chains to unlock supply, and considering how innovation could help manage the magnitude of demand for such inputs. In some cases, playing a role in unblocking bottlenecks also represents an opportunity for value creation. For example, regions and companies that are major players in the global supply of critical inputs and technologies could become critical to scaling the decarbonization of other organizations. Policy makers can play a role in helping coordinate action across stakeholders and in untangling constraints—for example, related to permitting for transmission and distribution or to land availability.

— *For Level 3 challenges, where and how can these hardest challenges be addressed?* Addressing these challenges is subject to the greatest uncertainty, and they have the furthest to go to scale. Companies can consider where they may be best positioned to resolve these challenges, and how. Approaches should be guided by where companies can create a comparative advantage, where there is potential for value creation, and based on a deep understanding of the features that make Level 3 challenges particularly difficult. Companies should consider where they individually may be able to innovate to address performance gaps or weigh—often in collaboration with others—the broader system-level changes in how technologies mesh together and how end-use sectors employ technologies that could also address performance gaps. Importantly, while these challenges are the farthest from being fully solved, there are still opportunities to make some progress in the short term, such as improving energy efficiency or using recycled inputs in industrial processes. Policy makers will have a critical role to play in helping to create the incentives to invest in innovation and in fostering cross-sector collaborations for broader system-wide changes.

Of course, the nature and levels of challenges are not immutable. For each company, closely monitoring how the roles of policy makers, regulators, and competitors influence technologies, interdependencies, and scaling is crucial.

■ ■ ■

There is little doubt that the physical transformation of the energy system is complex and difficult. Nearly half of the 25 challenges—and about half of energy-related CO_2 emissions—are in areas that are particularly tricky to address.

The exact path forward remains uncertain, but it is clear that tackling these challenges would take individual and system-wide innovation and new ways of solving problems. The world has not yet figured it all out, but neither is the path forward entirely in the dark. In the past, new ways of transforming energy have been achieved that had been unthinkable, from liquefying natural gas to splitting the atom. Such ingenuity is now needed again. What lies ahead is a new energy transition on a monumental scale that would require setting a bold aspiration and proceeding with commitment and action. Above all, understanding the physical realities can help navigate the way forward to a successful transition.

The exact path forward remains uncertain, but it is clear that tackling these challenges would take individual and system-wide innovation and new ways of solving problems.

The 7 domains

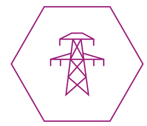
High voltage towers in the dusk of the evening

5. Power

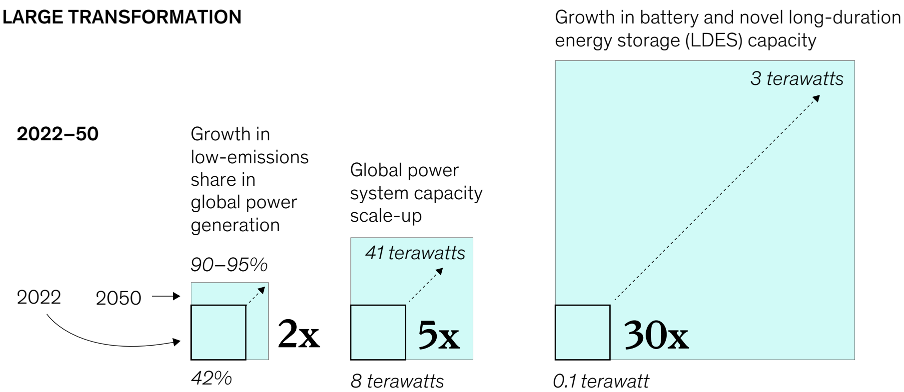
Coauthored with Jesse Noffsinger and Diego Hernandez Diaz

DOMAIN

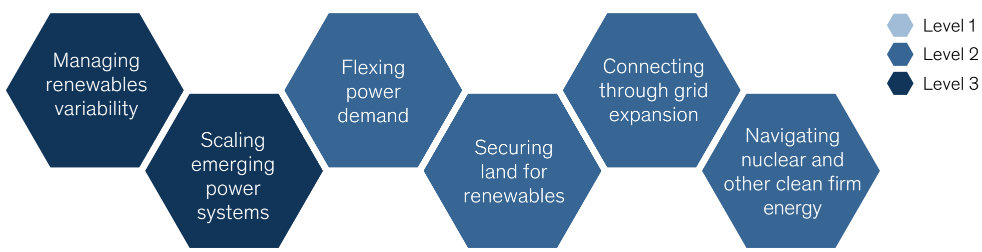
Power



A LARGE TRANSFORMATION



6 CHALLENGES



Note: This research examines 25 significant physical challenges in seven domains at the core of the energy transition, categorized in three levels. Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning. The focus is on physical realities because they influence the ability to design an interdependent system that has performance comparable to that of the current system and to reduce emissions feasibly. These factors influence cost and affordability. Nonphysical factors—notably cost—are important but are not the focus of this research. Assessment of required deployment of technologies primarily draws on McKinsey's 2023 Achieved Commitments scenario, which assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and in which warming reaches 1.6°C relative to preindustrial levels by 2100. This scenario is used because it provides sufficient regional and sectoral granularity for assessing required deployment. In some instances, this research also uses scenarios from other sources for reasons of data availability.
Source: *Global energy perspective 2023,* McKinsey; McKinsey Global Institute analysis

The power system is at the heart of the energy transition. Abating carbon emissions in the large energy-consuming sectors of mobility, industry, and buildings requires an electrified world. Electricity currently serves only about 20 percent of final energy consumption, about four percentage points higher than in 2000, and some 760 million people lack access to this source of power.[166] Even at its current size, the power sector generates significant emissions because most electricity systems rely primarily on fossil fuels. On average, electricity generation produces about 445 grams of CO_2 per kilowatt-hour in G-20 economies, although there are large differences among them. For instance, France, with extensive nuclear generation, produces 60 grams per kilowatt-hour. Germany produces more than five times that, at 330 grams, but is in the process of decommissioning coal-fired electricity generation. India's emissions are almost 12 times those of France at 715 grams.[167] All told, the power sector contributes about 36 percent of the global CO_2 emissions of the energy system.[168]

During the energy transition, the power system would need to grow as end-use sectors like mobility and buildings electrify and decarbonize. It also needs to expand to broaden access to electricity around the world. In McKinsey's 2023 Achieved Commitments scenario, total installed capacity would have to grow by about five times to 41 terawatts, and total electricity generation would triple to 77,000 terawatt-hours. And these additions would need to come from lower-emissions sources. Only about 40 percent of total power generated today derives from low-emissions sources, with the rest coming from fossil fuels.

By 2050, in this scenario, the share of low-emissions power would need to more than double, exceeding 90 percent. This would require adding more low-emissions sources of power, including VRE, such as solar and wind, and clean firm power. Firm power includes assets such as nuclear and hydropower plants whose output can be controlled (albeit not immediately) to meet fluctuating demand. Thus far, only about 10 percent of the low-emissions assets required by 2050 have been deployed. There are also new and rapidly growing sources of power demand that could impact the scale of the transformation needed in the near term. For example, in 2022, approximately 450 terawatt-hours—around 2 percent of total global power demand—were attributed to data centers, including artificial intelligence and other applications.[169] By some estimates, this demand could more than double to over 1,000 terawatt-hours as soon as 2026.[170] Furthermore, most of the deployment of low-emissions assets to date has been in comparatively easier use cases where VRE penetration has been relatively low. VRE is, by its nature, intermittent—there are periods when the sun does not shine and the wind does not blow. This creates a management issue for the power system. As VRE penetration increases, that management becomes incrementally harder, and additional backup capacity would be needed to cope with intermittency.

This chapter focuses on six interdependent physical challenges that would need to be addressed in order to power the world through the energy transition: (1) managing renewables variability; (2) scaling emerging power systems; (3) flexing power demand; (4) securing land for renewables; (5) connecting through grid expansion; and (6) navigating nuclear and other clean firm energy.

The extent of decarbonization that is realizable in other domains would depend on decarbonizing the power system on which they would depend for providing low-emissions energy. This analysis identifies two fundamental and difficult challenges that relate to managing the variability of intermittent renewables, including in economies that are still growing their power systems. Both are classified as Level 3 challenges because more variable power systems are more demanding use cases that require new forms of flexibility. The four other challenges categorized as Level 2 require the deployment of known technologies to accelerate and require associated infrastructure and inputs to be scaled.[171]

Challenge 1

Challenge 1: Managing renewables variability (Level 3)

Historically, electrical systems have been built on the backbone of firm energy generation. A key part of the energy transition would involve deploying VRE assets, such as solar and wind power, whose output depends on weather conditions and is therefore not guaranteed at all times. As VRE penetration increases, the performance profile of power system output would change, notably becoming more variable. The primary physical challenge, therefore, is how to manage the variability of the power system when VRE reaches high levels of penetration.

Tackling this challenge would require a high degree of transformation of the power system to increase the sources of supply-side flexibility to cope with this increasing variability. Some uncertainty remains about which technological pathways would be used to manage the variability, and very large scale-ups of technologies whose deployment has been limited thus far would be required.

The variability of power generation increases as solar and wind are added into the system
As the share of power generated through VRE increases, so do the variability of the power system's output and its ability to meet demand at any given time. Matching supply and demand both within and between days becomes trickier.

— *Intraday.* In the course of a day, there are large fluctuations in both the supply of variable renewable power—solar in particular—and total power demand, which can lead to significant mismatches in supply and demand. In California, for instance, the intraday variability of solar output produces the "duck curve" as the grid tries to cope with sharp swings in supply and demand during the day (Exhibit 17). Demand that is not met by VRE supply—the residual net load—bottoms out around midday, when solar output peaks, and spikes in the evening, when solar output is not available and demand for power increases (the shape of this profile is what gives the curve its name). This mismatch means that forms of backup power are needed to smooth daily imbalances. Growth in VRE capacity in California has made the curve more pronounced over time. The spread between the peak and trough of residual net load more than doubled between 2015 and 2023.[172]

Exhibit 17

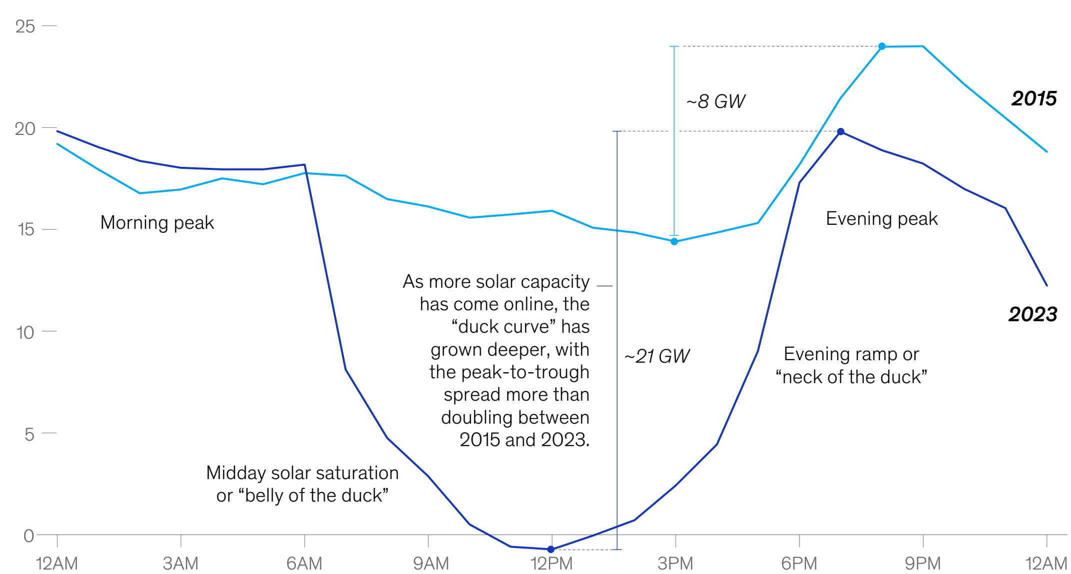
Growth in variable renewable energy capacity in California has made the 'duck curve' more pronounced.

CHALLENGE

1 Managing renewables variability

Lowest minimum residual net load day each year in CAISO, 2015–23, GW[1]

Demand not met by VRE—the residual net load—bottoms out around midday, when solar output peaks, and spikes in the evening, when solar output is not available and demand for power increases. The shape of this profile is what gives the curve its name.[2]



[1]The California Independent System Operator (CAISO) is responsible for operating the majority of California's high-voltage wholesale power grid as well as administering the state's wholesale electricity market.
[2]Net residual load shown is demand minus utility-scale wind and solar.
Source: CAISO; McKinsey Global Institute analysis

— *Interday and seasonal.* Wind and solar output varies from day to day depending on the weather and, in particular, on the seasons. There can be long periods when generation is not sufficient to meet demand, and this can also be hard to predict, particularly in the case of wind. In McKinsey's 2023 Achieved Commitments scenario, in Germany, for example, VRE would account for about 90 percent of annual generation by 2050, but this does not mean that VRE would meet needs on 90 percent of days. Based on detailed modeling of future power demand and the potential generation of renewables, McKinsey Power Model estimates suggest that on about 75 days of the year, one-quarter or more of power demand would not be met by VRE generation (Exhibit 18).[173] On the flip side, Germany would produce more from VRE than it would consume on more than half of the days of the year. This mismatch would have to be smoothed over time by storing excess power to be used when needed, or over space through interconnections with other power markets.

Exhibit 18

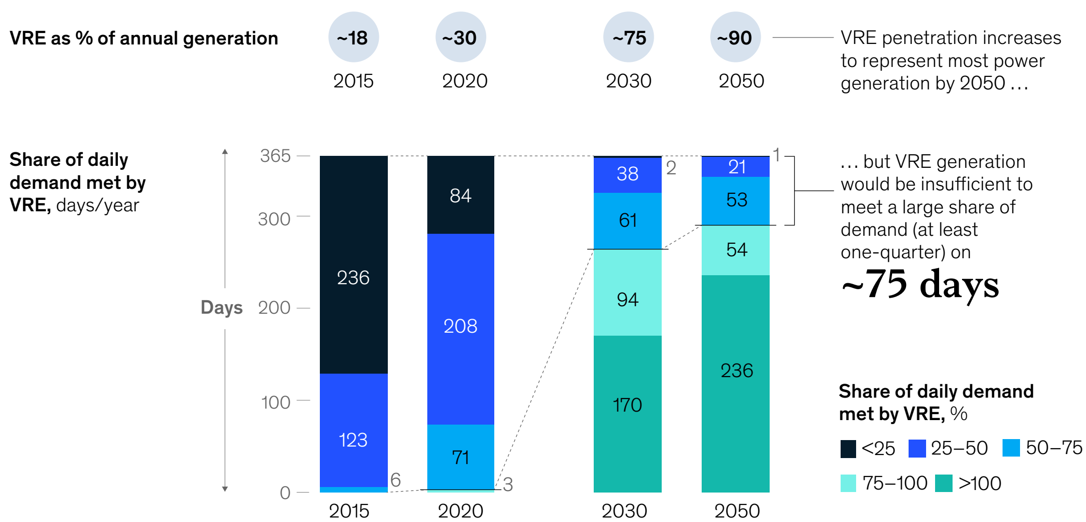
When variable renewable energy makes up a large share of annual electricity generation, backup power would be needed for much of the year.

CHALLENGE

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO | GERMANY ILLUSTRATION

1 Managing renewables variability

Evolution of Germany's variable renewable energy (VRE) generation,[1] 2015–50



[1]Germany data for 2015–22; 2030 and 2050 projections from the McKinsey Power Model.
Source: Fraunhofer Institute for Solar Energy Systems; McKinsey Power Model; McKinsey Global Institute analysis

The power system would also transform into a higher-capacity, lower-utilization system as VRE is added

As VRE scales, higher variability would lead to a major shift in how power systems evolve. VRE-heavy systems require much faster growth in installed generation capacity than in actual generation. Consider Germany again. In McKinsey's 2023 Achieved Commitments scenario, the capacity of Germany's system would triple, while generation would increase by about 85 percent (Exhibit 19).

The reason more installed capacity would be needed relative to increases in power generation is the fact that VRE assets usually have low utilization rates—also called capacity factors—in comparison with thermal-based assets, because their output fluctuates with sun and wind resources. While gas plants employed to generate baseload can have about 60 to 70 percent capacity factors over the course of a year, US utility-scale solar capacity factors average about 25 percent.[174]

Power systems with high VRE penetration would also have lower utilization of the remaining assets, notably thermal generation assets. In Germany, for instance, the average utilization rate of the thermal generation system, comprising conventional assets such as gas, coal, and biomass, and, in the future, potentially even new assets such as hydrogen turbines, could drop from a baseline of about 35 percent today to below 10 percent in 2050.[175] This is because these assets would become providers of flexibility—rapidly adjusting generation to match demand not met by VRE assets—instead of running continuously as providers of baseload (see the next section for further discussion on this point).

These changes in the utilization of existing assets mean that in systems with a high share of VRE, the system cost is not just the result of the average generation costs (often studied using levelized cost of electricity, or LCOE, metrics) but is also affected by flexibility costs. For example, as the thermal system faces reduced utilization, its relative cost per unit of energy generated increases because fixed costs are diluted by smaller total generation.[176]

As VRE scales, higher variability would lead to a major shift in how power systems evolve.

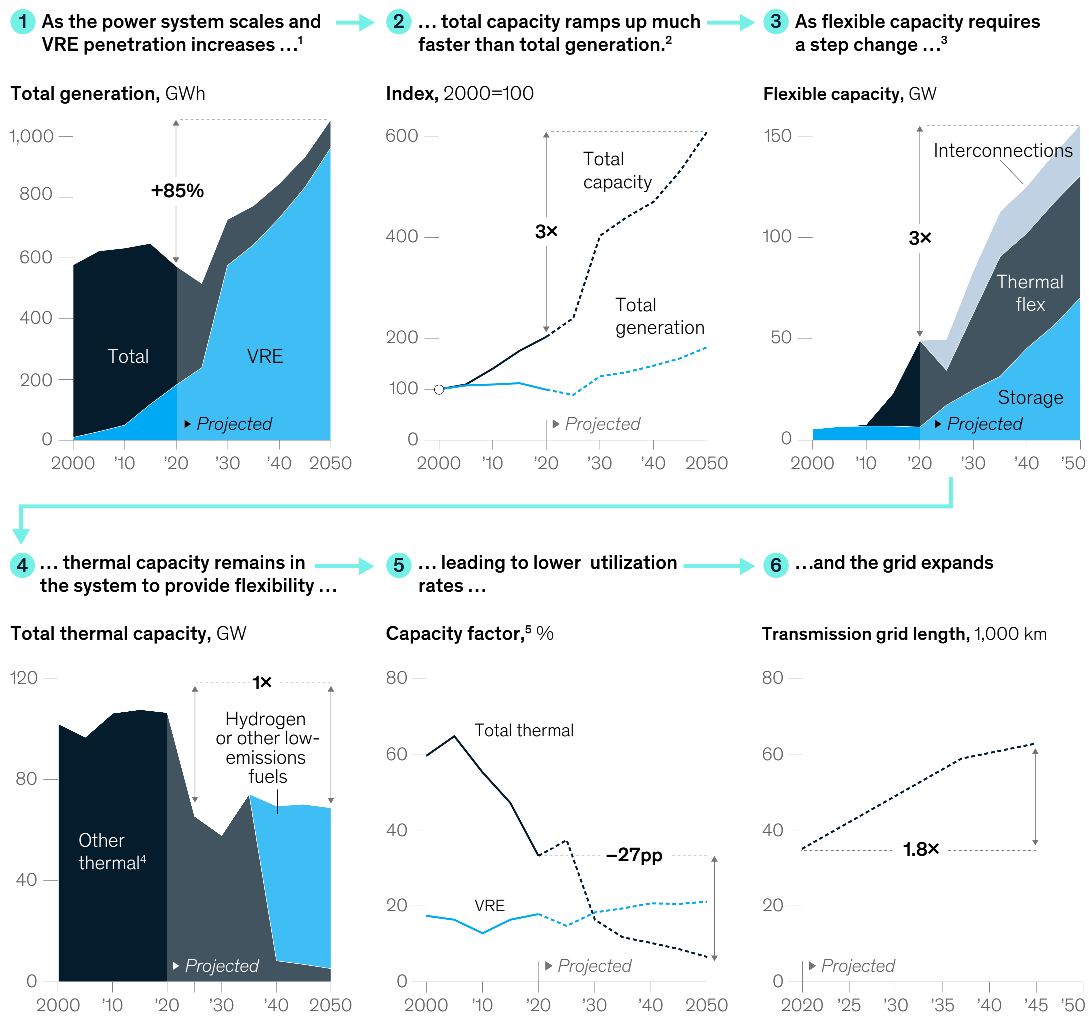
Exhibit 19

VRE-heavy systems require more capacity to provide flexibility.

CHALLENGE
1 Managing renewables variability

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO | GERMANY ILLUSTRATION

Changes in German power system, 2000–50



[1]Variable renewable energy (VRE) refers to energy sources such as solar and wind, which produce electricity depending on natural conditions (for example, when the sun is shining or wind is blowing).
[2]Capacity includes all forms of generation assets.
[3]Flexible capacity includes dispatchable generation assets running at low utilization (benchmarked against 50% utilization), interconnections, and storage. Thermal flexibility encompasses coal, gas, gas with carbon capture and storage, nuclear, oil, other clean thermal assets, and other renewable energy sources. Interconnections refer to physical connections with other power systems, measured in megawatts representing the maximum amount of electricity that can be imported. Storage includes pumped hydro, long duration electricity storage and lithium-ion batteries.
[4]Includes coal, natural gas, and oil.
[5]The capacity factor of a generation asset is calculated by dividing output over a period of time by the maximum possible output if the asset were running at full capacity continuously over the same period.
Source: International Energy Agency; US Energy Information Administration; McKinsey Power Model; Federal Network Agency (BNetzA); McKinsey Global

Addressing the variability of solar and wind would require a large scale-up of flexibility solutions
Additional flexibility would need to be built into power systems to manage the intermittency of VRE. On the supply side, there are a number of ways to add flexibility to deliver power when and where it is needed, including energy storage, backup thermal generation (as previously discussed), and more extensive interconnections with other power systems (see Sidebar 3, "Power systems exhibit

different forms of supply-side flexibility”). Demand-side flexibility could also play an important role (as discussed later in this chapter as part of Challenge 3).

For the majority of economies that achieve high VRE penetration, defined here as more than 50 percent of total supply by 2050, the amount of generation that total flexible capacity (assets and interconnections that could quickly deliver power when required) could deliver would have to grow two to three times faster than overall demand for power.[177] This would be the case, for example, in Brazil, China, Germany, and Italy. In other economies, including India and South Africa, the increase could be substantially larger, at close to seven times (Exhibit 20).

Different scenarios and options could lead to different technology mixes, such as more storage or more flexible clean thermal generation. But while the specific mix may vary, multiple forms of flexibility are likely to be required, as they play a complementary role to some extent. Some are more suitable for short-term flexibility needs, such as Li-ion batteries. Others, such as novel LDES, are more suited for longer-term needs.[178]

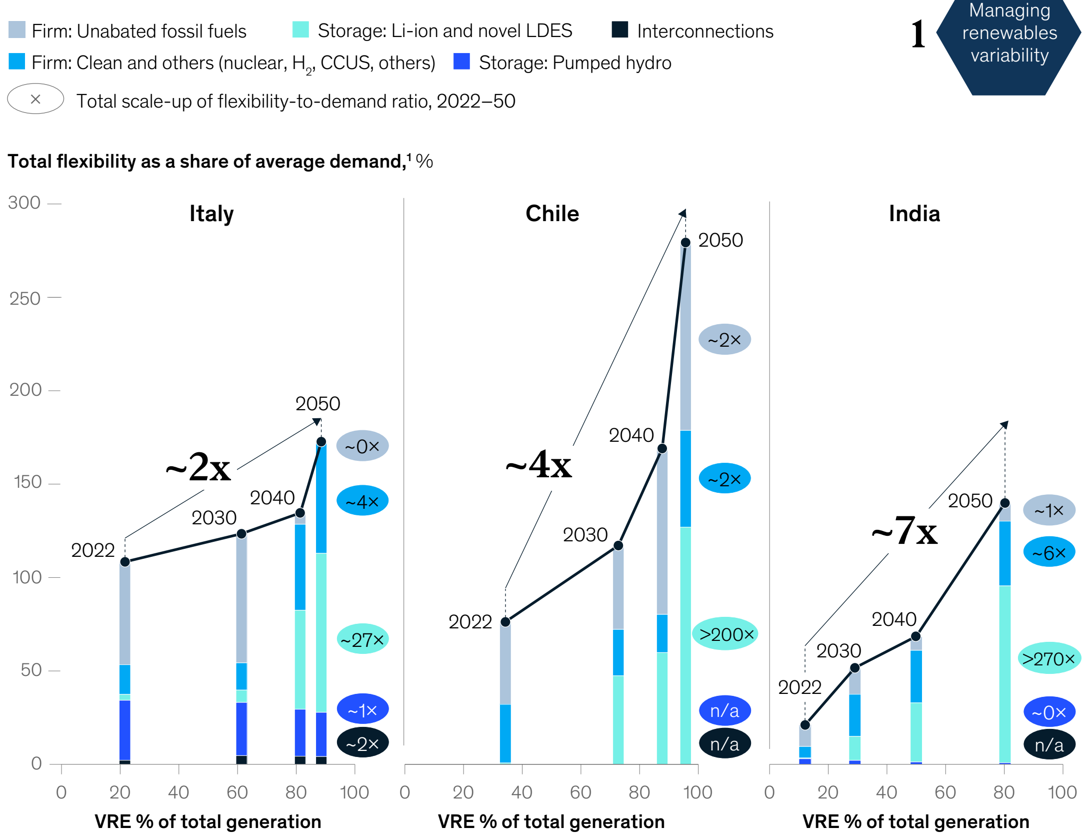
Exhibit 20

On power systems with a high share of VRE, flexibility would have to increase about two to seven times faster than demand for many countries by 2050.

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO

CHALLENGE

1 Managing renewables variability



Note: Representative examples. Other countries also typically exhibit similar trends.
[1]Flexible capacity includes dispatchable generation assets running at low utilization (benchmarked against 50% utilization), interconnections, and storage. Calculated as the total amount of generation that flexible capacity could deliver in a given hour, divided by average hourly demand. Dispatchable generation assets include coal, gas, gas with carbon capture and storage, nuclear, oil, and other clean thermal assets. Interconnections refer to physical connections with other power systems, representing the maximum amount of electricity that can be imported at a given time. Storage includes pumped hydro, batteries, and novel LDES.
Source: *Global energy perspective 2023*, McKinsey; McKinsey Global Institute analysis

It should be noted that the additional flexibility required is likely to increase nonlinearly with the VRE share in power generation—required flexibility rises increasingly steeply once higher shares of VRE penetration are achieved in order for the system to cope with the increased variability and lower proportion of installed capacity that is dispatchable.[179]

Two main factors dictate differences in the total amount of required flexibility additions in different markets. The first is how much flexibility already exists. Economies that can already draw upon a high thermal generation asset base to meet their flexibility needs are less likely to need to scale it significantly, especially in the short term. The second is what renewable endowments are present. Economies with complementary and favorable sun and wind profiles in particular would require comparatively less total flexibility as a share of total demand, because uncorrelated wind and solar generation can be complementary and create a smoother profile overall.

Regardless of the extent to which flexibility needs to increase, different forms of supply-side flexibility are likely to exist, and the roles played by each form could change over time. For some markets (in particular advanced markets) with existing thermal generation footprints, this system is likely to play the lead role in flexibility, at least over the next decade. These markets have the potential to effectively repurpose existing thermal assets to provide flexibility and can defer building net new flexible capacity such as storage. As VRE penetration increases, capacity factors of thermal generation assets would therefore decline, but their actual installed capacity would initially mostly be retained.

As more VRE continues to be added and thermal generation flexibility is exhausted, economies may reach a tipping point at which storage becomes the main source of added flexibility. This increase in storage could be achieved using both mature technologies such as batteries—often scaling up at least 30-fold for some economies in the scenarios modeled in this research—and as yet nascent technologies such as novel forms of LDES, hydrogen through power-to-gas, and other low-emissions fuels. By 2050, these nascent technologies could increase capacity hundreds of times from today's negligible base in many economies (see also Challenge 2 for a discussion of emerging power systems).

Total flexible capacity would have to grow two to seven times faster than overall demand for power between now and 2050.

Sidebar 3. Power systems exhibit different forms of supply-side flexibility

Supply-side flexibility can be built into power systems in three main ways. All can be beneficial, but each faces different physical constraints. (Demand-side flexibility is discussed later in this chapter).

Energy storage. Storing energy for later use could play the largest role. Some forms of storage are already mature. Roughly 250 gigawatts of global electricity storage currently exist, about two-thirds from pumped hydro storage (PHS) and the rest from Li-ion batteries.[1] Although these storage technologies are commercially mature, they face substantial physical challenges in their ability to scale up—in particular, for PHS, limits on the availability of suitable sites and, for Li-ion batteries, insufficient supply of raw materials (see chapter 9 on the raw materials domain).

Technologies that are currently nascent, such as novel LDES and hydrogen through power-to-gas, are expected to meet a large share of flexibility needs by 2050, potentially scaling hundreds of times from virtually no deployment to date. These two technologies could account for as much as one-third of energy storage capacity for power systems by 2050 in McKinsey's 2023 Achieved Commitments scenario. Novel LDES technologies can be thought of as a portfolio of many options. Some can store power for later use through mechanical or electrochemical means. Mechanical systems include, for example, compressed air, which is already being deployed and accounts for the majority of novel LDES power storage capacity announced to date, as well as gravity-based systems. Such forms of storage can be difficult to scale because they can need particular locations, such as a mountain or mine shaft. Other approaches, such as electrochemical applications (essentially batteries other than Li-ion), can offer flexibility on location and high energy efficiency but are not technologically mature and not yet deployed at scale. In some cases, storing heat through thermal energy storage (TES) instead of storing power may be preferred. TES systems account for more than half of announced novel LDES capacity to date.[2]

Thermal power backup. Existing thermal generation systems could be operated at lower utilization rates rather than providing continuous firm power, thereby creating flexibility in the system by being able to quickly ramp up unused capacity when it is needed.[3] Most of these assets were developed assuming high utilization. Therefore, power markets would have to be designed or redesigned with regulatory support to make feasible the expansion and maintenance of low-utilization thermal generation assets, which can provide flexibility.[4] Many markets do not have sufficient thermal capacity to provide flexibility, and building that capacity may be unlikely if low utilization rates are expected with a redesign.[5] Another issue is that fossil-fuel thermal systems, even at relatively low utilization, still produce emissions. In the short term, one solution would be using natural gas power plants for intermittent operation because they can ramp up very rapidly when needed.[6] In the long term, turbines fueled by hydrogen or other low-emissions fuels, such as biogas or landfill gas, could provide flexibility with lower emissions.

Interconnections. Another form of flexibility could be achieved by connecting separate grids to pool resources among regions or economies that may be experiencing different weather conditions: the sun may be shining in Spain but not in Germany, or the wind blowing in Texas but not California. The EU has set interconnection targets to encourage members to have electricity cables that enable at least 15 percent of electricity produced to be transported within the EU, although even this increase could be insufficient to meet the EU's needs.[7] One limitation on the degree to which interconnections expand would be potential energy losses during the transportation of electricity over long distances.[8] But there are also important nonphysical barriers, including "right of way" to pass along a particular route as well as alignment among stakeholders on the proper allocation of the benefits and costs of new lines.

1 *Grid-scale storage*, IEA, accessed May 2024; and Nelson Nsitem, "Global energy storage market records biggest jump yet," BloombergNEF, April 25, 2024.
2 TES covers a range of technologies that allow for the capture and retention of thermal energy for later use. TES technologies include sensible heat storage, which stores thermal energy by changing the temperature of specific materials, such as silica or water; latent heat storage, which changes the phase or state of materials, for example from solid to liquid; and thermochemical heat storage, which uses reversible chemical reactions, such as hydration and dehydration reactions. *Net-zero power: Long-duration energy storage for a renewable grid*, LDES Council and McKinsey, November 2021.
3 Increasing generation from clean thermal sources could also reduce the total amount of VRE deployment required and reduce overall system variability. See Challenge 6 for further discussion.
4 Jamie Brick, Dumitru Dediu, and Jesse Noffsinger, "The role of natural gas in the move to cleaner, more reliable power," McKinsey, September 2023.
5 *An affordable, reliable, competitive path to net zero*, McKinsey Sustainability, November 2023
6 Jamie Brick, Dumitru Dediu, and Jesse Noffsinger, "The role of natural gas in the move to cleaner, more reliable power," McKinsey, September 2023.
7 *Electricity interconnection targets*, European Commission, accessed May 2024; *European resource adequacy assessment*, European Network of Transmission System Operators, 2023.
8 *Electricity grids and secure energy transitions*, IEA, 2023; and M.J.N. van Werven and F. van Oostvoorn, *Barriers and drivers of new interconnections between EU and non-EU electricity systems*, Energy Research Centre of the Netherlands, May 2006.

Each form of flexibility comes with physical barriers, notably technological maturity for some newer flexibility options

Scaling up flexible supply capacity to address variability would require solving physical challenges that each source of flexibility faces. The challenges run the gamut—from performance issues in certain use cases, to technological nascency, to the need for appropriate physical inputs.

For example, novel LDES and hydrogen-based generation technologies, such as turbines, have high potential as solutions for long-duration flexibility for interday or seasonal purposes. In McKinsey's 2023 Achieved Commitments scenario, they would make up as much as one-third of total energy storage capacity for power systems by 2050. There have already been encouraging developments. In 2024, the world's largest grid-connected compressed air energy storage project, the Hubei Yingchang project, with capacity of 300 megawatts, came online in China.[180] In 2023, the US Department of Energy approved 15 novel LDES projects for government support.[181] However, neither technology has been deployed to a meaningful extent to date. Novel LDES projects are still relatively small in scale, and many of the novel LDES variants are completely new and do not yet have a track record. Widespread adoption of these technologies would depend on their commercial demonstration and cost developments.[182] The fact that they are at a very early stage in their development poses a significant technological risk, which would need to be addressed when tackling the physical challenge of variability at high VRE penetrations.

Deployment of other types of storage has increased rapidly. There was a step change in adding battery storage globally in 2023, with industry deployment roughly doubling to about 40 gigawatts.[183] China led the way, accounting for more than 50 percent of annual additions and deploying roughly as much storage in 2023 as the entire world did in 2022.[184] But, for a number of reasons, mature forms of storage still face constraints on scaling that would need to be addressed. For example, Li-ion batteries are most suitable for multihour rather than longer-term (multiday/seasonal) energy storage. Another factor is whether critical inputs are available. Li-ion batteries rely on minerals that may be in short supply and would also be required for mobility applications (see chapter 6 on the mobility domain and chapter 9 on the raw materials domain).

The primary issue for thermal generation systems is the need for new market design mechanisms that enable them to be viable even at lower utilization levels, while for interconnections, the main issues are limits on available land and, often, long lead times.

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Managing the variability of renewables-heavy power systems is a Level 3 challenge, and one that would have to be addressed to support the decarbonization not only of the overall power system but also of other sectors that rely on power.

As more VRE is deployed, the performance of power systems would change, and supply would become more variable. Addressing this variability would require deployment of multiple options, including various types of energy storage, thermal backup systems, and interconnections. While some of these forms of flexibility are mature, deploying them would require solving issues related to critical inputs (for energy storage) as well as nonphysical factors such as market design mechanisms (for thermal backup systems). Some flexibility solutions would require additional innovation, particularly in the cases of newer forms of flexibility whose deployment to date is close to zero and that face technological uncertainty—notably, novel LDES and hydrogen.

Challenge 2

Challenge 2: Scaling emerging power systems (Level 3)

Many people, particularly in emerging economies where power systems are less developed than those in advanced economies, have relatively low access to power from the grid. About half of the world's population consumes less than two megawatt-hours of electricity per capita per year, which is approximately one-sixth of the per capita consumption in the United States.[185]

Emerging power systems face a different and more complex physical challenge than mature power systems. This applies not only in the degree to which they need to scale, but also in the extent to which they would need to achieve a faster ramp-up of flexibility to accommodate increasing levels of VRE penetration.

In McKinsey's 2023 Achieved Commitments scenario, emerging power systems would need to scale capacity as much as sixfold from 2022 to 2050 as they broaden access to electricity, compared with threefold in the case of more mature systems. The need to ramp up the deployment of renewable energy in emerging power systems starting from a lower base would be even larger—an increase of 18 times, compared with eight times in mature systems. They would also need to navigate uncertain technological pathways in their efforts to provide flexibility and manage increasing penetration of VRE.

Emerging power systems have an opportunity to broaden access to power while decarbonizing and to make the system more reliable. In African economies, the frequency and duration of electric outages are nine times higher than in advanced economies.[186] To pull this off would require recognizing the particular needs of these economies, designing power systems to meet them, thoughtfully staging their development, and ensuring the most appropriate flexibility mix. Overall, a high degree of transformation of their power systems would be needed.

Power systems have historically been built on firm power

Around the world, power systems have tended to be built around firm power. As emerging power systems attempt to expand and decarbonize, they would need to add both firm power and VRE, and strike the right balance between the two.

Most of the deployment of new VRE in recent years has been in mature power systems where overall per capita power generation did not grow. In Germany and the United States, for instance, VRE generation increased from virtually zero in 2000 to about 2.0 to 2.5 megawatt-hours per capita in 2023, while total generation per capita remained roughly stable. These economies and others were able, in part, to add VRE because the existing firm power system was sufficiently flexible. Germany, for instance, was able to increase generation from VRE without developing new sources of flexibility by using existing thermal generation assets, mostly coal and gas (albeit at lower utilization rates).

Those economies that have expanded overall power generation have done so mostly on the back of firm power. China and India, for instance, increased per capita power generation from 2000 to 2023 by 8 percent and 4 percent a year, respectively, of which more than 80 percent was firm (mostly coal) in both cases (Exhibit 21). But this trend has started to shift. In the last 5 years, VRE made up around 30 to 40 percent of growth in generation in these two markets.[187] Nigeria grew per capita power generation by only 2 percent per year between 2000 and 2023, with virtually all the growth from firm sources (mostly natural gas).

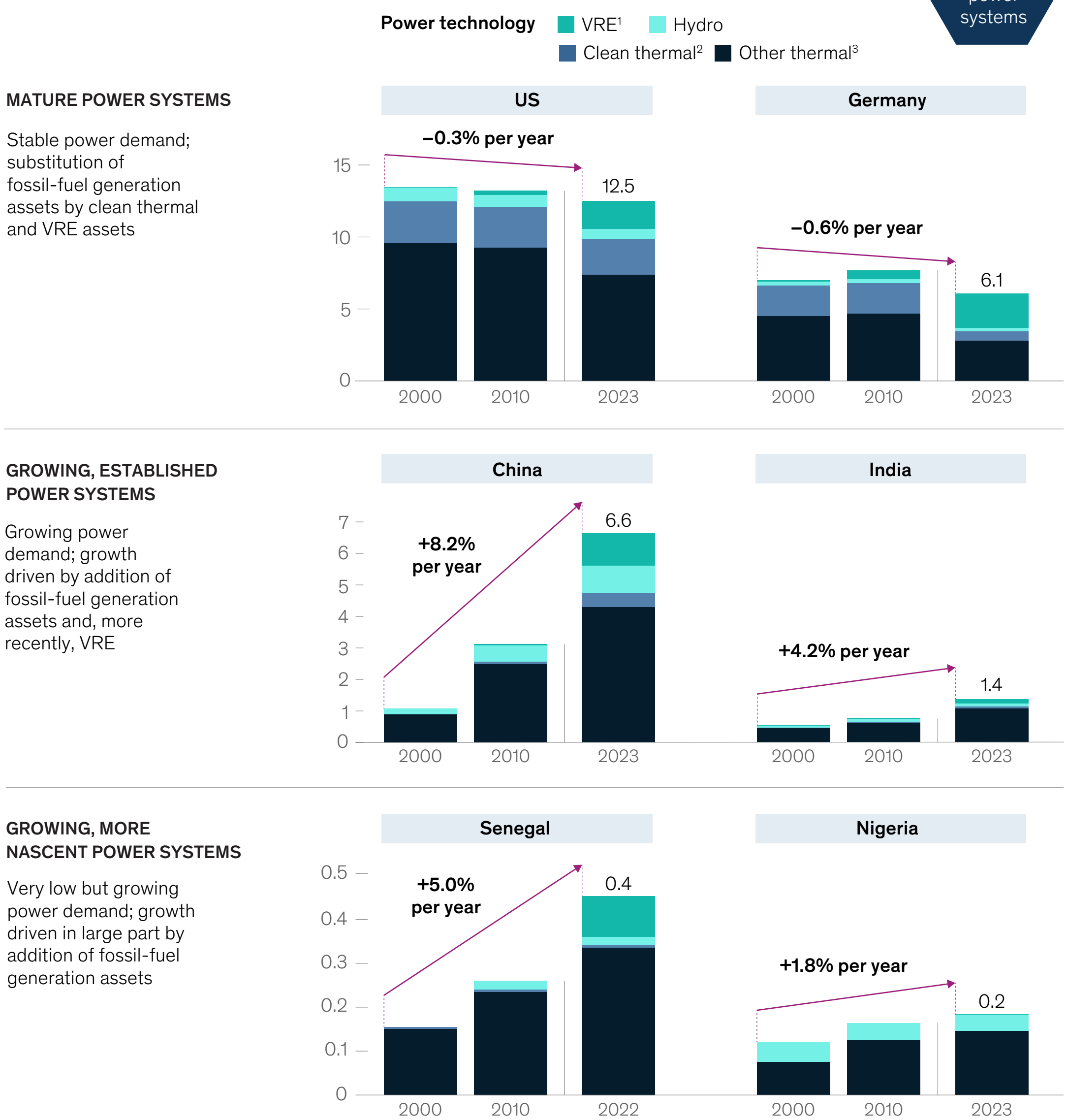
Exhibit 21

Power systems are at different stages of development.

CHALLENGE

2 Scaling emerging power systems

Per capita electricity generation, MWh



[1]Variable renewable energy, includes solar and wind power.
[2]Includes biofuels, geothermal, nuclear, and waste.
[3]Includes coal, natural gas, and oil.
Source: Ember; Energy Institute; Our World in Data; McKinsey Global Institute analysis

Emerging power systems would need to build more flexibility to accommodate VRE

Emerging power systems have less flexible capacity than mature ones to accommodate extensive growth in the penetration of VRE that building a larger low-emissions power system would entail.

Mature power systems currently have about three times more flexibility available than their emerging counterparts. For instance, Germany and the United States have flexibility today equivalent to roughly 40 to 70 percent of expected average power demand in 2030, but economies such as China, India, and South Africa have only 10 to 25 percent (Exhibit 22).[188] In large part, this reflects the flexibility provided by existing thermal generation assets in mature markets.

Exhibit 22

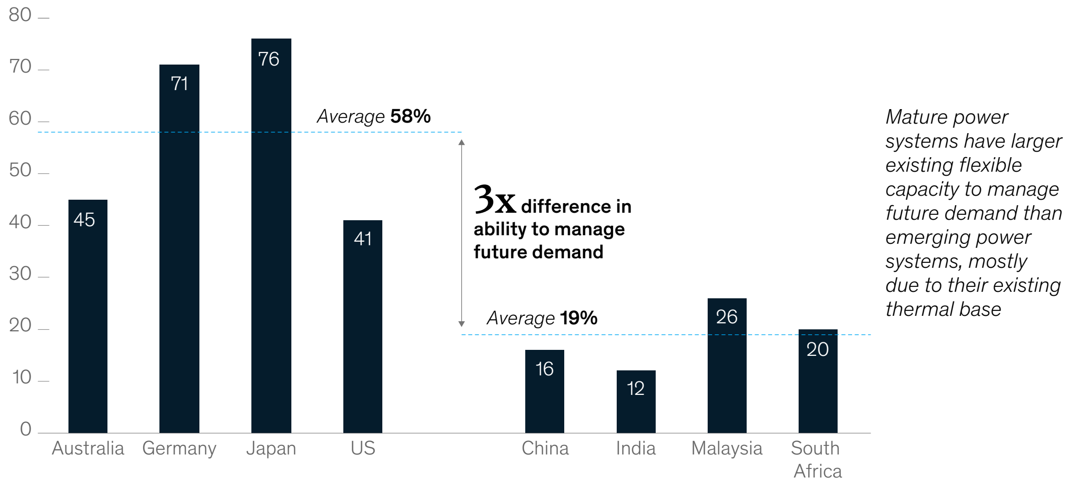
Emerging power systems currently have less flexibility to accommodate VRE additions

CHALLENGE

2 Scaling emerging power systems

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO

Available flexible capacity today as a share of expected average power demand in 2030,[1] %



[1]Calculated as the total amount of generation that flexible capacity could deliver in a given hour in 2022, divided by average hourly demand in 2030.
Source: *Global energy perspective 2023,* McKinsey; McKinsey Global Institute analysis

For example, in the United States today, roughly 75 percent of flexible capacity resides in thermal capacity, most notably gas generation assets.

As a result, in addition to adding proportionately more flexible capacity, emerging power systems would often need to do so relatively faster than mature power systems. Take Italy and India as examples (see Exhibit 20 in the previous section). In McKinsey's 2023 Achieved Commitments scenario, Italy's flexibility needs would mostly ramp up around 2040, when VRE penetration hits about 80 percent of total generation. However, for India, a doubling of total flexibility could be needed as early as in 2030, when VRE would account for 30 percent of generation.

They could achieve incremental flexibility in three main ways. First, they could add thermal generation assets such as gas, which could provide firm power as well as flexibility (although, of course, this approach could increase emissions in the short term). Second, they could ramp up storage proportionately faster. Depending on the specific geography and its needs as well as affordability considerations, these approaches could be used in parallel or sequentially. For instance, an emerging power system could prioritize building some gas assets in the short term and then roll out storage.[189] Third, in some cases, additional interconnections could create more flexibility.

Some emerging power systems have made progress in developing more flexibility. In a single year, China quadrupled new energy storage from about eight gigawatts in 2022 to about 30 gigawatts in 2023. Of all energy storage tenders ever awarded in India, 60 percent were granted in 2023 alone.[190] In 2022, Egypt and Saudi Arabia announced the construction of the first large-scale high-voltage direct-current interconnection between the Middle East and North Africa, creating flexibility for both.[191]

But despite such examples of progress, a long road lies ahead. After 2030, storage technologies would need to grow hundreds of times in some economies. Moreover, as discussed in Challenge 1, novel technologies to provide long-term flexibility needs would also be required as emerging power systems reach higher levels of VRE penetration.

■ ■ ■

This is a Level 3 challenge. The required degree of transformation would be considerable in emerging power systems and comparatively larger than in mature power systems, given that they start from a lower flexibility base. Addressing this challenge would require deploying a combination of sources of flexibility. Some of them are mature technological options, namely thermal generation, and could support flexibility in the short term. But as in Challenge 1, further down the line, novel technologies would be required, and deploying them would require additional innovation.

Challenge 3

Challenge 3: Flexing power demand (Level 2)

With demand for power rising quickly and new end-use sectors, from cars to industries, being electrified, there could be an opportunity to reengineer power systems and create new sources of demand-side flexibility. These forms of flexibility could complement the supply-side flexibility options discussed in Challenges 1 and 2. Adoption scenarios vary, but under the IEA Net Zero 2050 scenario, the overall scale-up of demand-side flexibility capacity required could be up to tenfold in 2030 relative to today.[192]

What does demand-side flexibility mean in the context of the energy system? Essentially, it involves offering users incentives to consume power at times when it is more plentiful—that is, when net demand on the grid is lower. This is not a new idea. About 50 gigawatts of demand-side flexibility is already in place in Australasia, Europe, and North America, split evenly between buildings and industry.[193] Differentiated intraday power prices have been used for more than 60 years in some economies, encouraging people to run some appliances at night, for example.[194]

In a more electrified and connected world, the number and volume of options for demand-side flexibility potentially increase. They could include small adjustments, such as deploying automated controls of home thermostats to avoid demand peaks, or larger shifts, examples being using residential batteries or EVs to flow stored power back to the grid when needed and reconfiguring industrial processes by electrifying them and coupling them with TES.

Increasing demand-side flexibility would need not only the deployment of new technologies, but also a high degree of transformation of both hardware and software. Estimates of the magnitude of increase in flexible demand vary, but under the IEA Net Zero 2050 scenario, more than one-quarter of total power system flexibility in advanced economies could come from demand-side flexibility by 2050.[195]

A portfolio of demand-side flexibility technologies would likely be needed
Across end-use sectors, different technologies and assets could create demand-side flexibility. A combination of them would likely be required.

— *Residential.* Distributed energy resources could be pooled into residential virtual power plants (VPPs). These could include residential ("behind the meter") storage solutions and appliances. VPPs can control the amount of energy homes and buildings use at a given time to reduce demand on the grid. For example, smart water heaters and smart thermostats can adjust when they consume electricity to shift demand to off-peak times, preheating or precooling the home when power is abundant.[196] Similarly, residential batteries can charge when power is abundant and discharge during peak hours. Pooling such resources into a single VPP can provide utility-scale flexibility that is comparable to that of a traditional power plant. For instance, estimates suggest that VPPs could create more than 350 gigawatts of flexible capacity in the European Union by 2050.[197] For the sake of comparison, existing gas capacity in the EU sums to about 192 gigawatts.[198]

— *Mobility.* EV batteries can be used as spare storage capacity for the grid. Although patterns of use vary, on the whole EVs constitute a large source of unused flexible capacity. They are driven for only a fraction of the day, lying idle for many hours. Moreover, batteries in newer models have more storage capacity than needed for most daily use. For example, in the United States an average EV can power 400 kilometers a day against an average of 50 kilometers actually driven (see chapter 6 on the mobility domain).[199] Two measures could help propel the use of EV batteries to create demand-side flexibility. First, smart charging could be switched to off-peak hours to lower demand on the grid when demand is higher. Second and more radical, EVs could act as additional storage for the grid. Vehicle-to-grid (V2G) technology—currently nascent—could enable an EV to discharge its battery to provide additional power to the grid. In the EU, this could offer as much as 700 additional gigawatts of flexible capacity by 2050.[200] Pilots are under way in many economies. In the United States, California is piloting a program and considering mandating bidirectional chargers by 2027 that would be needed for V2G to work.[201] The largest EV school bus fleet in the United States is implementing smart charging and aims to incorporate V2G in the future on the grounds that school buses are used at predetermined times and have long periods when they are idle.[202] China has also released plans for the integration of EV charging infrastructure into the electricity grid; they include time-of-use electricity pricing and bidirectional charging stations.[203]

— *Data centers.* Another source of flexible capacity could come from computer data centers, which account for a high, and growing, share of electricity consumption. In 2022, as much as 450 terawatt-hours were attributed to data centers, including AI applications such as large language model training.[204] By some estimates, this could more than double to more than 1,000 terawatt-hours as soon as 2026.[205] Using this demand to add flexibility to the grid could be crucial. Depending on the business model and application, some power-hungry computing operations, such as training large language models, could be executed with more flexibility. This is already happening among large players, for instance by shifting some nonurgent computing tasks to times when demand for power is lower.[206] Another option is building new data centers in regions where more spare capacity is available; this would be contingent on overcoming technological constraints, for instance ensuring access to data network infrastructure and maintaining latency levels or delays in data transmission within acceptable levels. Large companies with a portfolio of locations could offer incentives to dynamically reallocate loads that are not critical between regions according to the needs of the grid.[207]

— *Industry.* The growing electrification of the heat generation needed in industry also offers potential for new sources of demand-side flexibility. Several provinces in China have launched demand-side flexibility pilot programs focused on industry, with the goal of having a demand-response capacity of 3 to 5 percent of annual peak load by 2025.[208] Three main opportunities to enhance demand-side flexibility could play out, as follows:

- Shifts in power consumption could be achieved by adjusting the timing of some industrial processes so that they can accommodate changes in production levels with proper notice.
- Some processes could use hybrid heating, switching between fossil-fuel and electric-powered boilers to adjust power demand for excess or scarcity in the power supply. In Europe, these two technologies together could create as much as 150 gigawatts of capacity by 2050.[209]
- Supply-side flexibility technologies such as TES could help manage power demand from boilers and furnaces. Some of the heat produced could be stored in TES and then drawn on when needed. Europe has 8.5 gigawatt-hours of TES that is either operational or under construction. The opportunity for growth is significant. The global potential of TES by 2040 could range from 800 to 4,800 gigawatt-hours.[210] (See chapter 7 on the industry domain, for a discussion of using TES to increase the flexibility of industrial demand).

— *Hydrogen.* Producing hydrogen via electrolysis is particularly energy-intensive and could account for as much as 20 percent of total final energy consumption in 2050, according to McKinsey's 2023 Achieved Commitments scenario (for more detail, see chapter 10 on the hydrogen domain).[211] Electrolyzers can adjust energy consumption by reducing hydrogen production when power demand is at its peak and increasing production when there is excess VRE. This would create flexibility in two ways: demand for power from electrolyzers could adjust to the needs of the grid, and the hydrogen itself could be used as a fuel for generation—a supply-side lever.

These technologies vary in both the degree of flexibility they offer and the type of flexibility. For instance, VPPs controlling residential housing could provide a fast burst of additional capacity to the grid for a limited amount of time before consumers resume their energy use. Smart charging of EVs and V2G could be less available during peak commuting times but could provide off-peak power for longer durations courtesy of the large number of EVs that charge during work hours and overnight. Hybrid heating in industry could switch from electric boilers to gas power boilers for large periods of time to provide continuous flexibility, but this would require time to adjust production processes. Some data centers could provide large amounts of flexibility for sustained periods. A combination of these technologies would offer demand-side flexibility in size, availability, duration, and responsiveness.

The power system would need to change to enable demand-side flexibility

To fully unlock the potential of demand-side flexibility options would require the power system to change. Historically, grids were configured to send power to users one way, with some communication between the stages. But if "load shaping" is to work, demand and supply signals would need to be communicated between grid system operators and users in real time, and some bidirectionality in the power flow would need to be enabled. This would require hardware and software to manage and integrate the new assets into the system; behavioral changes, such as accepting the need to shift when consumers use energy-intensive assets such as EV charging and washing machines to different times of the day; implementing control measures to ensure the optimization and stability of the grid; and managing system security risks that could potentially increase as more assets can be controlled remotely.

Hardware and digital grids would need to be upgraded.[212] A smart grid is important for integrating distributed energy resources. McKinsey research finds that the grid would require smart meters, advanced transformers, controllers, and software systems for the grid to be sufficiently adaptable.[213] Progress on smart meter installation varies around the world. The United States has achieved a penetration rate of approximately 80 percent, while coverage averages about 60 percent in the EU and about 50 percent in the Asia–Pacific region, driven largely by national rollouts in China and Japan.[214] However, in many geographies, including Africa, India, and Latin America, coverage is less than 10 percent.[215] In addition to deploying hardware, software such as advanced distribution management systems can be used to monitor, control, and optimize the distribution of electricity, enhance the reliability, efficiency, and resilience of the grid, and complement upgrades in physical infrastructure.[216]

New assets would also need to be integrated. EVs and distributed energy resources would need to be incorporated into the grid and managed. This would require software such as VPP to be scaled up to manage and automate the demand response from distributed-energy-resource assets. The US Department of Energy estimates that VPP capacity could increase from 45 gigawatts to between 80 and 160 gigawatts, or the equivalent of supplying 10 to 20 percent of US peak power demand by 2030.[217]

There are some important nonphysical challenges, too. Among others, markets would need to be designed with the right price signals to encourage participation and change behavior among energy users, who would need to be willing to participate in such schemes.[218]

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This is a Level 2 challenge. Many economies are already upgrading grids, increasing adoption of distributed-energy-resource assets, and building VPPs to create flexible capacity. However, the pace would need to accelerate, and a moderate degree of transformation would be required. Moreover, some—although not all—technologies that would be needed are still only in the early stages of their deployment.

Challenge 4

Challenge 4: Securing land for renewables (Level 2)

A larger power system, in particular one with a large share of VRE, would need more land, creating a physical challenge of managing different land uses. There are also pertinent nonphysical issues, such as pushback from communities that do not want land used for renewables and permitting delays that could limit the amount of land that is available for VRE.

VRE has a different, often larger, land footprint than other energy sources but can share space with other uses

Solar and wind energy are less energy-dense power sources, which means that they have a larger land footprint per unit of generated energy than other sources when considering indirect land use—that is, land that is directly covered by a power source as well as land used indirectly to ensure that there is appropriate space between assets as well as upstream extraction of materials.

On average, total land use (including indirect use) per unit of electricity of onshore wind is about 100 square meters per megawatt-hour per year. Utility solar projects use about 20 for silicon-based panels, while cadmium-based ones use about 13. The precise amount of land needed varies widely depending on the location and the materials used. In the case of solar projects installed on the ground, the range is 10 to 30. For comparison, coal plants use about 15 square meters per megawatt-hour per year (also with a large range, and mostly arising from land use of upstream coal mining), and nuclear power uses 0.3 square meter per megawatt-hour per year.[219]

The situation is nuanced, however. Unlike other energy sources, some of the land that renewables need can often be managed with other uses. Wind farms have a large footprint in indirect land use to ensure sufficient spacing between turbines—and that land can be used in other ways. Their direct land use is relatively small at about 0.4 square meter per megawatt-hour.[220] Solar panels mounted on roofs effectively have no direct land use, and only about one to three square meters per megawatt-hour of indirect use, mostly from the mining of the minerals needed. In short, the specific ways VRE is deployed greatly influence how much land is required.

Overall, VRE needs a limited amount of all available global land, but there may be bottlenecks

Taking both direct and indirect land into consideration, most net-zero scenarios project that VRE would use less than 1 percent of global land by 2050. This would be roughly double the share currently used by fossil-fuel energy sources.[221] Accounting for natural restrictions, such as areas that are regularly flooded, and artificial structures, like urban areas, the figure is 2.5 percent of available land.[222]

This may seem a small share of land, but in many economies there are restrictions on where VRE can be deployed that could still produce bottlenecks—often related more to social acceptance and regulations than to technical feasibility—especially in economies with higher population density or poorer endowments of renewables. This is the case in some parts of Europe, Japan, and South Korea, for instance. In Germany, less than 20 percent of total land is available for onshore wind. Technical constraints, including, for instance, steep slopes that are unsuitable for VRE and environmentally protected areas, are part of the story, applying to about 6 percent of all available land. But an even larger factor is regulation that prevents VRE from being too close to where people live. This rules out 60 percent of land that would otherwise be available.[223] As a consequence, as much as 50 to 80 percent of technically available land could be needed to reach Germany's deployment targets.[224] In Italy, only about 1 percent of land is technically available for utility solar projects, and as a result almost all of it would be required. As much as 60 to 85 percent of that would be needed to meet renewable-energy source targets.[225]

Land constraints for VRE can be unlocked in a number of ways

There are a number of ways to minimize the amount of land VRE uses. One option is to choose potential multiuse sites, such as placing solar panels on rooftops or over canals, or combining onshore wind or solar with agriculture. In Europe, two-thirds of solar capacity added since 2020 has been on rooftops.[226] In Europe and the United States, farmers are sharing their cropland with wind farms. Economies that have limited technically available land could build interconnections to bring renewable power generated from other economies. Another option is co-locating solar and wind power, which can boost the project's energy density by using the indirect land that wind needs, but this would depend on favorable operating conditions. Innovation could also help. If the efficiency of VRE continues to improve—from 2010 to 2022, solar efficiency increased 1.5 times—the amount of land needed would decline.[227] Finally, the amount of land available would rise if regulations across regions were harmonized in a way that reconsiders limitations on the development of renewable energy supply near settlements.[228]

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This is a Level 2 challenge. The amount of land devoted to VRE would need to expand at a rapid pace to match accelerating deployment. To address this challenge, a combination of options could be needed. They include nonphysical aspects, such as regulatory restrictions on deployment, but also innovation and transformation of how VRE is deployed, including, for instance, improving the energy efficiency of VRE and co-locating solar and wind to mitigate the amount of land required.

In Europe, two-thirds of solar capacity added since 2020 has been on rooftops.

Challenge 5

Challenge 5: Connecting through grid expansion (Level 2)

The electricity grid is the cornerstone of the power system, and the ability to expand it to cope with rising electrification could dictate not only whether the power system can be transformed but the success of the entire energy transition.

Energy grids are massive. In the United States alone, transmission and distribution lines stretch the equivalent of the distance to the moon and back more than ten times.[229] During the energy transition, a high degree of transformation would be needed. These behemoths would need to be expanded, replaced, and transformed faster than is occurring today.

Grids would need to undergo a multifaceted transformation

As part of the energy transition, grids would need to be transformed in four main ways.

— *Larger.* Global power capacity could grow about fivefold by 2050 to absorb new technologies such as VRE—running at relatively low utilization rates—and meet increased demand for power from new use cases, including EVs and heat pumps.[230] This growth would be in the form of longer power lines as well as larger capacity, such as bigger transformers.

— *More distributed.* The makeup of the power system would change with more, but smaller, assets. For example, new utility solar fields have about one-quarter of the generation capacity of coal plants; more sites would therefore be needed with a greater number of transmission lines to connect to the grid.[231]

— *More dispersed.* Some VRE, such as offshore wind, is further from population centers and therefore would require longer transmission routes.[232]

— *More regionally interconnected.* Because of the need for more flexibility to be built into the power system, more interconnections among different economies and regions would be needed, and this would require additional transmission lines.

The size of the grid may need to double or quadruple and to scale faster than it is today

Over the past decade, global electricity grids have grown by about one-quarter at a pace of about 2 percent per year, from just over 60 million to just under 80 million kilometers.[233] Advanced economies and China, in particular, have accelerated grid expansion, but the pace needs to be even faster in the future in order to keep up with the needs of the transition and expanding access to energy.[234] Projections for the required scale-up by 2050 vary widely, but all agree on the need for this to happen quickly. Estimates forecast a two- to threefold increase in the length of the global grid by 2050.[235] The International Energy Agency, for instance, projects that the volume of transmission and distribution lines would need to almost triple, or grow by more than 3 percent per year. That implies accelerated deployment at a pace that is 40 to 50 percent faster than over the past ten years.[236]

In emerging markets where access to power is still far from universal and where economies are posting relatively robust growth, the grid would need to grow especially fast. Overall, 80 percent of gross global additions between now and 2050 are expected to be in emerging markets and developing economies.[237] At the same time, a large part of the existing grid also needs to be replaced. In the United States, it is estimated that 70 percent of transmission lines are over 25 years old and would need to be replaced within ten to 20 years.[238]

Increasing the size of the grid is only part of the story—it would also need to be smarter to coordinate the various parts of the system and optimize for reliability, flexibility, resilience, and stability. This might include monitoring real-time information to support the matching of supply and demand as VRE introduces more variability and intermittency. It would also include supporting the coordination of distributed energy resources and facilitating demand-side flexibility strategies, such as time-of-use pricing.

The required pace of expansion and replacement would be testing. Lead times for the permitting and construction of transmission lines in mature markets such as the EU and the United States have tended to be between five and 15 years, compared with one to seven years to build renewable assets.[239] Among the reasons for extended lead times are issues about where to site plants and operations and, in particular, lack of social acceptance and limited access to rights-of-way.[240] In other economies, such as China and India, lead times have tended to be shorter, at about two to six years. Important components of the grid could face shortages due to manufacturing bottlenecks. For instance, many newer, larger transformers would be required, and their production has faced constraints.[241]

Various measures would help address issues about grid expansion but would require a large transformation

More ambitious grid plans and approaches that accelerate the ability to deploy them would be needed for a successful energy transition. The United States is one of many countries that are putting in place targets to ensure that grid expansion and replacement both happen. The US Department of Energy has launched a Building a Better Grid initiative with the aim of accelerating the deployment of transmission in high-priority areas. One of the key features of this plan is a more streamlined permitting process. It is also considering modernization of the grid, with $20 billion allocated to states and utilities to be split equally between grid expansion and resilience.[242] Additional interconnections are also required. The EU is proposing new legislation focused on grid expansion and digitalization to connect VRE, and the European Network of Transmission System Operators for Electricity is coordinating the expansion of interconnections on a smart grid across 39 European transmission system operators.[243] In China, the National Development and Reform Commission has announced plans to establish a unified national power market by 2030, merging six regional grids into a single electricity market.[244] In 2022, China invested $166 billion in its transmission grid, more than all other countries put together at $118 billion.[245]

...

This is a Level 2 challenge—and one that is vital because many other physical challenges across domains, directly or indirectly, would rely on it being addressed. The grid would need to expand significantly and faster even while modernizing, which would require a large degree of transformation. Several countries have put in place targets for grid expansion, but reaching the required pace of deployment would require new measures, notably permitting changes.

Challenge 6

Challenge 6: Navigating nuclear and other clean firm energy (Level 2)

Clean firm power sources, such as nuclear, hydro, and thermal assets with carbon capture, could be crucial pieces of a decarbonized power system. They combine low emissions with the ability to be called upon when needed and can therefore help to reduce the variability of the power system. They often have lower (or different) constraints on inputs, needing fewer critical minerals and less land than VRE, and their infrastructure needs are also different from VRE. Moreover, some types of clean firm power, including nuclear fission, have already demonstrated their potential to scale up rapidly and serve as a significant source of power.[246]

Several options exist, and a mix of technologies could be pursued. Overall, the pace of transformation in deploying these options would need to accelerate. For all their benefits, clean firm power sources face two main hurdles. First, many of them are nascent. For example, small modular reactors, carbon capture, or even much more nascent nuclear fusion still have meaningful technological uncertainty. Second, even mature technologies, such as large-scale nuclear fission and hydropower, face deployment constraints. In the case of the former, for example, a number of physical hurdles related to large and complex engineering projects would need to be addressed.

Clean firm power can help reduce power system variability

Expanding the different sources of clean firm power would help to address the other physical challenges in the power domain (see Sidebar 4, “Different types of clean firm power”). A combination of clean firm power and VRE could enable a power system that is less variable and reduce the need to build an oversize system.[247] One study found that, in California, every megawatt of clean firm power installed could reduce new VRE capacity needed by ten megawatts even while cutting the degree of variability.[248] This would especially help emerging power systems that do not have existing thermal generation assets that can support the provision of firm power, as discussed in Challenge 2, to grow while adopting VRE.

Between 1970 and 1995, the share of nuclear fission in total power generation globally increased from 2 to 18 percent.

Sidebar 4. Different types of clean firm power

Most net-zero scenarios assume rapid scale-up of clean firm power sources, although estimates vary widely. In McKinsey's 2023 Achieved Commitments scenario, for example, total clean firm power would scale by 2.5 times between 2022 and 2050, from about 1,800 gigawatts to 4,500 gigawatts.

Clean firm power capacity could come from a number of sources. While promising, each faces numerous physical barriers, ranging from technological immaturity to competition for inputs, that would need to be overcome.

Biomass. Burning organic matter from plants and animals creates heat that can be used to make steam to generate electricity, which can offer a low-emissions source of power.[1] The largest physical challenge is ensuring that sufficient land is available to grow feedstock in the face of competing demand, such as from agriculture to grow food. There is competition, too, for the biomass itself, often from sectors whose emissions are hard to abate. Biomass could be turned into sustainable fuels in sectors such as aviation and cement (as a source of heat) and even used as a feedstock for plastics. One positive is that not all biomass requires land where there are competing demands. The EU, for instance, is updating regulation to promote the use of advanced biofuels mainly produced from waste and residue instead of conventional biomass.[2]

Fossil-based generation with CCUS. Gas power plants could be paired with carbon capture, use, and storage (CCUS) to capture emissions. This would require solving the physical challenge of natural gas fumes having low concentrations of CO_2, which makes it harder to capture (see Challenge 24 on capturing point-source carbon). However, as innovation proceeds with technologies such as oxyfuel precombustion and adsorption capture, and as gas systems improve, gas with CCUS could play a role in providing clean firm capacity.[3] Of course, upstream emissions related to extraction of natural gas would also need to be abated.

Geothermal. Conventionally, hot water or steam is piped to the surface to generate electricity or heat, usually by turning turbines. The key challenge is the dependency on naturally occurring underground reservoirs of hot water or steam and the permeability of surrounding rock formations so that fluids can flow through at relatively high rates. These conditions tend to exist in specific locations, such as areas with high levels of volcanic or tectonic activity. This issue could be overcome by building enhanced geothermal systems, artificial geothermal reservoirs in areas that have thermal energy but lack adequate permeability, water, or both, and by pumping subsurface water using techniques similar to hydraulic fracturing, as in oil and gas extraction. Today, this technology is in the early stages of development, but progress is rapid.[4]

Hydrogen and other low-emissions fuels. Traditional gas turbines can be converted to use hydrogen as fuel, which can be burned without emitting CO_2 (see chapter 10 on the hydrogen and energy carriers domain).

Hydropower. Hydropower is mature and economical, but its supply can be limited by reduced rainfall or drought.[5] The EU and the United States have few remaining sites, and there are some environmental and social concerns.[6] But according to McKinsey's 2023 Achieved Commitments scenario, in some economies in Africa and Asia, capacity could grow 2.3 times by 2050, compared with 1.1 times elsewhere.

Nuclear fission. Heat from splitting an atom is used to make steam that spins turbines to produce electricity (see the following discussion).

Nuclear fusion. When two atomic nuclei are fused, huge amounts of energy are released, producing heat for steam used to generate power. Were fusion to be achieved at scale, it could produce firm, low-emissions energy without creating long-lived nuclear waste from spent fuel. Deploying fusion as a meaningful part of the energy transition has been nearly impossible for decades, and the future is highly uncertain. Thus far, fusion machines consume more energy than they create. Moreover, the equipment needed is tremendously complex, including the world's most advanced magnets, materials that can withstand the intense temperatures on the machine's inside wall that are hard to make, and submillimeter precision for machined parts several meters across. Many notable advances in fusion have been achieved and private investment in it has surged, but substantial uncertainty remains about both feasibility and timelines.[7]

1 Burning biomass releases CO_2 that had been taken out of the atmosphere through photosynthesis and therefore does not lead to a net addition of CO_2 as would be the case when fossil fuels are burned.
2 *Biomass*, European Commission, accessed May 2024.
3 Jamie Brick, Dumitru Dediu, and Jesse Noffsinger, "The role of natural gas in the move to cleaner, more reliable power," McKinsey, September 2023.
4 GeoVision, Geothermal Technology Office, Office of Energy Efficiency & Renewable Energy, US Department of Energy; and *Pathways to commercial liftoff: Next-generation geothermal power*, US Department of Energy, September 2023.
5 *Hydropower special market report, analysis and forecast to 2030*, IEA, June 2021.
6 For example, hydroelectric dams and their reservoirs can generate substantial amounts of greenhouse gases, notably methane, as organic matter that is flooded and, when submerged, decomposes. However, in general, hydropower emissions tend to be lower than for fossil-fuel-based power, and there are a number of measures that could reduce emissions that relate, for instance, to water level and vegetation management. See, for example, Ilissa B. Ocko and Steven P. Hamburg, "Climate impacts of hydropower: Enormous differences among facilities and over time," *Environmental Science & Technology*, November 2019; and Henriette I. Jager et al., "Understanding how reservoir operations influence methane emissions: A conceptual model," *Water*, volume 15, issue 23, November 2023.
7 Miklós Dietz, Bill Lacivita, Amélie Lefebvre, and Geoff Olynyk, "Will fusion energy help decarbonize the power system?" McKinsey, October 2022.

Another advantage of clean firm power is that it needs less land than solar or wind. For example, nuclear and gas with carbon capture would need less than 1 percent and 25 percent, respectively, of the land required to produce the same amount of power as VRE, considering indirect land use.[249] The extent to which grids would need to scale could also be reduced with clean firm power, which would be less modular and, for some sources, less constrained to specific locations and therefore closer to population centers.[250]

Also beneficial is the fact that many forms of clean firm power have lower critical minerals intensity than VRE. Nuclear, for instance, needs five tonnes of critical minerals per megawatt, compared with seven in the case of solar and ten in the case of onshore wind.[251] Of course, clean firm technologies have their own input requirements in the form of fuels. Nuclear needs uranium, while biomass or fossil fuels are required for other clean firm thermal-based power plants.

Nuclear fission is a mature technology that can provide additional clean firm capacity but faces some hurdles

Of the various clean firm sources of power, large-scale nuclear fission combines both technological maturity and concrete commitments from many economies to scale deployment further. At COP28 in 2023, a group of economies announced commitments to triple capacity by 2050.[252] This section takes a closer look at the physical challenges associated with expanding the deployment of nuclear power.

Nuclear fission has already demonstrated its potential to be a significant source of firm clean power. Between 1970 and 1995, nuclear energy's share of total power generation globally increased from 2 to 18 percent, the largest rise in share of any clean power source.[253] Deployment peaked at 23 gigawatts a year between 1981 and 1990 before declining to about six gigawatts a year from 2011 to 2022.[254] In this period, the geographic mix also changed. While some advanced economies made material additions to capacity—South Korea by 25 percent—85 percent of additions to nuclear capacity between 2011 and 2020 was in emerging and developing economies. Of these, China stands out with a fourfold increase in capacity, and Russia with 25 percent. The United Arab Emirates connected its first reactor in 2020.[255]

However, nuclear expansion would require overcoming a range of physical barriers, including the following:

— *Complex engineering and design.* Engineering plans are often unique to each site, and project teams can choose from as many as 20 different reactor models. Because projects are so different, there are fewer learning opportunities for improving the next one.

— *Inefficient planning and construction.* Because they have tended to be bespoke, new nuclear projects—especially in the United States and Western Europe—have faced planning and construction challenges. Without a consistent pipeline of standardized nuclear projects, it is difficult to pass on expertise and lessons to the next project.

— *Nuclear waste.* Currently, the amount of nuclear waste generated is relatively small. In the United States, which is the largest nuclear energy producer in the world, waste each year amounts to less than half the volume of an Olympic-size swimming pool.[256] Nonetheless, spent fuel rods that have been removed from the reactor core remain highly radioactive and continue to generate large amounts of heat for decades, and they therefore need to be managed. Some countries, including France, reprocess nuclear fuel, and advances in reactors could increase reuse.[257] However, storage options would also be needed. In the near term, spent nuclear fuel is usually stored on-site at nuclear power plants in cooling pools and dry cask storage systems. In the United States, for instance, the Nuclear Regulatory Commission licenses dry cask storage systems for 40 years and allows license renewals for 40 additional years.[258] Over the long run, solutions such as deep-geological waste storage facilities would be required. Finland started construction in 2016 on the world's first site, which is expected to begin operations in the mid-2020s.[259]

— *Shortage of labor for construction and operations and maintenance.* McKinsey estimates that the nuclear industry employs about 600,000 people in Canada and the United States, and in these two economies alone, this would need to increase to one million to support an increase in capacity to 50 gigawatts a year.[260]

- *Siting requirements.* Finding the right location for a nuclear plant depends on a range of physical factors such as access to the grid, the presence of cooling water, safety and navigating public misgivings about safety, nuclear waste disposal, and proliferation.[261]
- *Specialized supply chain.* Nuclear has a limited and fragmented supply chain for components, with stringent standards for many parts of different designs. A brand-new supply chain would need to be developed to support more standard and modular designs.[262] Furthermore, the supply of uranium, the key input, would need to be secured.

These physical barriers have often contributed to the construction delays and cost overruns frequently associated with new nuclear projects. Addressing them could make nuclear power more competitive.[263]

Economies that are scaling nuclear have found ways to overcome key challenges
As of early 2024, about 35 economies had nuclear power plants that were active or under construction.[264]

Asian economies account for 50 percent of current nuclear capacity being constructed.[265] They have demonstrated how to overcome some key challenges. For instance, they have opted for standardization and back-to-back builds. Between 1989 and 2005, South Korea constructed 12 reactors in quick succession, eight of which were the same model (OPR-1000).[266] The average construction period was 56 months, more than three times faster than the historical average period in other economies. This repeat build in a short time frame increased the pace of learning across projects while developing a robust and skilled labor force and supply chain. Construction delays in China and other East Asian economies have been two to three years, compared with four years in Europe and six in the United States, where some recent projects have been delayed by as much as eight years.[267]

Technology could also play a role in overcoming physical challenges. Smaller-scale Gen-III+ reactors that are modularized could be ready by 2030. These reactors could reduce construction time to three to four years from more than six in the case of Gen-III a. Gen-IV are more fuel-efficient reactors that could be ready after 2030, with the potential to be built in less than four years.[268] In addition, innovation in ways to process spent fuel into a source of fuel could alleviate concerns about nuclear waste.[269]

...

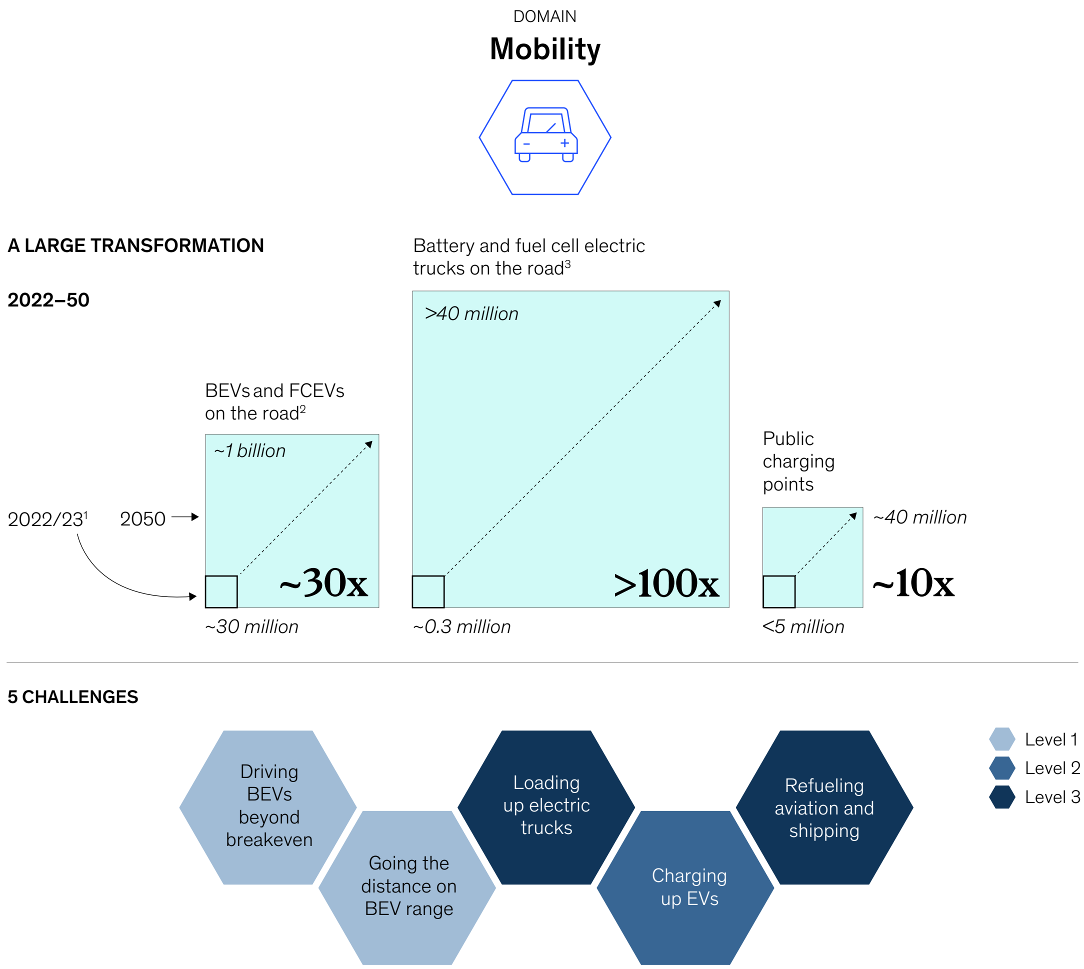
This is a Level 2 challenge. Expanding clean firm power capacity would require an acceleration in the pace of deployment of nuclear, among other sources. In the case of nascent technologies, such as enhanced geothermal, the lack of maturity creates uncertainty about the technological pathway ahead. These technologies would need continued innovation to attain their required performance and scale up. In the case of more mature technologies, such as nuclear, the scale of transformation required, combined with input and infrastructure requirements, is the key issue. There are proven ways to scale these technologies—more quickly, for example, through standardization of nuclear designs and back-to-back plant builds—but more effort would be required to do so.

Asian economies account for 50 percent of current nuclear capacity being constructed.

Electric car charging

6. Mobility

Coauthored with Timo Möller



Note: This research examines 25 significant physical challenges in seven domains at the core of the energy transition, categorized in three levels. Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning. The focus is on physical realities because they influence the ability to design an interdependent system that has performance comparable to that of the current system and to reduce emissions feasibly. These factors influence cost and affordability. Nonphysical factors—notably cost—are important but are not the focus of this research. Assessment of required deployment of technologies primarily draws on McKinsey's 2023 Achieved Commitments scenario, which assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and in which warming reaches 1.6°C relative to preindustrial levels by 2100. This scenario is used because it provides sufficient regional and sectoral granularity for assessing required deployment. In some instances, this research also uses scenarios from other sources for reasons of data availability.
[1]BEVs and FCEVs on the road are for 2023.
[2]BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. Vehicles included are passenger vehicles, trucks, light commercial vehicles, and buses.
[3]Battery electric and fuel-cell-powered medium- and heavy-duty trucks.
Source: *Global energy perspective 2023,* McKinsey; International Energy Agency; McKinsey Global Institute analysis

Mobility accounts for about 21 percent of the global CO_2 emissions in the energy system, with road mobility representing the bulk of these, at about 17 percent.[270] The remaining 4 percent comes primarily from aviation and shipping. While there are significant physical challenges with decarbonizing aviation and shipping, we focus here on the challenges associated with decarbonizing road mobility, given its large contribution to emissions (see Challenge 11 in chapter 2 for a brief discussion of the physical challenge associated with decarbonizing aviation and shipping).

Driving from place to place is an integral part of our daily lives—for work, shopping, meeting friends and family, recreation, and moving goods from place to place. The large share of road mobility in global emissions reflects the enormous fleet of 1.5 billion internal-combustion engine vehicles, or ICEs, on the road today. These vehicles collectively drive nearly 15 trillion kilometers a year.[271] Passenger cars account for about 85 percent of vehicles on the road and about half of emissions from road mobility.[272] The remaining share of emissions comes from light commercial vehicles, trucks, and buses, with a small portion made up of emissions from two- and three-wheelers.[273] These various types of vehicles are used in very different ways, and those uses vary by region, from long commutes from the suburbs to the cities in the United States, to zipping through the crowded streets in Delhi, to hauling tonnes of cargo across entire countries.

In these use cases, the vast majority of vehicles on the road today are powered by fossil fuels. These fuels offer many advantages: they have high energy density, are fast to refuel, and are relatively easy to transport and store. But vehicles powered by fossil fuels are relatively energy inefficient. Even best-in-class ICE vehicles in the United States convert only about 15 to 30 percent of the energy stored in gasoline to useful work at the wheels.[274] They also emit a great deal of CO_2.

The energy transition in road mobility would require shifting the vast stock of ICE-based vehicles on the road toward lower-emissions options that use both demonstrated and evolving technologies.

Two notable solutions are battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) powered by hydrogen.[275] Over the past decade, sales of BEVs, in particular, have experienced rapid growth. More recently, momentum has slowed in some regions. For example, in the United States, BEV sales increased by around 40 percent in 2023, but this was slower than in the previous two years. In the first quarter of 2024, sales rose by about 3 percent year over year, again, below the previous two years.[276]

There would need to be a large scale-up of BEVs and FCEVs under the energy transition. In McKinsey's 2023 Achieved Commitments scenario, about 270 million of these vehicles (all types) would be needed on the road by 2030, and about one billion by 2050.[277] Current deployment of EVs is only 3 percent of what would be required by 2050. In this scenario, sales of low-emissions vehicles would surge from more than 15 percent of new vehicles today to more than 75 percent in 2030 and to almost 100 percent by 2050. In some segments, the increase in sales of low-emissions vehicles relative to today's levels would likely be especially large. For instance, there are very few electric medium- and heavy-duty trucks on the road today, but by 2050 there could be more than 40 million—about 65 percent of all medium- and heavy-duty trucks operating in that year.[278]

Besides driving down emissions, the electrification of mobility could unlock efficiency gains. For example, BEVs can convert more than 80 percent of the energy in the batteries to useful work at the wheels.[279]

Advances are being made, and investment in critical EV infrastructure and supply chains that would be required is accelerating, though more in some regions than others. China already has more public EV-charging points than the rest of the world put together and is expected to account for 50 percent of worldwide battery capacity additions in the period to 2030.[280]

But physical challenges remain. Four physical challenges need to be addressed to ensure the decarbonization of road mobility: (1) driving BEVs beyond breakeven; (2) going the distance on BEV range; (3) loading up electric trucks; and (4) charging up EVs.

The first two challenges, relating to passenger EVs, are categorized as Level 1 physical challenges, defined as requiring progress in deploying established technologies and facing the least hurdles. Scaling the infrastructure and supply chains required to support EVs is a Level 2 challenge: accelerated progress and a relatively high degree of transformation are needed. Road mobility also has a Level 3 challenge: the use case is hard and the transformation is just beginning. In trucking, current battery density is not high enough to support all use cases of vehicles with large payloads traveling over long distances—an example of a property gap colliding with a difficult use case. At the same time, scaling FCEVs for trucking is dependent on the build-out of the hydrogen supply chain and the hydrogen-refueling infrastructure.

This report focuses on decarbonization relating to the adoption of EVs, because this is expected to be the main lever for reducing emissions, and there are large physical challenges in this area. This research does not explore in detail other ways to decarbonize road mobility that either are based on improvements in energy efficiency, including improvements in existing fossil fuel technologies, such as ICE engines (covered in Challenge 23), or entail behavioral changes, including modal shifts related to new or existing technologies (see Sidebar 5, “Modal shifts can support the decarbonization of mobility”).

Similarly, we do not explore in detail hybrid-vehicle technologies that combine an internal-combustion engine with an electric propulsion system. But hybrids, too, may play some role in the decarbonization of road mobility (see Sidebar 6, “Hybrids can also support the decarbonization of mobility”).

The first two challenges, relating to passenger EVs, are categorized as Level 1 physical challenges.

Sidebar 5. Modal shifts can support the decarbonization of mobility

A mobility decarbonization measure being considered is to shift not only the power train of the vehicles in which people travel (from ICE to electric) but also their very mode of travel. Mobility could be transformed if there were a significant shift in the use of private cars in urban areas to other, lower-emissions and higher-utilization modes of travel (Exhibit 23). Globally, on average, about 45 percent of passenger-kilometers traveled today are by private car.[1] However, previous McKinsey analysis suggests that—given regional trends and shifting consumer preferences for travel, and assuming that the appropriate alternate modes of transportation are developed—this share could fall to 29 percent by 2035 under McKinsey's 2023 Achieved Commitments scenario.[2]

Part of the shift in this scenario would be toward existing technologies, including public transportation, shared mobility, and micromobility (for example, motorcycles, e-bikes, and e-scooters). All would entail large shifts in how people travel, and that, in turn, would require behavior to change and the development of associated infrastructure, such as building new modes of public transportation and carving out more bike lanes in cities.

New technologies that are anticipated to come on the market in coming years could also make it easier to shift how people travel. Autonomous vehicles could be on the market at scale by 2030, with a range of applications. For example, robo-shuttles (shared autonomous minibuses with four to ten seats) could pool travelers.[3] Mobility-as-a-service applications could make mixed-mode traveling easier, for example by creating an itinerary for public transportation, shared mobility services, and parking lot services in one app that requires a single payment.[4] Again, all of this would require continued innovation in new technologies and the build-out of appropriate infrastructure.

Other modal shifts could also play a role in decarbonizing mobility more broadly. Shifting freight transportation from trucks and planes to lower-emissions options such as rail or ships is being considered to reduce emissions from freight transportation. Of course, this would also involve developing new routes and building associated infrastructure.

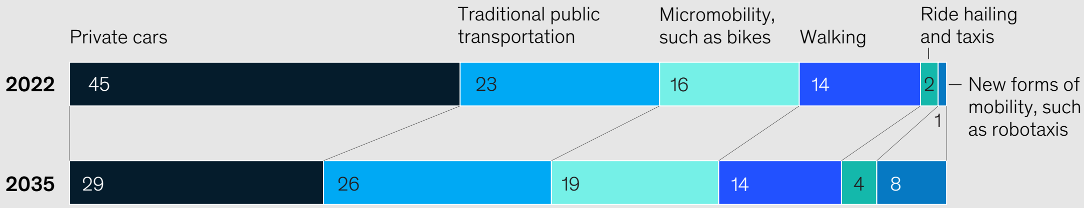
In summary, while there may be potential to reduce emissions by shifting how people travel, there would still be physical challenges to overcome.

Exhibit 23

Private cars are currently the most popular transportation option for passengers, but their share of total mobility could decline.

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO

Mobility split by mode of transportation worldwide, % of passenger kilometers



Note: Figures may not sum to 100% because of rounding.
Source: McKinsey Center for Future Mobility; McKinsey Global Institute analysis

1 "The big picture: Worldwide mobility in 2035," *McKinsey Quarterly*, April 19, 2023.
2 Ibid.
3 Kersten Heineke, Ruth Heuss, Philipp Kampshoff, Ani Kelkar, and Martin Kellner, "The road to affordable autonomous mobility," McKinsey, January 2022.
4 Riccardo Boin, Timo Möller, Vadim Pokotilo, Andrea Ricotti, and Nicola Sandri, "Infrastructure technologies: Challenges and solutions for smart mobility in urban areas," McKinsey, March 2023.

Sidebar 6. Hybrids can also support the decarbonization of mobility

Hybrid vehicles may also play an important role in the decarbonization of road mobility. The following are the four main types of hybrid vehicles:

1. Mild hybrids (MHEVs). These are the entry point to electric powertrain technologies. A low-voltage system (mostly 48 volts) enables the use of efficient electrification elements, such as start-stop, regenerative braking, and some level of power assist. MHEVs typically use a relatively small battery pack, primarily charged through regenerative braking and excess power generated by the ICE. They usually do not have an exclusive electric-only mode of propulsion.

2. Hybrid electric vehicles (HEVs). These are designed to optimize the use of the ICE through an interplay with a small low-range electric powertrain for low-speed cruising or a power boost. HEVs are similar to MHEVs in battery size and how the battery is charged.

3. Plug-in hybrid electric vehicles (PHEVs). These have an architecture similar to that of HEVs but a significantly larger battery. Notably, however, that battery is still only about one-fifth the size of a BEV battery. PHEVs also have a more powerful electric engine and can be recharged by plugging into an external source of power. They are designed for a significant share of pure electric driving and typically offer a range of around 80 kilometers. In some regions, such as China, where PHEV batteries tend to be larger, some vehicles can achieve ranges of up to 100 kilometers.[1]

4. Other hybrids. Other new types of hybrids include range-extended EVs (REEVs), which combine a battery with an auxiliary power unit to extend the driving range. This is typically a small ICE that functions as a generator to produce electricity, although in the future the same role could be played by a fuel cell. When the battery's charge is low, the ICE activates, recharges the battery, and extends the vehicle's range. Unlike other types of hybrids, REEVs draw most of their power from the battery rather than the ICE engine.

The role of hybrids in the energy transition is debated. They still generate tailpipe emissions and carry the risk that not enough decarbonization is achieved to align with global decarbonization goals, or that they are not achieved quickly enough. But hybrids can be used as a bridging solution on the path to the widespread adoption of full EVs. Over the course of their lifetimes, hybrids are generally expected to produce emissions that fall between those of ICE vehicles and BEVs (considering all sources of emissions, including manufacturing and running the vehicles). For example, the IEA estimates that a medium-sized PHEV in the United States could produce about 55 tonnes of CO_2-equivalent emissions over its life cycle, approximately the midpoint between the emissions of a comparable ICE (75 tonnes) and a BEV (27 tonnes).[2] Of course, these values vary significantly, depending on a range of factors, which are explored in the next section.

Moreover, in the short to medium term, hybrids may help address some of the challenges associated with BEVs explored in this chapter. Hybrids may disrupt consumer lifestyles less and therefore encourage consumers to switch away from ICEs. For example, hybrid vehicles, particularly PHEVs, combine the benefits of electric propulsion with the extended driving range provided by ICEs, potentially alleviating consumer concerns about current limits on BEV range. They may still provide an emissions benefit relative to ICEs by enabling drivers to depend on battery power for frequent short journeys and to utilize the power of the combustion engine on longer journeys. Hybrids can leverage the existing infrastructure for gasoline refueling—a particularly important feature while BEV charging infrastructure is limited. In 2024, the McKinsey Mobility Consumer Pulse surveyed more than 35,000 people worldwide who regularly use mobility. The survey revealed that among respondents not considering switching to EVs, the top reasons cited were high cost of ownership (45 percent), charging concerns (33 percent), and range concerns (29 percent). About the same percentage of respondents who do not currently own an EV are considering buying a PHEV and a BEV as their next vehicle (18 and 20 percent, respectively).[3]

Many proponents of hybrids point out that demand for the critical minerals needed for full EVs—such as lithium, cobalt, nickel, and graphite—is likely to exceed supply in the short to medium term (see chapter 9 on the raw-materials domain) and that the volume of minerals used in a single BEV could power several PHEVs. A single BEV may have lower lifetime emissions than a single hybrid vehicle, but there is potential for the broader adoption of hybrids, so using them could achieve greater overall emissions reductions.[4]

1 Andreas Cornet, Russell Hensley, Carsten Hirschberg, Patrick Schaufuss, Andreas Tschiesner, Andreas Venus, and Julia Werra, "Reboost: A comprehensive view on the changing powertrain component market and how suppliers can succeed," McKinsey, November 2019; Loren McDonald, "BEV batteries average 83 kWh versus 15 kWh for PHEVs," EV Statistics, April 2022; and "Electric vehicle sales headed for record year but growth slowdown puts climate targets at risk according to BloombergNEF report," BloombergNEF, June 12, 2024.

2 This is based on the following assumptions—vehicle characteristics: country of purchase (United States), average mileage (61 kilometers per day) and vehicle lifetime (15 years). ICE characteristics: fuel consumption (7.4 liters per 100 kilometers). PHEV characteristics: utility factor (30 percent of kilometers traveled on battery power) and fuel consumption (6.2 liters per 100 kilometers). BEV characteristics: BEV range (300 kilometers) and power consumption (22.3 kilowatt-hours per 100 kilometers). Energy supply: electricity emissions (under IEA Stated Policies scenario). See EV Life Cycle Assessment Calculator, IEA, accessed June 2024.

3 MCFM Mobility Consumer Insights, Annual MCFM Mobility Consumer Survey 2024, McKinsey Center for Future Mobility, February 2024.

4 "Toyota's goal: Reduce carbon emissions as much as possible, as soon as possible," Toyota Motor Corporation, April 2023; Tom McParland, "This is why Toyota isn't rushing to sell you an electric vehicle," Jalopnik, May 17, 2023.

Challenge 7

Challenge 7: Driving BEVs beyond breakeven (Level 1)

ICE passenger vehicles today account for substantial emissions. Burning a single liter of gasoline can lead to tailpipe emissions of more than two kilograms of CO_2.[281] BEV alternatives have no direct tailpipe emissions but still emit CO_2 over their lifetimes. Ensuring that the technology and power systems underpinning BEVs have lower emissions over their lifetimes than ICEs would be vital if the new road mobility system is to deliver on emissions reduction goals.[282]

Emissions from BEVs and ICE vehicles include those generated during their production (manufacturing emissions) and those produced to power the vehicles over their lifetimes (running emissions). For ICEs, running emissions include well-to-wheel emissions associated with the production and burning of fossil fuels. For BEVs, running emissions include indirect emissions associated with the production of the electricity they use, including any upstream emissions associated with the production of the technologies or fuels that are used to generate power.[283]

Although BEVs have higher manufacturing emissions than ICEs, they have lower running emissions per kilometer when they are driven. BEVs thus start their lives with a larger emissions footprint, but then the more they are driven, the lower their total emissions relative to ICEs. If BEVs are driven far enough during their lifetimes, they reach a carbon breakeven point, at which their total emissions—both manufacturing and running—fall below those of comparable ICEs. Beyond this point, BEVs achieve carbon savings relative to ICEs, with lower total lifetime emissions. The core physical challenges here are to ensure that the breakeven point occurs at as short a distance as possible and that the lifetime emissions of BEVs are far lower than those of ICE vehicles.

Three key factors determine BEVs' carbon breakeven point and carbon savings

The carbon breakeven point and overall carbon savings of a BEV passenger vehicle are determined by three key factors: manufacturing emissions; running emissions (that is, emissions per kilometer driven); and total lifetime distance traveled—all in comparison with similar ICE vehicles.

Consider how these factors may play out for illustrative grids with relatively higher and lower emissions intensities (Exhibit 24)[284]:

Although BEVs have higher manufacturing emissions than ICEs, they have lower running emissions per kilometer when they are driven.

Exhibit 24

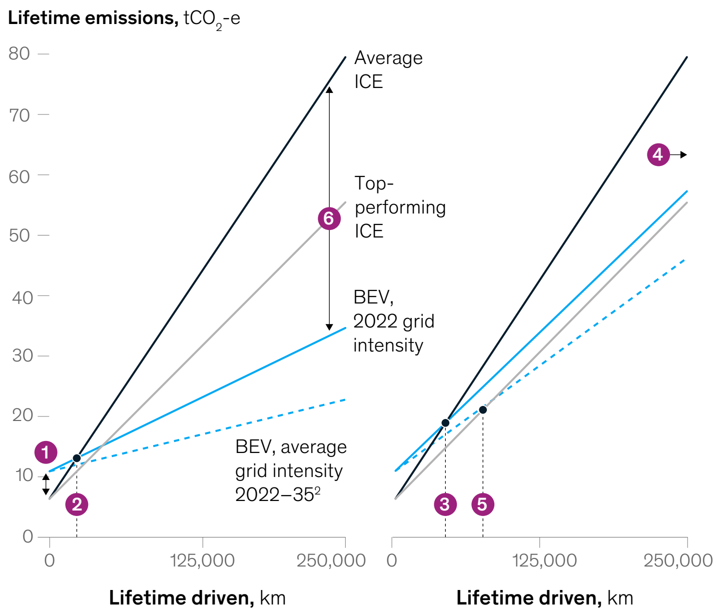
BEV carbon breakeven depends on manufacturing and running emissions and distance traveled.

CHALLENGE

7 Driving BEVs beyond breakeven

EXAMPLE 1: EARLIER BREAKEVEN
Average BEV replaces average or top emissions-performing ICE vehicle operating in a lower-emissions grid[1]

EXAMPLE 2: LATER BREAKEVEN
Average BEV replaces average or top emissions-performing ICE vehicle operating in a higher-emissions grid[1]



1. **Manufacturing emissions** (starting point before the car is driven) are higher for BEVs than for ICE vehicles, mostly due to emissions associated with battery manufacturing. These may fall over time
2. **Running emissions are generally lower for BEVs than ICE vehicles**; therefore, their trajectories intersect and BEVs achieve carbon breakeven against ICE vehicles
3. **In more emissions-intensive grids,** carbon breakeven is reached later in a vehicle's lifetime
4. **Comparing against top emissions-performing ICE vehicles** instead of average ones similarly delays carbon breakeven (if it is reached at all)
5. **Decarbonization of today's grids throughout a vehicle's lifetime** could lead to earlier breakeven
6. **Beyond breakeven, carbon savings are accrued** as the vehicle covers greater distances over its lifetime

[1]Assumes typical US manufacturing emissions, and tailpipe emissions based on US Environmental Protection Agency reporting. Lower-emissions grid is based on US generation mix; higher-emissions grid is based on Indian generation mix. 2022 grid emissions assume that the carbon intensity of the grid stays stagnant throughout the lifetime of the vehicle. BEV = battery electric vehicle; ICE = internal combustion engine.
[2]The dashed line represents average grid intensity decreasing throughout a vehicle's lifetime, in this example 2022–35. Based on McKinsey Power Model projections in McKinsey's 2023 Achieved Commitments scenario.
Source: European Environment Agency; US Environmental Protection Agency; GREET model (Argonne National Laboratory); Climate Transparency; McKinsey Center for Future Mobility; McKinsey Global Institute analysis

— *Manufacturing emissions.* BEVs have higher manufacturing emissions than ICEs, largely due to the emissions intensity of battery manufacturing. During their manufacture, passenger BEVs generate approximately eight to 12 tonnes of CO_2-equivalent per vehicle—up to double the up-front emissions of passenger ICE vehicles. This difference is illustrated in the left-hand panel of Exhibit 24 by the vertical intercepts of the BEV and ICE emissions trajectories (point 1).[285]

On average, about half of the manufacturing emissions associated with BEVs come from battery manufacturing and the balance from other components, such as energy use tied to manufacturing the vehicles and upstream processing of metals or components.[286] The exact emissions from battery manufacturing vary depending on several factors, including the battery capacity, battery type, specific materials used, where those materials are sourced, and the mining practices involved. (And, of course, these emissions may fall over time).

— *Running emissions.* BEVs have lower running emissions than ICE vehicles. For example, BEVs running on a US grid typically have 35 to 50 percent lower running emissions per kilometer than even a top-performing ICE vehicle.[287] In Exhibit 24, the slopes of the vehicle emissions trajectories capture their running emissions. The BEV trajectories are flatter than those of ICEs because the addition to lifetime emissions is smaller per additional kilometer driven.

The exact difference in running emissions between BEVs and ICEs depends on how clean or dirty the power grid is where the BEV is driven, as well as the efficiency of the vehicles being considered (influenced by factors such as their size and weight).[288] In Exhibit 24, the grid powering the BEV in the left-hand panel is about half as emissions intensive as the grid in the right-hand panel.[289] The cleaner the grid, the flatter the BEV trajectory. For the lower-emissions grid, the BEV carbon breakeven point against an average ICE—where the emissions trajectories intersect—is reached relatively quickly, at about 25,000 kilometers (point 2). Under the higher-emissions grid, breakeven is reached at about 45,000 kilometers (point 3).

The BEV carbon breakeven point also depends on the efficiency of the ICE vehicle the BEV displaces. An ICE vehicle with top mileage performance may produce running emissions about 40 percent lower than those of an average-performing one.[290] In the example considered in the right-hand panel of Exhibit 24, the combination of a more emissions-intensive grid and the comparison with a top-performing (rather than average) ICE means that breakeven may not be reached even after 250,000 kilometers (point 4). In this example, a BEV could therefore have higher rather than lower lifetime emissions than an ICE.

In reality, however, grids are decarbonizing over time.[291] This means that even a BEV put on the road today would, over the course of its lifespan, run on a grid that could be progressively less emissions intensive. If grids decarbonize in line with stated climate commitments, even an average BEV starting on a high-emissions grid today could break even against a top ICE by about 85,000 kilometers in this example (point 5).

— *Lifetime distance traveled.* Once the breakeven distance is crossed, the longer a BEV is driven, the greater its carbon savings against an ICE. In the left-hand panel in Exhibit 24, a BEV running on a relatively low-emissions-intensive grid, in comparison with an average ICE, accumulates carbon savings of about 25 percent after 50,000 kilometers and 55 percent by 250,000 kilometers (point 6). For reference, in the United States the average passenger vehicle is driven more than 200,000 kilometers over its lifetime. Even the least-driven vehicles (first quartile) cover up to 150,000 kilometers, while the most-driven ones (third quartile) cover up to over 250,000 kilometers.[292] Recently released BEVs are expected to be able to reach such distances without needing battery replacements, therefore avoiding additional battery-manufacturing emissions. For example, in the United States, BEV battery warranties are set at a minimum of 160,000 kilometers, while some manufacturers offer battery warranties of up to 240,000 kilometers.[293]

Most BEVs are expected to save on carbon over their lifetimes, but this varies significantly among regions

Regional differences in manufacturing emissions, relative running emissions (including the emissions intensity of the power grid and the efficiency of the displaced ICEs), and lifetime distance traveled can be considerable. For example, battery manufacturing in China (where most batteries are currently made) may be up to 50 percent more emissions intensive than it is in South Korea or the United States and twice as emissions intensive as in Sweden.[294] The grid that powers electric vehicles in Europe is about 35 percent less emissions intensive than the grid in the United States and about 65 percent less emissions intensive than the grid in India.[295] ICE passenger cars in the United States also tend have lower fuel economy—producing more emissions per kilometer—than those in Europe.[296]

Despite this variability, in general most BEVs should surpass carbon breakeven during their lifetime of driving, even assuming that current grid emissions intensities persist over time (see the left-hand panel of Exhibit 25).[297]

In Europe and the United States, carbon breakeven against even a top-performing ICE comes at 35,000 to 105,000 kilometers for passenger cars under constant grid emissions intensity. As a result, in Europe and the United States, BEVs may produce emissions that are about 15 to 50 percent lower than those of top-performing ICEs over their lifetimes (and 30 to 65 percent lower than average-performing ICEs), assuming distances driven of 200,000 kilometers (see the right-hand panel of Exhibit 25).[298] Others have found similar savings for vehicles running on US and EU grids over their lifetimes.[299]

Globally, on average, BEVs are also expected to produce carbon savings. However, they would generally have to be driven for longer distances than in the EU and the United States before they reach their carbon breakeven, because the global average emissions intensity of power grids is higher than it is in these two geographies. Assuming constant emissions intensity, the global average carbon breakeven of an average BEV against an average ICE could be about 25,000 to 70,000 kilometers, and carbon savings could be about 20 to 45 percent. Against a top-performing ICE, BEV carbon savings could be less than 25 percent and even below 5 percent.

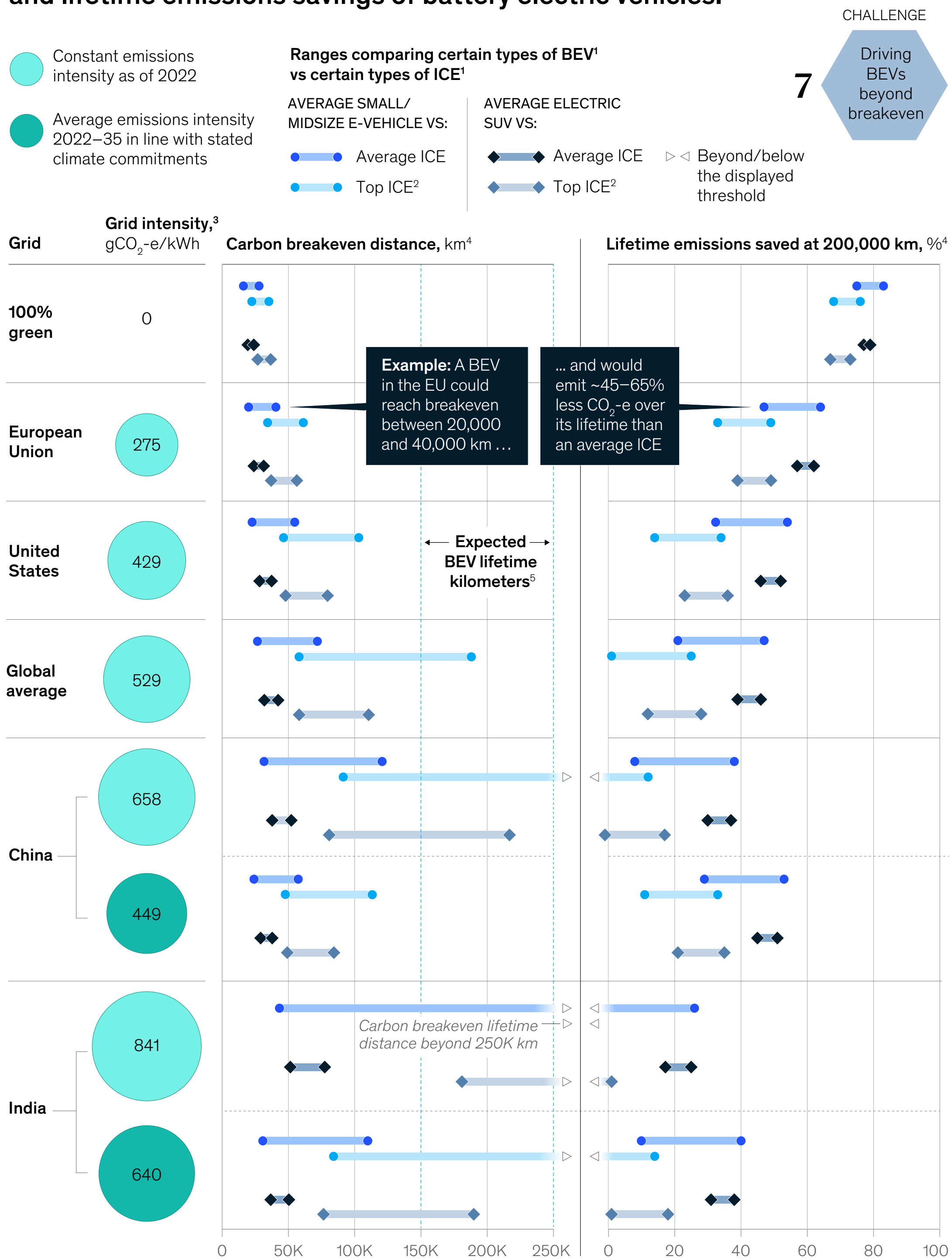
In some geographies, vehicles that are powered by high-emissions grids may not reach breakeven within their lifetimes if grids do not decarbonize quickly enough. In India today, for instance, about 75 percent of all electricity is generated using fossil fuels, notably coal.[300] If the emissions intensity of India's grid were to remain as it is today, the carbon breakeven point for average BEVs would exceed 40,000 kilometers in comparison with an average ICE and could be greater than 250,000 kilometers in comparison with a top-performing ICE. In this case, therefore, a BEV could end up emitting more rather than less emissions than an ICE.

This means that for BEVs being deployed today to reach carbon breakeven, grids need to decarbonize over time. If India's grid were to decarbonize in line with McKinsey's 2023 Achieved Commitments scenario, its emissions intensity in 2035 would be about 50 percent lower than today.[301] This would enable a BEV purchased today in India to reach breakeven and achieve lifetime carbon savings of as much as 15 percent, even in comparison with a top-performing ICE. Furthermore, for BEVs manufactured in coming years, lower manufacturing emissions could also help achieve larger carbon savings. If manufacturing emissions were 20 percent lower than today, in India carbon savings against a top-performing ICE would increase to about 20 percent.[302]

In some geographies, vehicles that are powered by high-emissions grids may not reach breakeven within their lifetimes if grids do not decarbonize quickly enough.

Exhibit 25

Grid emissions intensity has a large impact on the carbon breakeven point and lifetime emissions savings of battery electric vehicles.



[1]BEV = battery electric vehicle; ICE = internal combustion engine. Small/mid-size vehicles include sedans, coupes, and hatchbacks.
[2]Top-performing vehicles in fuel efficiency (95th percentile).
[3]This includes upstream emissions related to power generation, encompassing emissions from extraction, processing, and transportation of fuels.
[4]Range in the exhibit is driven by spread of values for the emissions performance of average BEVs and electric SUVs against average and top ICEs, due to specifics of the cars driven, different emissions estimates across different regions, and other factors.
[5]Based on the first and third quartiles in the distribution of odometer readings of cars 12 years old (average lifespan of vehicles) or more in the United States in 2017.
Source: European Environment Agency; US Environmental Protection Agency; GREET model (Argonne National Laboratory); Climate Transparency; McKinsey Center for Future Mobility; McKinsey Global Institute analysis

New manufacturing approaches, a lower-emissions power mix, and increasing BEV range could improve BEV carbon savings

Ultimately, the carbon breakeven point between ICEs and BEVs is dynamic over time. Both vehicle technologies are on a path of progressively lowering emissions. For example, ICE fuel efficiency and tailpipe emissions are improving over time.[303] Broadly, to deliver on emissions reduction goals, it would be necessary to tackle all three drivers of breakeven discussed above:

— *Manufacturing emissions would need to be reduced.* BEV manufacturing emissions may fall over time as automotive original equipment manufacturers seek to tackle them. Previous McKinsey research estimated that the automotive industry could reduce emissions from manufacturing batteries by as much as 75 percent by 2030 if it recycled minerals from used batteries and adopted new cell-manufacturing technologies that require less heat, among other levers.[304] Based on announced projects, global battery recycling capacity could grow five times by 2030.[305] Lower manufacturing emissions will also depend on decarbonizing power grids, as well as decarbonizing the production and use of key materials in the industrial domain (see chapter 7).

— *Running emissions would have to fall.* Globally, power generation is expected to trend toward lower-emissions sources over time, even in relatively slower transition scenarios. The emissions intensity of grids in G-20 countries has dropped by about 8 percent over the past five years.[306] This means that even a BEV hitting the road today would, over the course of its lifetime, run on gradually cleaner grids and generate declining emissions. Changes in the timing of BEV charging can also affect emissions. In reality, people charge their cars at various times of the day, and therefore the marginal emissions created by BEV charging may be different from the grid average. In California, for example, charging a BEV during the day could produce about half the emissions that would be produced if charging were to occur during the night.[307] According to one study, optimizing BEV charging for the carbon intensity of the US grid throughout the day could yield an 8 to 14 percent reduction in related carbon emissions.[308] In addition, as BEVs become more efficient over time, they consume less power for a given distance driven, resulting in even lower running emissions.

— *BEVs would need to be driven past their breakeven distances over their lifetimes.* Many of the first BEVs deployed were driven less than an average ICE. This raised questions about whether they would attain enough lifetime mileage to generate carbon savings.[309] BEVs tended to be driven less often because they were bought as second cars or with the intention of using them for shorter commutes. However, over time improvements in performance mean that newer BEVs are expected to achieve longer lifetime distances, enabling larger carbon savings over their lifetimes.[310] Despite these improvements, the current range of BEVs still falls short of the range of ICE vehicles, potentially limiting their lifetime distances. For BEVs to continue expanding their lifetime distances, they must be capable of covering more and more ICE use cases, in particular those involving long-distance driving. The range of BEVs would need to continue to improve, as discussed in the next challenge.

■ ■ ■

This is a Level 1 challenge. Ensuring that BEVs abate CO_2 emissions over their lifetimes relative to ICEs is a significant physical challenge. But there are many indications that tackling it appears to be on track at the current course and speed. Much of the transformation to lower breakeven distances and higher lifetime carbon savings has been addressed in areas where grids are relatively clean. Even where grids are relatively dirty, there are signs that the transformation is progressing, so that grids across the world are becoming cleaner over time. Manufacturing emissions related to batteries could also fall, and BEVs may become more efficient.

Challenge 8

Challenge 8: Going the distance on BEV range (Level 1)

Range matters. The ability to drive passenger vehicles long distances without stopping to refuel is a quality many drivers value. BEVs drive shorter distances than ICEs before they need to refuel: an average passenger BEV currently has a range of about 400 kilometers, in comparison with about 650 kilometers for an ICE vehicle. Moreover, BEVs currently take at least 25 to 50 times longer to fully charge than ICEs take to refuel (and five to ten times longer than FCEVs). An ICE takes about 12 seconds to refuel for 100 kilometers of driving, while current best-in-class BEVs take about five to ten minutes for the same driving range when using a fast charger.[311]

So long as passenger BEVs have limited range before they need recharging, and charging times are long, these will be large barriers to adoption.

Passenger BEVs can meet most range needs across regions, though some harder use cases remain

Passenger BEVs are currently able to meet most use cases in driving range needed, but not all. In the United States, the average reported range of a BEV is about 400 kilometers.[312] However, factors such as cold temperatures, battery deterioration, and driving conditions can reduce this range.[313] Accounting for these factors, the median BEV range would still enable more than 70 percent of US households to complete almost all of their long single-day journeys (more than 100 kilometers) without stopping to recharge—they would have to do so on fewer than five days a year (Exhibit 26).[314] Best-in-class BEVs can do even better. With a reported range of over 800 kilometers, even factoring in potential range loss, such BEVs could enable more than 90 percent of US households to complete their longest driving journeys while having to stop to recharge on fewer than five days a year.[315]

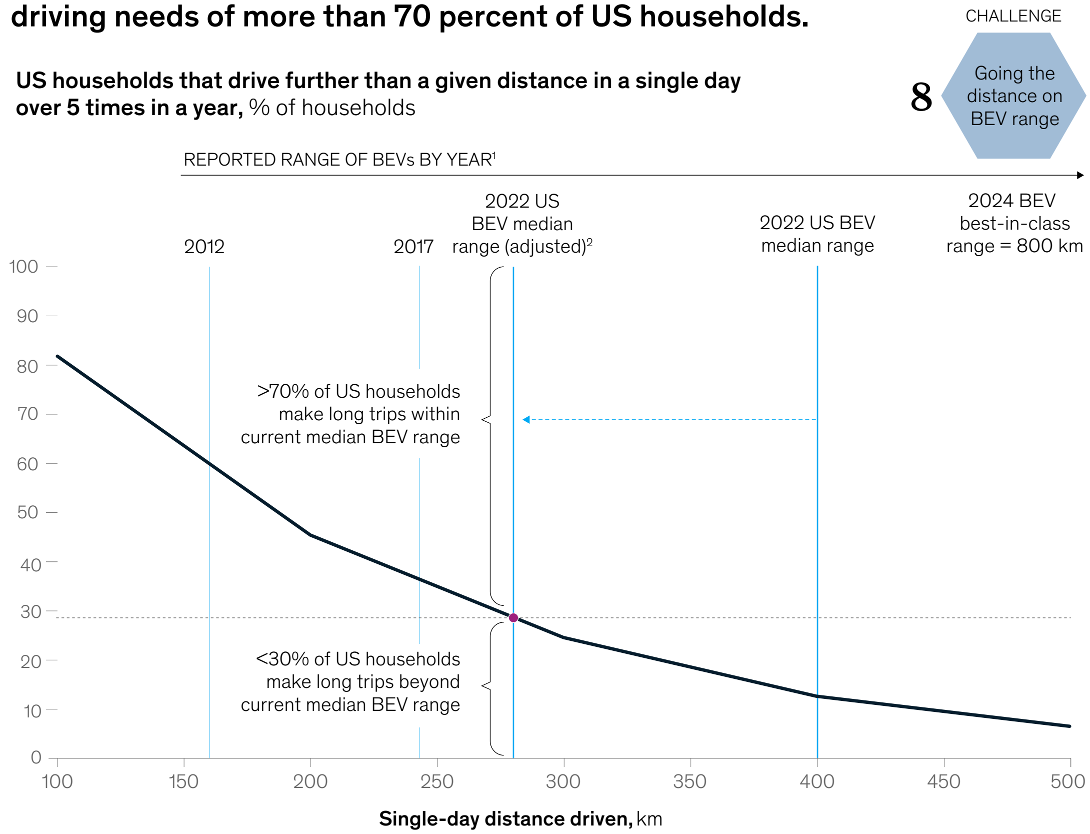
In other parts of the world, where daily driving distances tend to be lower than in the United States, the share of use cases currently met by BEVs would be even higher. The average driver in the United States drives almost twice as far each year than drivers in Australia, France, and the United Kingdom.[316]

Passenger BEVs are currently able to meet most use cases in driving range needed, but not all.

Exhibit 26

Electric vehicles can already meet the long-distance driving needs of more than 70 percent of US households.

US households that drive further than a given distance in a single day over 5 times in a year, % of households



[1]2012, 2017 range is sales-weighted and normalized to the Worldwide Harmonized Light Vehicle Test Procedure for all regions. 2022 US median reported BEV range. BEV = battery electric vehicle.
[2]US median reported BEV range (400 km) is adjusted down by 30% to account for range loss due to operational conditions and cold temperature.
Source: International Energy Agency; McKinsey Center for Future Mobility; Geotab; US Department of Energy; US Environmental Protection Agency; US Federal Highway Administration; Consumer Reports; Recurrent; McKinsey Global Institute analysis

Although passenger BEVs can already cover the majority of driving use cases in range, consumers may place significant weight on unmet, edge, use cases. This could even be the determining factor in whether they decide to buy a BEV. Therefore, ensuring that BEVs have sufficient range is a key physical challenge.

Continuing innovation to increase the energy density of batteries and other measures would be needed

Technological innovation offers a way forward to use cases that remain unmet. Indeed, this is already happening. Between 2011 and 2021, the average range of BEVs increased by about 100 kilometers every five years.[317] It is possible that the remaining tail of unmet use cases could be served by a continuing increase in the energy density of batteries. Although there is some uncertainty, battery energy density could improve by about 2 to 3 percent a year as battery technology improves.[318]

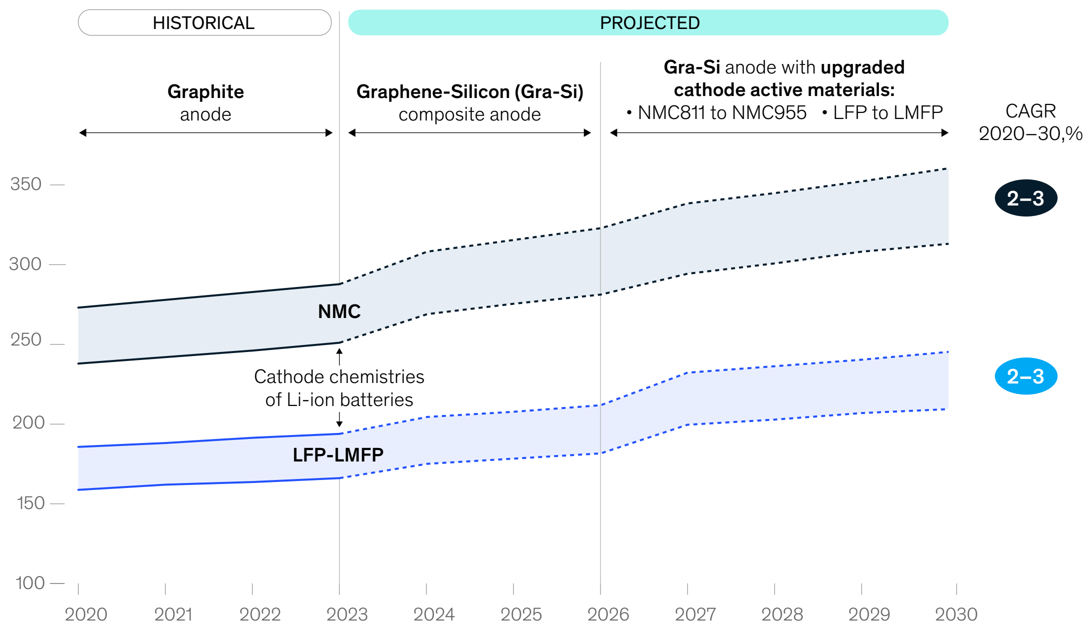
Increasing energy density would be enabled by changing battery chemistry.[319] Within this decade, graphite anodes are expected to be replaced by graphene–silicon anodes (Exhibit 27). Popular cathode chemistries, such as nickel manganese cobalt and lithium iron phosphate, will also likely evolve. For example, NMC811 cathodes (80 percent nickel, 10 percent manganese, 10 percent cobalt) may be replaced by NMC955 (90 percent nickel, 5 percent manganese, 5 percent cobalt), and lithium iron phosphate (LFP) cathodes by lithium manganese iron phosphate (LMFP) ones.

Exhibit 27

Battery energy densities are projected to increase 2–3 percent a year over the next decade.

CHALLENGE
8 Going the distance on BEV range

Cell energy density projection by chemistry, watt-hour/kg



Source: McKinsey Battery Insights; McKinsey Global Institute analysis

Other battery technologies that are nascent today could be game changers. For example, some observers suggest that solid-state batteries could have about double the energy density of today's lithium-ion batteries.[320]

Innovation can also mitigate some of the factors that reduce the range of BEVs. For example, newer BEVs equipped with heat pumps can experience much lower range losses in cold temperatures than BEVs equipped with resistance-based heating, given the much higher efficiency of heat pumps.[321]

Beyond extending the range that batteries can offer, there are nontechnological options, including behavioral change, such as accepting the need to charge midtrip. Of course, some users may not be willing to accept this trade-off, since charging takes so long in comparison with filling up an ICE and, as discussed later, there may be concerns that charging points may not even be available. Other approaches to improve the situation have been emerging. One option being discussed is battery swapping: EV drivers would make midtrip stops at battery-swapping stations and switch out drained batteries for fully charged ones, with time saved relative to charging. This approach could be applied to use cases ranging from two-wheelers to heavy-duty trucks.[322]

▪ ▪ ▪

This is a Level 1 challenge. Battery technologies today already cover the majority of driving use cases in range. Only the hardest use cases—long-range driving—remain particularly challenging. Technological innovation has helped continue to improve battery energy density, and numerous alternate battery chemistries are being explored to continue improvements. Given anticipated technological developments, over the next decade all but the very hardest use cases could well be met.

Challenge 9

Challenge 9: Loading up electric trucks (Level 3)

For many use cases, the ability to carry (or tow) payloads without stopping to refuel or recharge is important. Newer trucking technologies, such as battery electric trucks and hydrogen-powered trucks (also known as fuel cell electric trucks), are being considered as replacements for traditional ICE-based medium- and heavy-duty trucks, in an effort to reduce emissions. Both technologies currently have significant physical challenges that will need to be overcome.

Battery electric trucks' physical challenges relate to payload–range trade-offs; fuel cell electric trucks have gnarly interdependencies

Market penetration of electric trucks is small today. Adoption is at an early stage, especially for the very largest-payload use cases. The stock of such vehicles on the road would need to rise more than 100 times by 2050 to achieve the decarbonization of the sector modeled in McKinsey's 2023 Achieved Commitments scenario.[323] China accounted for nearly 90 percent of medium- and heavy-duty electric truck sales in 2022, but other regions have experienced growth only recently.[324]

Heavy-duty battery electric trucks on the market today are far heavier—by two or more tonnes—than their diesel counterparts and need to be charged after driving relatively short distances, often less than 400 kilometers.[325]

One potential solution to this challenge around range would be to deploy larger batteries in heavy-duty trucks. However, doing so would increase the weight of the trucks, and regulations in many geographies require trucks to stay within a certain weight limit. Currently, about 50 percent of all heavy-duty trucks in the United States carry payloads within 10 percent of the federal total weight limit. The extra weight of battery electric trucks is likely to affect the payloads they can carry.[326] Battery electric trucks therefore reach a critical point at which any additional battery weight to improve range would require them to sacrifice payload. In other words, to increase the range of a battery electric truck by an additional kilometer, more battery capacity is needed, which would require extra battery weight and therefore reduced payload capacity.

Simulations to quantify the trade-off between payload and range, controlled by the weight of the battery, indicate that, to meet a range of 600 kilometers, a battery electric truck could lose approximately 2,500 kilograms (about 10 percent) of its payload capacity compared with a diesel truck (Exhibit 28).[327] Longer ranges mean losing even more payload capacity. To meet a range of 725 kilometers, a battery electric truck could lose about 4,000 kilograms (some 15 percent) of its payload capacity in comparison with a diesel truck. For reference, more than 50 percent of regional freight in the United States travels further than 600 kilometers, and 50 percent of long-haul freight travels further than 725 kilometers.[328]

This implies that major changes to the weight trucks carry, the distances they travel, or a shift in today's trucking logistics and charging optimization would be needed to decarbonize trucking—a high degree of transformation.

The trade-off between payload and range differs by region because the profiles of trucking fleets and regulations vary among geographies. For instance, the average load for domestic transportation in Finland is about twice the average in Denmark—that is, weight limits differ significantly even within the EU.[329] Based on the energy density of batteries today and illustrative weight regulations and driving profiles across payloads and distances (using US and EU data), roughly 20 to 45 percent of current long-haul trucking use cases could be unmet on a single charge.[330]

Several use cases thus continue to require higher energy densities than batteries can currently offer, at least with current driving patterns and weight regulations. Fuel cell electric trucks offer an alternative. They can carry more than battery electric trucks do, because hydrogen is more energy-dense than batteries (it can carry a larger amount of energy for a lower weight). In general, such trucks may still carry a lower payload than ICE trucks for the same range because hydrogen storage tanks can shift weight distribution toward the drive axle, potentially above regulated limits on axle loads. This case is shown in Exhibit 28.[331]

However, scaling up fuel cell electric trucks has a different physical challenge. It would require building separate hydrogen-refueling stations, which have been only minimally deployed to date, and substantial growth in the hydrogen supply chain—a gnarly interdependency with tackling another Level 3 challenge (see next section and chapter 10 on the hydrogen domain).

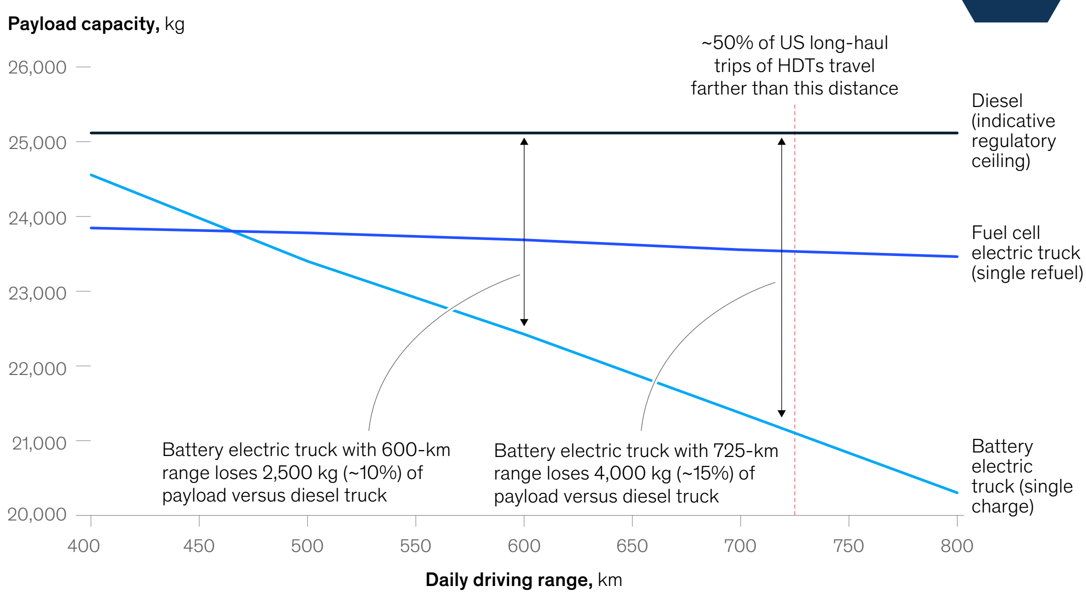
Exhibit 28

Battery electric trucks have a payload–range trade-off.

Payload capacity of heavy-duty trucks (HDTs) at different driving ranges

CHALLENGE

9 Loading up electric trucks



Source: International Council on Clean Transportation; North American Council for Freight Efficiency; McKinsey Global Institute analysis

In the United States, 50 percent of long-haul freight travels further than 725 kilometers.

Technological advances and changes to trucking logistics and regulations could help address these physical challenges

A portfolio of approaches is being considered to solve payload–range trade-offs. Deploying battery electric trucks and fuel cell electric trucks in use cases that make sense specifically for each will be important to help mitigate problems stemming from the physical challenges discussed. For example, fuel cell electric trucks could be particularly suited to transporting freight over very long distances, where BEVs could struggle to meet range requirements.[332] While many options are on the table, each of them will require large-scale system transformations, continued innovation, or both.

1. *Technological advances in battery energy density.* The relatively low energy density of batteries is arguably the largest physical challenge holding back battery electric trucks. If the technology can continue to improve—specifically, increasing battery energy density—such trucks would be able to carry larger payloads over long distances without stopping to refuel. By 2030, some estimates suggest that assuming battery densities improve, an average battery electric truck could carry as much payload as diesel trucks do today for almost all use cases.[333] While most electric trucks deployed to date have ranges of less than 500 kilometers, over the past year manufacturers have launched new battery electric trucks that have reported ranges of 800 kilometers while carrying full payloads.[334] Nonetheless, only a few dozen trucks capable of the longest ranges were on the road as of early 2024, so there is a limited track record of performance.[335] Recent innovations would need to continue to be scaled commercially. Alternative battery chemistries with higher densities could play an important role, but continued innovation would be needed, as discussed in the previous challenge.

2. *Changes in weight limits.* By relaxing the total weight limit of trucks, additional battery weight could be carried for a given payload and range, effectively reducing the trade-off. In Europe, proposals are currently in place to allow the total weight of zero-emissions trucks to be 4,000 kilograms higher than that of ICE trucks.[336] However, there are limits to how much additional weight trucks will be allowed to carry, for safety and operational reasons (for example, damage to roads and bridges).[337]

3. *Operational route and charging optimization.* In some cases, reconfiguring routes could reduce the need to carry large payloads over longer distances. Such reconfigurations could include making short-haul routes more frequent—a recent trend—which could increase the share of use cases being met by current battery electric trucks.[338] Or trucks could stop to recharge during any mandatory breaks. In the EU, truck drivers are required to take a break every 4.5 hours; they can travel about 400 kilometers between breaks.[339] For regions with such regulations, high-power charging en route during mandated breaks could enable trucks to travel the same distances they could in an ICE, with limited impact on operations.[340] However promising, these approaches do have limitations and difficulties. For instance, route reconfigurations could require significant changes in the planning of logistics for companies, and this may not be feasible, especially for floating (not preplanned) routes or those handled by third-party logistics operators, where routes are subject to daily demand. The option of charging during mandated breaks could be limited by both the availability of the charging infrastructure (which would need to match the places where stops would occur) and routes operated by two alternating drivers, so that mandatory breaks are not needed.[341]

4. *The development of hydrogen infrastructure.* The development of fuel cell electric trucks would also heavily depend on the development of hydrogen infrastructure, namely supply and refueling stations along main routes. Some players are experimenting with the development of modular refueling stations, with decentralized on-site hydrogen production, which may support relatively flexible, rapid, and cost-efficient deployment. That could potentially enable operators to keep pace with demand by expanding.[342] (For more information on the development of hydrogen infrastructure, see chapter 10).

■ ■ ■

This is a Level 3 challenge, where the use case is hard and the transformation is only just beginning. Both technologies for trucking have substantial physical challenges that need to be overcome. For battery electric trucks, a major challenge is that the energy density of battery technology today is insufficient for some use cases—a significant gap in comparison with fossil fuels to power trucks. For fuel cell electric trucks, the largest challenge is that the hydrogen supply chain is not yet mature enough to support trucking. Overall, technological innovation would need to continue, the deployment of trucks would need to be tailored by use case, logistical planning could require an overhaul, and interdependencies with other challenges would need to be solved.

Challenge 10

Challenge 10: Charging up EVs (Level 2)

If the world is to shift gears toward lower-emissions mobility, there will be a need for more manufacturing capacity (particularly of batteries for BEVs and fuel cells for FCEVs), as well as for infrastructure, such as charging stations and hydrogen-refueling stations. The physical challenge lies in building out capacity and infrastructure at a sufficient pace and scale to meet decarbonization goals. This, in turn, also depends on meeting other complex interdependent physical challenges in critical minerals, hydrogen, and power—an example of a difficult interdependency between physical challenges. Mineral extraction and refining capacity would need to be scaled up, and electricity generation from the grid and hydrogen supply would both need to meet demand for charging where it takes place.

Smooth-running battery and fuel cell supply chains are needed

In McKinsey's 2023 Achieved Commitments scenario, manufacturing capacity for batteries used in mobility would need to grow tenfold, to about 5,800 gigawatt-hours, by 2030.[343] Manufacturing capacity for fuel cells would similarly need to grow, by five to six times by 2030.[344]

This scale-up appears to be proceeding at a robust pace. If battery production capacity growth were to continue at the pace observed from 2018 to 2022, this would be sufficient to meet required capacity by 2030.[345] Planned announcements suggest that additional manufacturing capacity for batteries could be built to achieve 2030 targets, assuming a factory construction time of six months to four years.[346] In the United States and Europe, recent policy initiatives aimed at providing incentives for battery manufacturing have triggered announcements of new capacity additions, often from players in Asia.[347] China is expected to play a large role, accounting for more than 50 percent of total battery production capacity in 2030.[348]

Similarly, fuel cell manufacturing capacity has been growing. Today, global capacity is about 20 gigawatts.[349] Companies have announced about 70 gigawatts of new capacity. Existing and announced capacity are sufficient to cover about 70 percent of the capacity targeted by 2030.[350]

However, several key challenges remain. The scaling of battery and fuel cell manufacturing depends on smooth, uninterrupted supply chains. Although there have been a number of announcements of new battery production facilities, the supply chain could also remain relatively concentrated. China alone is responsible for more than 70 percent of battery production today.[351] Upstream extraction and refinement of minerals also needs to scale up substantially and is concentrated.[352] This latter key interdependency could prove to be the most difficult feature of the challenge (see chapter 9).

Charging and refueling infrastructure needs to be scaled up

More charging and refueling infrastructure would also be needed for BEVs and FCEVs. In the case of BEVs, both private and public chargers would be required—chargers at homes and in public places, such as parking lots at work or school, or along highways and city streets. In McKinsey's 2023 Achieved Commitments scenario, global public charging infrastructure would need to grow by 24 percent per year between 2022 and 2030, from 2.8 million charging points to about 16 million in 2030, and more than 40 million in 2050.[353] In the United States, for example, demand for public and private chargers could each grow by 40 percent a year from 2022 to 2030.[354] Notably, the number of EV-charging points would need to be much higher than today's tally of gasoline pumps for a simple reason: an EV takes longer to charge sufficiently to cover a given range than an ICE vehicle does to refuel.[355]

For hydrogen to play a role in decarbonizing trucking, a network of hydrogen-refueling stations for FCEVs would need to be built virtually from scratch because current deployment is minimal. Today, there are just over 1,000 hydrogen-fueling stations around the world, with the majority located in China, Japan, and South Korea.[356] The number would need to grow dozens of times by 2050 to support the adoption of hydrogen-powered trucks.[357] Ensuring the supply of hydrogen to refueling stations would be a particularly hard challenge (for further discussion, see chapter 10).

The places where charging and refueling stations are built would need to be considered carefully. For example, high-powered fast chargers would need to be placed along major logistics routes so that truck drivers can charge during mandatory breaks.

There are signals that the EV-charging infrastructure is now being ramped up, particularly in China, which today has about three million public charging points—more than the rest of the world combined.[358] In the United States, the Bipartisan Infrastructure Law of 2021 and the Inflation Reduction Act of 2022 have spurred additional investment. Seven auto manufacturers are partnering to strengthen the fast-charger network in North America, adding more than 30,000 chargers across cities and highways starting at the end of 2023.[359] In the European Union, the Alternative Fuels Infrastructure Regulation mandates hydrogen-refueling stations serving both cars and trucks in all urban nodes and every 200 kilometers along major roads from 2030 onward.[360]

Rolling out the charging and refueling infrastructure has momentum. Nevertheless, the pace and scale needed for this scale-up to meet decarbonization goals is very large. Even where legislation has been passed to enable the rollout, it has been slow. The United States, for instance, passed a bill in 2021 to build a national charging network, but chargers had been installed in only two states as of late 2023.[361] In the European Union, planning and installing a fast BEV charger can take two years on average.[362]

Electric grids need to meet demand where the charging is taking place
A final part of this challenge is ensuring that the grid can supply enough power for rising numbers of EVs, notably large fleets of medium- and heavy-duty trucks. By 2050, in McKinsey's 2023 Achieved Commitments scenario, the power supply to road mobility amounts to about 5,500 terawatt-hours (about 7 percent of total supply in 2050, equivalent to more than 20 percent of supply today). Trucks have substantially larger batteries than passenger BEVs and tend to travel on similar routes, which could also lead to high electricity demand in geographically concentrated areas. According to the International Council on Clean Transportation (ICCT), California alone would require more than 11 gigawatt-hours a day to meet the projected 2030 charging needs of medium- and heavy-duty vehicles. This would be roughly equivalent to 2 percent of current daily electricity demand in California on a winter day, which appears to be modest, but since it is only to charge trucks, it is still significant.[363] Across the United States, this number could be nearly 140 gigawatt-hours, requiring nearly 69 gigawatts of additional power capacity across local distribution grids. The ICCT further predicts that the charging needed would be geographically concentrated, with 1 percent of US counties accounting for 15 percent of medium- and heavy-duty vehicle-charging demand.[364] Sufficient grid capacity would need to be available, and the careful planning of transmission and distribution systems would also be required—and the additional generation capacity would need to generate low emissions (see chapter 5).

■ ■ ■

This is a Level 2 challenge. Manufacturing and infrastructure capacity have been growing. Still, the size of the required scale-up is massive, indicating a relatively high degree of transformation and a need to manage interdependencies with other physical challenges, including securing minerals and hydrogen, as well as scaling the power system to meet charging demand.

Worker inspecting parts from plastic injection moulding machine in plastics factory

7. Industry

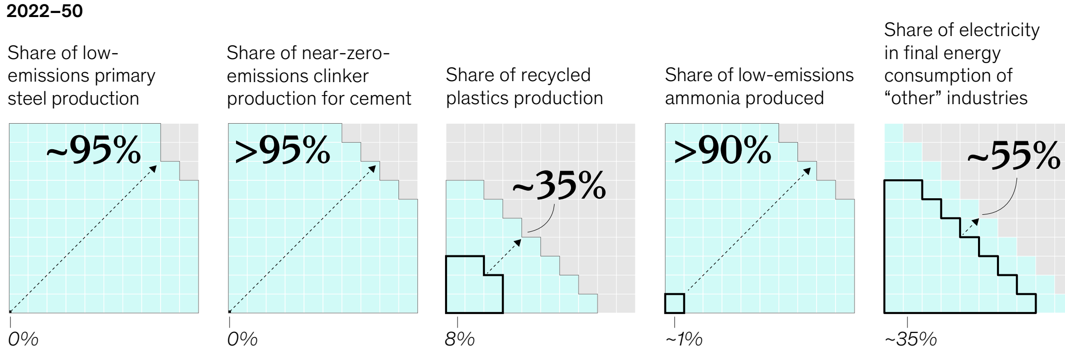
Coauthored with Michel Van Hoey

DOMAIN

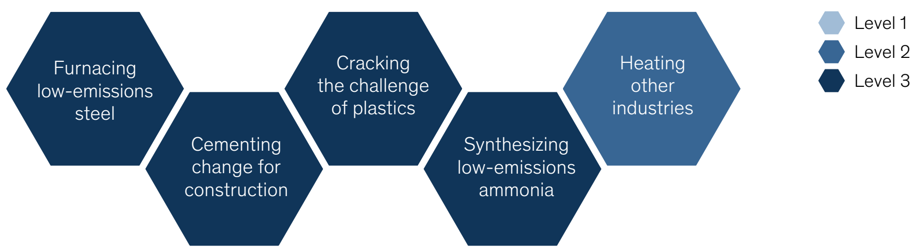
Industry

A LARGE TRANSFORMATION

2022–50



5 CHALLENGES



Note: This research examines 25 significant physical challenges in seven domains at the core of the energy transition, categorized in three levels. Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning. The focus is on physical realities because they influence the ability to design an interdependent system that has performance comparable to that of the current system and to reduce emissions feasibly. These factors influence cost and affordability. Nonphysical factors—notably cost—are important but are not the focus of this research. Assessment of required deployment of technologies primarily draws on McKinsey's 2023 Achieved Commitments scenario, which assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and in which warming reaches 1.6°C relative to preindustrial levels by 2100. This scenario is used because it provides sufficient regional and sectoral granularity for assessing required deployment. In some instances, this research also uses scenarios from other sources for reasons of data availability.
Source: *Global energy perspective 2023,* McKinsey; International Energy Agency; McKinsey Global Institute analysis

Industry accounts for about one-third of global CO_2 emissions in the energy system.[365] Within industry, decarbonizing steel, cement, plastics, and ammonia is a particularly important effort given that these four big material pillars of the modern world account for about two-thirds of industrial emissions.[366]

— *Steel.* This is a ubiquitous material, valued because of its durability, tensile strength, and versatility for multiple applications. About 1.8 billion tonnes is produced every year, enough to build the equivalent of 24,000 Golden Gate Bridges.[367] The construction industry is the largest consumer of steel, followed by transportation, machinery, and metal products.[368] Producing steel is the direct source of 10 percent of global CO_2 emissions from the energy system.[369] Each tonne of primary steel produced results in about two tonnes of CO_2 emissions.[370]

— *Cement.* A key ingredient of concrete, cement is a critical component of the built environment. Since 1950, as the global economy and population have grown and urbanized, cement production has soared 30-fold.[371] Every year, about 4.2 billion tonnes of cement are produced, or enough to build one million Statues of Liberty.[372] In fact, cement is the most consumed human-made material on Earth. It accounts for about 7 percent of global CO_2 emissions from the energy system.

— *Plastics.* The versatility of plastics means that they are used in myriad ways. Consider, for instance, that plastics account for about 15 percent of the weight of an average car and for about 50 percent of the weight of a Boeing 787 Dreamliner aircraft.[373] Every year, 380 million tonnes of plastic are produced, equivalent to the weight of about 1,000 Empire State Buildings.[374] They account for about 4 percent of global CO_2 emissions from the energy system.[375]

— *Ammonia.* Ammonia is essential for both agriculture and industry.[376] About 70 percent of ammonia produced is used in the manufacture of agricultural fertilizers. It has been estimated that, without the application of ammonia-based fertilizers and the corresponding increase in agricultural yields, it would not be possible to feed, at current levels, roughly half of today's global population.[377] The remaining approximately 30 percent of ammonia produced is used in a range of industrial applications, including in the manufacture of explosives, textiles, and pharmaceuticals and dyes.[378] Every year, more than 180 million tonnes of ammonia is produced. A new energy system would require new types of energy carriers to transport clean energy around the world, and ammonia could play a key role. The use of ammonia as a carrier in transporting hydrogen over long distances could potentially result in its production at even higher volumes than today. Hydrogen converted into ammonia has higher volumetric energy density and fewer safety concerns and could therefore be easier to move over long distances than hydrogen itself (see chapter 10).[379] Production of ammonia accounts for about 1 percent of global CO_2 emissions from the energy system. The main source of emissions is the production of hydrogen, which is a necessary input. More than 99 percent of hydrogen is currently produced in high-emissions processes using fossil fuels, namely steam-methane reforming.[380]

As part of the energy transition, these four materials would need to be decarbonized, and as yet, the transformation is in its early stages. As of 2022, about seven billion tonnes a year of steel, cement, plastics, and ammonia were produced, and less than 10 percent of that was through low-emissions processes. In the IEA's Net Zero scenario, that figure would need to rise to between 90 and 95 percent by 2050.[381] Furthermore, almost all of the progress thus far has been in low-emissions secondary production, such as recycling. Almost no primary production is low emissions today. Further decarbonization would require scaling recycling but also decarbonizing primary production, which would be a harder endeavor.

The production processes for these four materials are difficult to decarbonize. They often rely on fossil fuels both as feedstocks (for example, to produce plastics or ammonia), which creates a substitution need; and as sources of high-temperature heat (for example, burning coal to produce high heat for cement production). Decarbonizing the production of high-temperature heat is harder than decarbonizing low- and medium-temperature heat. Electrification, in particular, is often more difficult for two main reasons. First, a narrower set of low-emissions technologies can deliver high heat. For example, heat pumps and mechanical vapor recompression evaporators can only reach temperatures of about 250 to 300°C. Second, the delivery of higher-temperature heat can require larger asset reconfigurations, because the form of heat transfer often needs to change.[382] Other heat sources, such as alternative fuels, could play a role in producing high-temperature heat—often with less retrofitting required—but they also face significant challenges in securing reliable inputs.

The direct emissions of these four industries fall into two broad categories: (1) emissions from the burning of fossil fuels (accounting for about 55 percent of total emissions); and (2) process emissions released as a byproduct of the chemical processes that take place during production of these materials (about 45 percent of emissions).[383]

In addition to these four key materials, the research also looked at a category called “other industries.” This group encompasses a wide variety of industries, including food processing, papermaking, and other general manufacturing. In this category, emissions are largely from the production of heat, although at relatively lower temperatures.[384] Together, other industries account for about 12 percent of global CO_2 emissions from the energy system.

Five physical challenges have been identified in the broad industry domain: (1) furnacing low-emissions steel; (2) cementing change for construction; (3) cracking the challenge of plastics; (4) synthesizing low-emissions ammonia production; and (5) heating other industries. The first four relate to decarbonizing the four key industrial materials and are Level 3 challenges, reflecting the fact that the use case is hard and the transformation is just beginning. The remaining challenge, associated with decarbonizing other industries, is Level 2; deployment of known technologies would need to accelerate.[385]

Decarbonizing industrial processes would require a combination of approaches

Each specific industry faces different challenges in abating emissions, but there are some common approaches to decarbonization. In many cases, the easiest measure to implement is increasing efficiency by improving plant utilization, insulation, and equipment effectiveness, and recovering waste heat. Raising energy efficiency can cut emissions, and often costs, and is possible largely with mature technologies.[386] But raising energy efficiency is not sufficient—fundamental changes in today’s industrial processes are required. A combination of five approaches can be considered, and are explored across challenges.

— *Feedstock substitution.* Switching the inputs used in order to reduce emissions that are generated as a byproduct of the industrial process. An example is replacing coking coal with hydrogen to remove oxygen from iron ore during the production of steel.[387]

— *Electrification of heat.* Generating heat from electricity rather than fossil fuels. An example is electrifying crackers used to make plastics.[388]

— *Switch to alternative fuels.* Instead of electrifying heat production, different fuels could be used. An example is burning hydrogen or biomass.

— *Carbon capture.* Emissions not abated by other means could be removed via carbon capture. An example is carbon capture in cement production.

— *End-product substitution.* Industrial products that are hard to decarbonize could be replaced by low-emissions alternatives. An example is replacing cement with cross-laminated timber.

The following sections explore the role these approaches could play and the physical challenges that may stand in the way and that would need to be addressed for decarbonization. While this report does not focus on the cost of decarbonization solutions, many (but not all) of these new approaches to decarbonizing major industrial materials would likely entail an increase in cost, at least in the short term. Driving this increase would be new physical realities, including more expensive inputs (such as hydrogen), the need to reconfigure existing industrial assets and processes (such as adding carbon capture), and deploying more nascent technologies.[389]

Challenge 12

Challenge 12: Furnacing low-emissions steel (Level 3)

Coauthored with Christian Hoffmann

Decarbonizing the production of primary (virgin) steel—steel that is not recycled and is made from iron ore—is a hard physical challenge. Alternatives would be needed for both of the roles fossil fuels play, as a feedstock and as a source of energy.

Primary steel accounts for about 75 percent of total steel production today. Almost all production today follows a high-emissions process releasing about two tonnes of CO_2 emissions per tonne of steel created (see Sidebar 7, "Choices in steel manufacturing feedstocks and processes—and associated carbon dioxide emissions").[390] Secondary steel is essentially recycled steel and accounts for the remaining 25 percent of current steel production. It is made in electric arc furnaces (EAFs) that do not use fossil fuels directly.[391] This is a lower-emissions process than production of primary steel, releasing 50 to 85 percent less CO_2 for every tonne of steel produced.[392]

The asset base associated with primary steel production is enormous and global—more than 1,400 blast furnaces operate today around the world.[393] Most large integrated steel production facilities, which often contain many blast furnaces and basic oxygen furnaces, can produce two million to ten million tonnes of steel per year.[394] Some sites are even larger. For instance, South Korea's Gwangyang plant houses five blast furnaces and has the capacity to produce 18 million to 23 million tonnes of steel per year. This single facility is about six times the size of New York's Central Park.[395]

Decarbonizing steel production will require multiple technologies, both by scaling secondary steel production through the mature scrap–EAF pathway and by deploying new technologies to replace the blast furnace–basic oxygen furnace (BF-BOF) process for primary steel production. Four options are discussed: (1) the scrap–EAF recycling process; (2) a direct iron reduction–electric arc furnace (DRI-EAF) process that directly reduces iron using natural gas or hydrogen reductants; (3) a DRI–premelter–BOF process that follows the DRI with a premelter step and then produces steel in a BOF; and (4) a BF–BOF–CCUS process that adds carbon capture to the conventional BF-BOF process (Exhibit 29).

More than 1,400 blast furnaces operate today around the world.

Sidebar 7. Choices in steel manufacturing feedstocks and processes—and associated carbon dioxide emissions

The various steelmaking options differ in their feedstocks and process steps. Typical options are discussed below:

1. Choice of input iron. Steelmaking requires first and foremost a source of iron. In the case of primary steel, raw iron ore, which contains iron in the form of iron oxide, is used. This can differ in its grade and level of impurity. While the conventional BF-BOF process is fairly flexible on the grade it can process, DRI-EAF requires high-grade iron ore (see further discussion later in this chapter). In the case of secondary steelmaking, scrap steel is the main input.

2. Choice of reductant. In the case of primary steelmaking, reductants help split the oxygen from the iron oxide in the iron ore to convert it into iron. In the BF-BOF process, the reductant is coke, made from coal. In the DRI process today, either coal or natural gas is used as a reductant. The use of hydrogen (either pure or blended with natural gas) as an alternative reductant is being developed in new low-emissions steel processes.[1] In the case of secondary steelmaking, no reductant is required.

3. Iron-making process. In this step, applicable only in primary steelmaking, iron is produced from raw iron ore. Conventionally, this step is performed in a blast furnace, where pig (molten) iron is made from raw iron ore through a reduction process that removes the oxygen present in the iron ore. As mentioned above, this process uses coke as an input, producing CO_2. Today, this step accounts for most of the emissions—70 percent—in integrated steel production that uses the BF-BOF process.[2] An alternative process for iron making is the DRI process, in which the oxygen is removed using a reductant agent (which could be coal, natural gas, or hydrogen). In some cases, the DRI process is coupled with a premelter to separate the molten iron from impurities.[3]

4. Steelmaking process. Conventionally, this step takes place in a BOF in which pure oxygen is blown into a vessel containing pig iron to remove excess carbon and other impurities. In some cases, alloying agents such as nickel, vanadium, and manganese are added. This is comparatively a lower-emissions step, accounting for only 10 percent of steel emissions today.[4] Instead of a BOF, an EAF, which generates heat from an electric arc between electrodes, can be used.[5] EAFs can be used for making secondary steel and for making primary steel in processes following the DRI-EAF approach (when iron ore used in DRI is of sufficiently high grade).

5. Carbon capture process. In some technological pathways, a carbon capture step could be added to remove emissions not abated elsewhere. This is the case for the BF-BOF-CCUS process but could also be applied to some DRI-EAF variants where natural gas is used as a reductant.

The blast furnace step accounts for 70% of steel emissions.

1 The use of biomass as a reductant is also being explored.
2 All emissions figures in this section consider both process and heat emissions. See *Low-carbon production of iron & steel: Technology options, economic assessment, and policy*, Center on Global Energy Policy at Columbia University, March 2021; and Vaclav Smil, *How the world really works: A scientist's guide to our past, present and future*, Penguin, 2022.
3 Premelter technologies are also referred to as electric melters or electric smelting furnaces. See Marion Rae, *Iron ore giants join forces on electric smelter for green steel*, Renew Economy, February 2024.
4 Z. Fan and J. Friedmann, *Low-carbon production of iron & steel: Technology options, economic assessment, and policy*, Center on Global Energy Policy at Columbia University, March 2021.
5 Andrew Gadd et al., *Pathways to decarbonisation episode seven: The electric smelting furnace*, BHP, June 2023. The reason a BOF is used instead of an EAF as in the previous pathway is that the BOF manages to remove impurities more effectively than an EAF.

Exhibit 29

A portfolio of technologies would be needed to make low-emissions steel.

CHALLENGE 12 Furnacing low-emissions steel

Note: Not exhaustive.
¹Material properties of the end product (produced steel), where more favorable state is the same or better material performance compared with conventionally produced end products.
²Extent to which existing asset base needs to be replaced or can be repurposed.
Source: International Energy Agency; US Department of Energy; McKinsey Global Institute analysis

Note that other novel approaches, such as direct electrification (molten oxide electrolysis) and using biomass as a reductant, could also be explored further, but they are not analyzed in detail here.[396]

Scaling these approaches would require addressing several aspects of the process. Technological uncertainty remains regarding the viability of scaling different technologies, given that most of them are fairly nascent. A large degree of reconfiguration would be needed to replace existing assets (for instance, blast furnaces) with new low-emissions ones, and additional inputs and infrastructure would be needed. Furthermore, interdependencies with other challenges, namely hydrogen and carbon capture, would have to be tackled.

Overall, a mix of these technology options would likely be required, with particular options being deployed in different regions and with varied sequencing and timing. As discussed below, this is because physical challenges and trade-offs accompany each option.

Secondary steel production is relatively low-emissions and mature, but its use is currently limited by scrap availability and product performance

Producing secondary steel is a mature and low-emissions process. It emits 50 to 85 percent less CO_2 than the conventional BF-BOF approach depending on the emissions intensity of the grid used to power the EAF.[397] As such, ramping up secondary steel manufacturing could support the decarbonization of overall steel production.

There are two main limitations on scaling the production of secondary steel. The first is whether required inputs are available in sufficient quantities. Today, about 700 million tonnes of scrap are used a year, but increasing this amount would be needed to scale production of secondary steel.[398] To achieve this would require an expanded supply of scrap, which would entail changes across the life cycle of steel products, from design that makes recycling them easier to ensuring that they are collected and separated effectively when they reach the end of their usefulness, through improved recycling techniques. The second limitation is that steel produced from scrap may not meet the requirements of some steel products.[399]

Factoring in these hurdles, the share of global steel demand met by secondary steel could rise from the current 25 percent to about 45 percent by 2050, in McKinsey's 2023 Achieved Commitments scenario. The remaining 55 percent would need to be met through low-emissions manufacturing of primary steel, described in the following sections.

DRI-EAF requires access to crucial inputs, including low-emissions hydrogen and power, and suitable iron ore

The high-emissions blast furnace step could be replaced with direct reduction of iron ore using natural gas, hydrogen, or a combination, producing DRI.[400] This reduced iron is then loaded into an EAF to produce steel. When using natural gas (without carbon capture), between 25 and 50 percent of emissions could be abated relative to the conventional BF-BOF process. The use of hydrogen as a reductant, instead of fossil fuels, could abate between 75 and 90 percent of emissions depending on the emissions intensity of the grid used to produce hydrogen and power the EAF.[401]

The DRI process itself is mature. Natural gas–based DRI plants have existed for decades, mostly in the Middle East.[402] Now options are being explored to replace or blend natural gas with hydrogen, which would produce lower emissions with the same technology. The first fossil-fuel-free steel was produced in 2021 in Sweden, and multiple industrial-scale projects are expected to begin operating in the mid- to late 2020s.[403] The primary hurdles are whether necessary inputs are available and addressing interdependencies with other challenges. They include the following:

— *Low-emissions power.* DRI-based steel requires a great deal of power to run the electrolyzers that produce hydrogen as well as for the EAF step.[404] For example, producing one tonne of hydrogen-based steel could require more than 3.0 megawatt-hours of power, compared with 0.1 megawatt-hour using BF-BOF.[405] Some players have plans to co-locate steel plants near low-emissions power sources built specifically to serve those plants. For example, the planned

HYBRIT low-emissions steel project in Sweden has located its hydrogen-based DRI plant near hydropower and wind power sources in order to have access to the low-emissions power it requires.[406]

— *Low-emissions hydrogen.* As discussed above, using low-emissions hydrogen in DRI can abate more emissions per tonne of steel than using natural gas.[407] But in many regions, natural gas is currently easier to source and distribute than hydrogen.[408] Some estimate that hydrogen-based steel production could account for more than 10 percent of hydrogen consumption by 2050, if efficiency, scale, transportation, and safety issues can be appropriately managed (for more detail, see chapter 10 on the hydrogen domain).[409] One option being considered is decoupling the manufacturing of iron and steel. Some steelmaking facilities may opt to source DRI directly, obviating the need to transport or produce hydrogen locally.[410]

— *High-grade iron input.* DRI requires high-grade iron input, supply of which is limited.[411] Using lower-grade iron ore is possible, but doing so reduces yields. Less than 10 percent of current global supply of iron ore is suitable for DRI, and it has proven hard to ramp up the amount available.[412] Iron-ore projects have long lead times, and few additional projects have been identified that could potentially produce high-grade ore.[413] Another option to consider is attempting to improve low-quality iron ore to make it more suitable for the DRI process, referred to as beneficiation. An estimated 5 percent of global iron-ore supply could be suitable for beneficiation in a cost-effective way.[414] Even if more DRI-grade iron ore mining projects were scaled, and even if potential for beneficiation were achieved, it is estimated that less than 20 percent of global supply would be suitable as an input.[415] Given this limitation, other technological options that can handle lower-grade iron would be required in order to produce low-emissions steel. These options are discussed next.

DRI-premelter-BOF is more flexible to accommodate lower-grade iron ore but is still in the demonstration phase
In this approach, the first step is the direct reduction of the iron (as in the approach just discussed). The DRI is then loaded onto a premelter, which melts and refines it before it is finally transferred to a BOF, where it undergoes further refining and alloying to produce steel.[416]

Theoretically, the advantage of this approach is that it can accommodate lower-grade iron because purification of the iron ore takes place in both the premelter and the BOF.[417] Like traditional DRI technology, this approach requires the availability of low-emissions power and reductants such as hydrogen. However, this approach is more technologically nascent and uncertain. While premelter technologies have been used in other metals, this approach has not been demonstrated at scale in steelmaking. Trials are ongoing at the Port Kembla Steelworks in Australia.[418]

BF-BOF-CCUS could be useful in managing asset turnover but has not been deployed yet and may not abate emissions effectively
In this process, the conventional BF-BOF is retained and CCUS added. The inclusion of CCUS could be particularly useful for minimizing asset turnover that would otherwise be required in existing high-emissions assets.

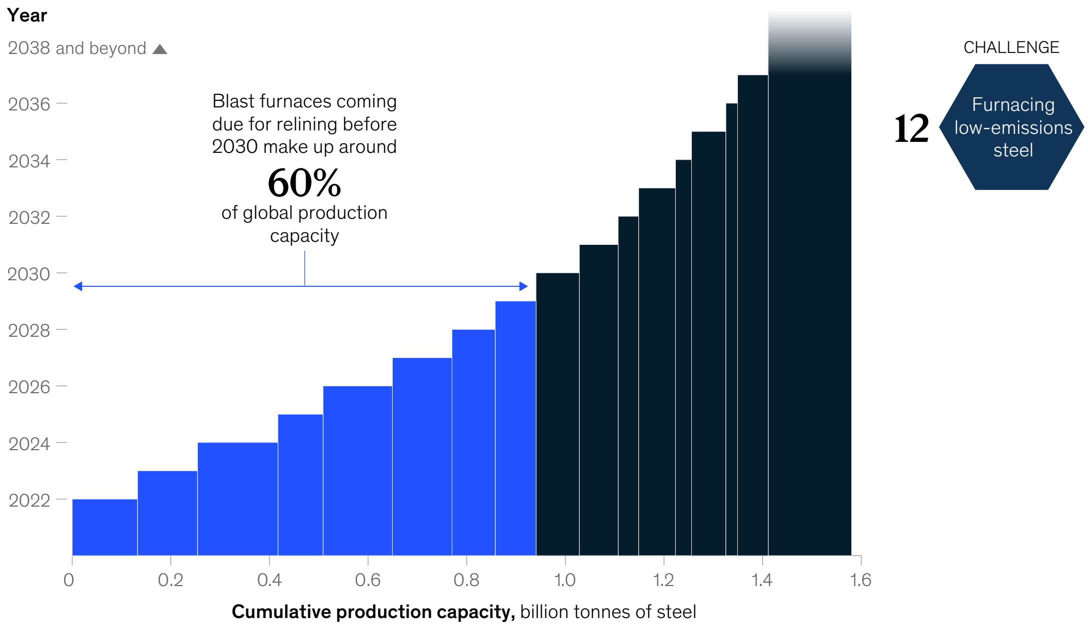
Between now and 2030, about 60 percent of the global blast furnace capacity is due to be relined, that is, have their interior linings replaced or refurbished (Exhibit 30).[419] This poses a choice for steelmakers: reline their blast furnaces or decommission them and replace them with lower-emissions processes, discussed above. This choice is complicated by the fact that alternative low-emissions steel technologies are only just being commercially deployed and are not yet cost competitive. In the cases where steelmakers opt to reline their existing blast furnaces, this would effectively extend their useful life, retaining a high-emissions asset in operation.

The advantage of CCUS would be that it could be deployed with existing assets, enabling emission abatement without cutting short the useful life of those assets and, therefore, essentially extending the time steelmakers have to consider other technologies.

Exhibit 30

A turnover window for blast furnaces is approaching, as around 60% of capacity require relining by 2030.

Global blast furnace cumulative production capacity due for relining by year[1]



[1]Based on campaign life (i.e., historically observed lifetime of equipment in-between major reinvestments).
Source: Vogl, Olsson, and Nykvist (2021); McKinsey Global Institute analysis

However, using CCUS in steel itself has issues. The relatively low concentration of CO_2 in BF-BOF flue gases makes it difficult and costly to capture carbon. In 2023, no BF-BOF was operating with CCUS, although large initial prototypes are being tested in China, Europe, Japan, and North America.[420] There is substantial uncertainty about achievable CCUS capture rates in BF-BOF, with estimates ranging from about 50 to 90 percent.[421] Another hurdle is the fact that capacity to store and use the captured CO_2 is location dependent and may face competition from carbon captured in other industries (for more details on these hurdles, see chapter 11).

Other technologies are even more nascent

As noted, other technologies are being studied, including molten oxide electrolysis and bioenergy-fueled heating coupled with CCUS. The issue is that both of these technologies are only in their early R&D phases.[422] Molten-ore electrolysis could be used to directly electrify the production of low-emissions steel—without requiring hydrogen or other reductants—and is expected to start being commercialized in the late 2020s.[423] Small-scale pilots of biomass reductant are under way in Germany.[424]

■ ■ ■

This is a Level 3 challenge. Decarbonizing steel is a hard physical challenge since primary production currently relies heavily on fossil fuels both for the production of high-temperature heat and as a reductant. Overall, the scale of the transformation is large; almost no low-emissions primary steel is produced today. A combination of technologies would be required, each with its own challenges. In some cases, technologies are already commercial and could be scaled further, notably scrap–EAF and DRI. In other cases, many other technologies needed are still nascent, notably premelters and CCUS when applied to BF-BOFs, which would require additional innovation and scaling. Scaling low-emissions primary steelmaking would also require additional inputs, notably scrap steel, low-emissions hydrogen and power, and high-grade iron ore. In addition, gnarly interdependencies with other challenges, including hydrogen and CCUS, would need to be tackled, and this would require collaboration among players across different sectors.

Challenge 13

Challenge 13: Cementing change for construction (Level 3)

Coauthored with Ken Somers

Decarbonizing cement is a hard physical challenge because producing this material generates emissions in two distinct ways. First, process emissions arise from the chemical processes associated with the conversion of limestone to lime. Second, the calcination and clinkerization steps create heat emissions from the burning of fossil fuels for the high-temperature heat they require (see Sidebar 8, "Cement production," for a detailed description of these processes). Together, these two account for about 85 percent of emissions associated with cement production.[425]

To replace current high-emissions production with lower-emissions alternatives, new technologies and processes would need to be scaled. It is likely that a combination of approaches would be needed. This research focuses on four: (1) clinker substitution to reduce process emissions; (2) alternative fuels and electrification options to replace fossil-fuel combustion; (3) carbon capture options; and (4) options to reduce cement emissions by replacing cement with alternative construction materials. Other novel approaches to decarbonizing cement have not been analyzed in detail in this research.[426]

Each of these approaches faces different issues, among them technological maturity and performance, including the ability to produce high-temperature heat without using fossil fuels; capture rates of CCS approaches and product performance in the case of some substitutes; required reconfiguration of existing assets; and the additional inputs that would have to be secured (Exhibit 31).

Sidebar 8. Cement production

Producing cement has three main stages:

1. Extraction and initial processing. Limestone and other raw materials are quarried, crushed, milled, mixed, and ground to a sufficiently small size. This stage accounts for about 5 percent of CO_2 emissions per tonne of cement produced.[1]

2. Clinker production. This mixture is preheated in a multistage combustion chamber called a precalciner and fed into a kiln, where two processes occur, both of which require high-temperature heat. First is calcination, which turns limestone into lime at about 800°C to 900°C. Calcination accounts for almost 90 percent of total energy consumption when producing high-heat in cement production. Second is "clinkerization," in which a reaction between the lime and other materials happens at even higher temperatures of about 1,500°C to 1,600°C, accounting for about 10 percent of energy consumption for heat.[2] CO_2 is a byproduct of these steps, both from the burning of fossil fuels and from the chemical conversion from limestone to lime. At the end of the clinker production stage, small lumps of stony residue called clinker, the key ingredient in cement, are left. Together, these stages account for about 85 percent of CO_2 emissions of cement production.[3]

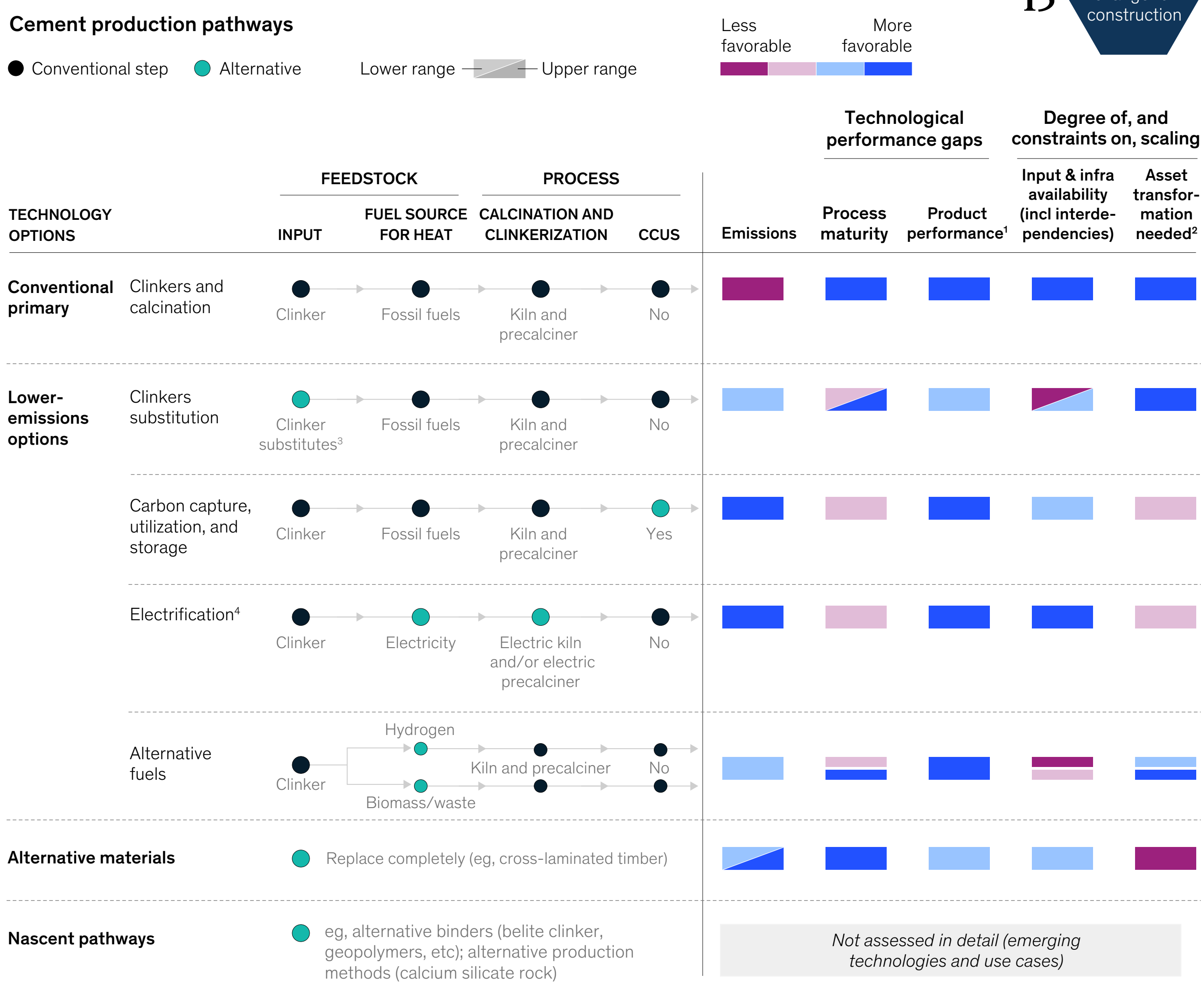
3. Final manufacturing. The clinker is ground to a powder and combined with other ingredients to produce cement. This final stage accounts for the remaining 10 percent of CO_2 emissions per tonne of cement.[4]

1 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020.
2 McKinsey Basic Materials Institute.
3 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020.
4 Ibid.

Exhibit 31

A combination of levers could be deployed to abate emissions from cement production.

CHALLENGE
13
Cementing change for construction



Note: Not exhaustive. Different options can be combined. For example, CCUS or clinker substitutes can be combined with either electrification or alternative fuels.
[1]Material properties of the end product (produced cement), where more favorable state is the same or better material performance than conventionally produced end products.
[2]Extent to which existing asset base needs to be replaced or can be repurposed.
[3]Eg, fly ash, pozzolans, and calcined clays.
[4]Emissions impact of electrification depends on energy mix of the grid; electrification can be applied across several different steps of the cement-making process.
Source: International Energy Agency; US Department of Energy; McKinsey Global Institute analysis

Substituting clinker can abate process emissions and faces the least hurdles in the near term

CO_2 emitted during the conventional production of cement is directly proportional to the amount of clinker used, since production of clinker accounts for the lion's share of cement emissions.[427] Therefore, a key way to abate emissions is partial substitution of clinker with alternative ingredients, also called supplementary cementitious materials (SCMs).[428] These materials serve a similar function to that of clinker, contributing to the binding, hardening, and strength development of cementitious materials, but with lower CO_2 emissions.

On the whole, the use of SCMs is commercially mature, and this option can be deployed in the near term. However, the cost of clinker substitutes varies greatly. They also face two main physical constraints: first, they vary in the degree to which they can replace clinker; second, they vary in availability.

In terms of performance, the substitutability of SCMs depends on the cement use case or the specific exposure conditions that structures may encounter. For example, there may be limits if cement is to be exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals, where the concern may be surface defects.[429] Moreover, the proportion of clinker that can be substituted by SCMs is governed by current industry and regulatory standards and guidelines.

Input availability may also be an issue in some cases. Some clinker substitutes, including fly ash from coal power plants and slag from blast furnaces, have already been deployed, but they may become scarce as power and steel decarbonize.[430] This could require other substitutes. Natural pozzolans and calcined clays are two promising alternatives to clinker that have demonstrated technical viability and could replace 30 to 40 percent of the clinker used today (depending on the application).[431] Natural pozzolans are made from natural fly ash produced from volcanic material and are relatively available in dry or volcanic regions. Calcined clays, also referred to as metakaolin, are produced from heating a source of kaolinite that is naturally occurring in clay deposits, tropical soils, and industrial byproducts such as paper sludge, waste, and oil sands tailings.[432]

While more effort is needed to scale the availability of inputs, substituting clinker is progressing, and some cements made with calcined clay are already available in Europe. In Denmark, calcined clay blended cement is being sold. In France, a flash calciner to produce calcined clay was commissioned early in 2023.[433]

Using clinker substitutes is promising in the short term, but there are constraints on how much substitution can be done, and therefore other approaches would also be required to decarbonize cement.

■ ■ ■

Switching to electrification or alternative fuels could reduce heat emissions, but technological maturity and input issues remain

Burning fossil fuels to produce high-temperature heat accounts for about 30 to 40 percent of total cement emissions, all of which could potentially be abated if heat could be produced with electrification or alternative fuels.

The main physical hurdles to full electrification are technological maturity and the need for asset reconfigurations or retrofits. Technological maturity, in particular, is relevant for electrification options for the clinkerization step. It has been demonstrated that it is feasible to electrify the calcination step (which accounts for 90 percent of the theoretical heat load for cement production and operates below 1,000°C) in the LEILAC pilot concept.[434] This pilot has used standard resistive elements and new technologies, such as rotodynamic heaters, to provide heat at the desired temperatures. The clinkerization step (which accounts for the remaining 10 percent of the theoretical heat load and reaches temperatures of around 1,500°C) is technically more challenging due to both the temperature increases and changes to material properties that occur in this step. The material becomes more viscous and sticky, which limits potential asset redesign options.[435]

More broadly, the need to substantially retrofit existing cement assets for full electrification is a challenge for both steps. This is because the heat delivery mechanism associated with electrification is different, and existing precalciners and kilns would need to be replaced by new electric alternatives. One option being considered is electrification of the calciner alone, as it is technically easier, and a larger fraction of the existing asset base could be reused.

Despite such challenges, commercial approaches to electrify calcination and even clinkerization are starting to be deployed. For example, in Finland, a project using a RotoDynamic Heater is expected to start industrial-scale operation by the end of 2024.[436] In Sweden, an electric arc calciner has been tested to produce clinker using electric plasma heating instead of a traditional kiln, albeit on a precommercial scale.

As well as reducing emissions, electrifying clinkerization and/or calcination could offer two additional benefits. The first is that it would make carbon capture easier—removing fossil fuel burning allows for more concentrated and controlled CO_2 streams from calcination (see the section below).[437] The second benefit would be that an electrified process, if coupled with thermal storage, would, in effect, be a large battery that would provide demand-side flexibility in the electricity network (see Challenge 3 in the discussion of the power domain).

Alternative fuels such as waste or biomass are already commercially deployed, and they could be combined with electrification (for example, by using electricity as a source of heat for calcination, while using biomass for the clinkerization step). For example, in Austria, up to 90 percent of the fuels used in the cement industry are alternative.[438] These fuels only require modest retrofits to be used in existing kilns, as they have similar properties to traditional fuels. However, some alternative fuels, notably hydrogen, require extensive kiln redesign and are less likely to play a significant role in cement decarbonization.[439] The main issue with alternative fuels is the extent to which they will be available.[440] Competition for such fuels may increase as other sectors decarbonize.

Carbon capture could be deployed in cement production, but it is nascent, and performance at scale remains uncertain

Carbon capture has the potential in theory to abate more than 85 percent, and as much as 99 percent, of cement emissions of a given asset if deployed to its full potential, and it could thus play a key role in decarbonizing cement.[441]

However, several difficulties exist. The main one is the fact that cement-related flue gases have low concentrations of CO_2—about 20 to 30 percent—and this makes it hard to reach high capture rates without substantial cost increases (see chapter 11).[442] Furthermore, the deployment of CCUS in cement is still relatively nascent and has not occurred at scale.

Initial projects are being developed in Belgium, Germany, Spain, and North America but are small in scale, with low target capture rates.[443] The LEILAC-1 project heats limestone in a steel reactor, using a physically separated heat convertor that enables pure CO_2 to be separated and captured as it is released from limestone (preventing CO_2 from being released with other exhaust gases).[444] Constructed next to a cement plant in Lixhe, Belgium, the first pilot was able to capture 5 percent of a typical cement plant's process CO_2 emissions. With the second pilot, the aim is to capture 20 percent of the process emissions of a full-scale cement plant.[445] Current CCUS processes would still have to be tested and developed at larger scales to achieve higher capture rates and increase their emissions abatement potential.

Alternative construction materials to cement could be deployed, but sufficient performance depends on the use case

Concrete today dominates urban landscapes, but a range of other materials could be used instead for many construction projects. Even today, the buildings of two major European airports have a similar shape but use different materials—Charles de Gaulle, in Paris, is primarily built using concrete, whereas Brussels Airport mainly uses steel.[446]

Some estimates suggest that alternative construction materials could substitute for more than 10 percent of cement, and potentially many times more than that.[447] One promising example is cross-laminated timber (CLT), which has a strength-to-weight ratio that rivals concrete. Its use has increased, particularly in Canada, Japan, and Sweden.[448] A review of 27 studies found that CLT could potentially reduce the carbon footprint of multistory buildings by about 40 percent, albeit with significant case-by-case variation because of factors such as the location and design of buildings.[449] There are a considerable number of CLT producers, mostly in Europe and North America.[450] Other materials could also be used in different types of buildings. For instance, the first zero-emissions brick production line opened in Belgium in 2022.[451]

One key limitation to the deployment of alternative materials is that their performance is different from concrete's, and so whether they can be deployed depends massively on the specific use case.

Overall, while many alternative construction materials are mature and could be scaled in the short term, there are limits—and uncertainty—about how large the substitution potential could be. Therefore, this approach would need to be paired with the cement decarbonization alternatives discussed.

■ ■ ■

This is a Level 3 challenge. Decarbonizing cement is a hard physical challenge because primary production relies heavily on fossil fuels for high-temperature heat production, and the production process itself creates emissions from the calcination of limestone. Almost no low-emissions cement is being produced today. Decarbonizing cement would require a mix of approaches, some of which are already feasible in the short term, especially by using alternative materials, clinker substitution, and some alternative fuels such as biomass—approaches that are mature and already deployed to an extent. However, many of the required approaches to advance decarbonization still face hard challenges, including technological uncertainty in electrification and performance limitations in current carbon capture rates. Decarbonizing cement would also require a large-scale retrofit and reconfiguration of existing assets as well as scaling access to important inputs, including clinker substitutes and biomass.

Challenge 14

Challenge 14: Cracking the challenge of plastics (Level 3)

Coauthored with Adam Youngman

Decarbonizing plastics, one of the key products of the petrochemical industry, is a hard physical challenge because fossil fuels are integral to their production. As the source of the essential molecules that make up plastics, oil and gas products are plastics' primary feedstocks and are also used to generate the high-temperature heat required for their production (see Sidebar 9, "The four stages of the plastics life cycle").

To replace the current approach with lower-emissions alternatives, new technologies and processes would be required. Four ways of decarbonizing plastics are discussed: (1) deploying new sources of heat and CCUS on processes that use fossil-fuel feedstocks; (2) switching to biobased or synthetic feedstock; (3) recycling end-of-life plastics to act as new feedstock; and (4) substituting plastics in products with other materials (Exhibit 32).[452] This section focuses on the contribution of these approaches to decarbonizing plastics production, but it is important to note that some of them would also contribute to abating emissions related to upstream oil and gas emissions by leading to a reduction in the use of fossil fuels.

Some of these approaches are mature and deployable in the short term, but others would require further innovation. To deploy these options at scale, several aspects of the challenge will have to be considered. First, the ability of some of the new technologies to match the performance of existing fossil-fuel-based approaches (specifically in the ability to generate high-temperature heat) has not been established, and many of these technologies are still nascent. To deploy these new technologies at scale would require securing additional inputs—notably alternative feedstocks. Finally, some of these approaches would entail a large reconfiguration of the existing asset base, retrofits, and, in some cases, potentially scrapping and rebuilding.

Sidebar 9. The four stages of the plastics life cycle

The plastics life cycle generally has four main stages, with some variations linked to the specific type of plastic being produced.[1] Each stage generates a meaningful share of emissions, although exact shares depend greatly on the specific plastic being produced, choice of feedstock, and end-of-life treatment. Plastics production in the EU is used as a reference, excluding emissions related to upstream extraction of fossil fuels.[2]

1. *Refining.* Natural gas and crude oil, which are separated into ethane, naphtha, and other components (precursors), account for 5 to 10 percent of emissions from plastics production. Emissions are generated largely from heating and cooling during separations.
2. *Intermediate synthesis.* Precursors are converted into ethylene and other monomers (short carbon chains) through reactions such as steam "cracking" in which feedstocks are heated to very high temperatures—as high as 850°C to 1,100°C—in the presence of steam.[3] Conventional steam cracking uses fossil fuels as the main energy source for heat. This stage accounts for 20 to 25 percent of emissions from plastics.
3. *Polymerization and product manufacturing.* The monomers are then combined to form the larger molecules (polymers) that make up the final plastic resin, which is melted, molded, cooled, and hardened to create end products. The polymerization process and product manufacturing account for 10 to 15 percent of emissions.
4. *End of life.* Used plastics are either disposed of (for example in a landfill, or by being incinerated) or recycled. The emissions generated depend on how plastics are treated at the end of their life. In the EU, end-of-life emissions account for more than 50 percent of all emissions, reflecting the fact that more than half of plastics may be incinerated, releasing additional CO_2 that would otherwise remain trapped in the product for a long period.[4] Globally, the share of emissions from end-of-life treatment is much lower—about 10 percent by some estimates—because incineration is less frequent, and landfilling is more common. [5]

1 Upstream oil and gas extraction and transportation operations are not included.
2 See *Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry*, Material Economics, October 2019. All emissions figures are taken from this report, which examines CO_2 emissions from the production of plastics and their end-of-life handling, both of which would need to be abated for the industry to achieve net-zero emissions. The extraction of oil and gas, the processing of polymers into finished plastic products, and the use phase of plastics are beyond the scope of this analysis. The outlined process in Exhibit 32 shows the production of plastics from naphtha from crude oil, which is the most common feedstock in the EU today. Processes involving other feedstocks would have different emissions footprints.
3 *Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry*, Material Economics, October 2019.
4 Ibid.
5 Incineration accounts for most end-of-life emissions, but landfilling and recycling also generate emissions. See *Examining material evidence: The carbon fingerprint*, Imperial College London, October 2020.

New heat sources and CCUS could abate emissions from fossil-fuel-based processes, but both are at an early stage in plastics

Substituting fossil fuels as a source of heat with new alternative heat sources or deploying CCUS technologies could help lower emissions in plastics production processes that retain fossil fuels in their role as an input feedstock. Three approaches could be used. The first two—electrifying heat and using alternative fuels—would both avoid fossil fuels being burned to produce heat, thereby reducing emissions. The third approach, using CCUS, would capture any emissions arising from using fossil fuels for heat generation. In all three approaches, fossil fuels would still be used as the input feedstock, and the plastics produced would be identical in both makeup and performance to existing ones. What would vary is how heat is generated for the different steps and how any resulting emissions are managed.

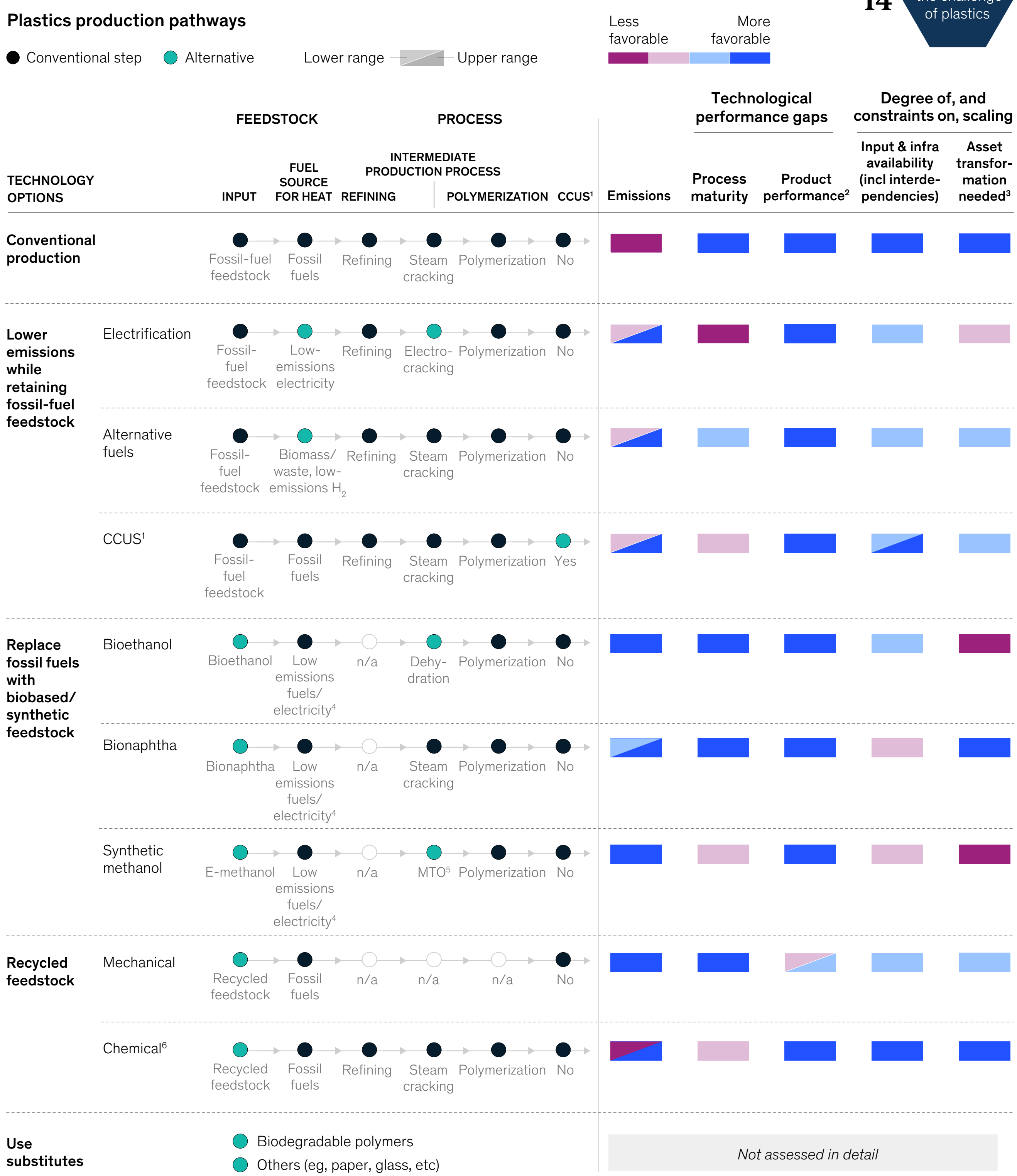
The three options differ in their maturity and in how much asset reconfiguration they would entail. Electrifying heating could be used in steam cracking (the stage that accounts for most fossil-fuel heat emissions) through electric crackers (e-crackers).[453] However, e-crackers face a number of obstacles. First, technologies have not been deployed commercially and are as yet untested at scale. Only small projects, including demonstrations being developed in Amsterdam since 2022, have been attempted.[454] Second, they require access to low-emissions power either from the grid or from dedicated generation capacity, such as renewables.[455]

Exhibit 32

A combination of levers can be deployed to abate plastics emissions, and each faces trade-offs.

CHALLENGE 14

Cracking the challenge of plastics



Note: Not exhaustive. Illustrative for polyethylene. Different options can be combined. For example, electrification can be combined with chemically recycled feedstock.
[1]Impact depends on which steps CCUS is applied to. [2]Material properties of the end product (produced plastics), where more favorable state is the same or better material performance compared with conventionally produced end products. [3]Extent to which existing asset base needs to be replaced or can be repurposed. [4]Fossil fuels could also be used. [5]Methanol to olefins. [6]Emissions abatement potential depends on the chemical recycling method. Pyrolysis is used in this analysis.
Source: Material Economics; US Department of Energy; International Energy Agency; McKinsey Global Institute analysis

Given that plastics production is highly energy-intensive, small-scale nuclear technologies could be an option in some instances.[456] Third, they would require retrofitting of current fossil-fuel-based assets, such as replacing the gas burners on the inside walls of the furnace with electric heating elements.[457] The size of such retrofits is contingent on the specific electrification technology deployed. For instance, resistance heating would likely require smaller retrofits than induction heating or electric arcs. Retrofitting can also include rewiring the steam balance of the plant, which can be a substantial task.

Instead of electrification, a second possibility to decarbonize the heat production in furnaces would be to use low-emissions hydrogen or biomass as fuel. This approach would require less retrofitting. In the case of biomass, its use as a source of heat in industry is more established, although it hasn't been deployed in plastics manufacturing to any significant degree. The main limitation of this approach is securing sufficient biomass and hydrogen, which in the latter case requires solving the interdependency with hydrogen's own challenges (see chapter 10).

Both electrification and alternative fuels would contribute to abating emissions from the burning of fossil fuels but would not, in and of themselves, address other emissions related to the use of fossil fuels as feedstocks for plastics (for example, emissions related to end-of-life combustion).

These approaches have another drawback, too—the need to find a use for the hydrogen and methane formed as byproducts during the cracking process. In the conventional steam cracking process, these byproducts are burned as fuel. But as part of the decarbonization of cracking through electrification and alternative fuels, other uses for those byproducts would need to be found, since burning them would continue to generate emissions. This would require setting up the infrastructure and logistics required to ensure that these byproducts can be used elsewhere in the facility or provided to the market, and that they do not result in additional emissions. For example, one option could be an additional build-out of assets, such as an autothermal reforming reactor coupled with CCUS, in order to convert methane byproduct into hydrogen and capture CO_2 emissions generated in the process.[458]

A third approach to decarbonizing existing processes would be to deploy carbon capture for emissions arising from fossil-fuel combustion. This approach would face several barriers. First, low concentrations of CO_2 in exhaust gases are more difficult to capture than high concentrations (see chapter 11). Second, exhaust gases may also be contaminated with other byproducts and may therefore need an additional step to remove contaminants. Finally, the CO_2 that is captured then would need to be stored or used.

Despite these limitations, the deployment of CCUS is being explored in two different stages of the plastics life cycle where its use could be comparatively easier. The first is refining when CO_2 concentrations are higher than 80 percent. The second is the intermediate synthesis stage, during the cracking process, which, because it tends to occur in the vicinity of industrial hubs with other heavy emitters, could mean that the infrastructure build-out for a CCUS hub could be more efficient. Nonetheless, to date, there is limited practical experience with this approach because CCUS in the production of plastics is under development and not yet at commercial scale.[459]

Overall, electrification, alternative fuels, and carbon capture face difficulties in relation to technological maturity, such as ensuring that e-cracking and CCUS approaches deliver the required performance in an industrial setting; asset reconfiguration that would be required; access to required inputs; and addressing interdependencies with other hard challenges (such as hydrogen and carbon capture, discussed in chapters 10 and 11, respectively).

Alternative feedstocks could directly replace fossil-based feedstocks but would entail significant asset reconfiguration

Biobased or synthetic materials could replace fossil fuels as feedstocks for the production of plastics. These approaches have in common that they replace fossil-fuel use as a material input but result in a chemically identical plastic. At the same time, they differ in important respects, including the degree of asset transformation required to accommodate new feedstock, how mature the processes using them are, how easily the required inputs for feedstock would be to secure, and how much they would cost.

Finally, the reduction of emissions over a full life cycle, relative to traditional fossil-fuel feedstocks, would significantly depend on the type of plastic being produced and the specific alternative feedstock used to produce it. For instance, biopolyethylene derived from plant material would have lower emissions than fossil-fuel-derived polyethylene. Nonetheless, there is a wide range of estimates of the potential for abatement of different feedstock options.[460]

Using biobased or synthetic materials entails capturing CO_2 from the atmosphere and converting it into feedstocks for new plastics. Consider biobased feedstocks. Here, CO_2 in the atmosphere is first sequestered when the biomass (such as sugar cane) is growing. Biobased feedstocks, such as bioethanol and bionaphtha, are then produced using this biomass. In the case of synthetic feedstocks (also called CO_2-to-X), CO_2 in the atmosphere is first captured and then combined with low-emissions hydrogen to produce a synthetic feedstock, an example being e-methanol (see Sidebar 10, "Different alternative feedstocks have different trade-offs").[461]

Converting bio or synthetic feedstock into plastics monomers could have an additional advantage. In some cases, synthesis can be achieved at lower temperatures, which would make it easier to replace fossil fuels in heat generation. For instance, the dehydration process used to produce ethylene from bioethanol can be carried out below 500°C, compared with about 850°C in steam cracking.[462]

Sidebar 10. Different alternative feedstocks have different trade-offs

Many different potential bio or synthetic feedstocks for plastics could be used, which entail different trade-offs in technological maturity, required asset reconfiguration, and economics. Below, three example feedstocks are discussed.

— *Bioethanol.* This is produced by fermenting sugar and transforming it into ethylene. The steam cracking process is replaced with a dehydration process. This technology is well developed and proven on a commercial scale. However, significant reconfigurations of the existing traditional production asset base would be required, since the dehydration process uses different equipment from existing crackers.

— *Bionaphtha.* Bionaphtha can be produced either as a byproduct in the manufacturing of hydrotreated vegetable oil (HVO) or through the pyrolysis of biomass.[1] Production of bionaphtha from HVO is a commercialized technology, while biomass pyrolysis is still in its early development phase. The use of bionaphtha as a feedstock for plastics could be limited by competition for its use from other higher-value use cases, such as aviation fuel.

— *E-methanol.* This is an example of a synthetic feedstock. It is formed by combining hydrogen with CO_2 and then using a methane-to-olefins process to produce ethylene. This approach faces three main barriers. First, e-methanol inputs—both biogenic CO_2 and low-emissions hydrogen—have limited availability.[2] Second, it hasn't been deployed at scale. At the time of writing, almost no e-methanol is produced, although projects are expected to come online by 2025.[3] Finally, significant reconfigurations of the existing production assets would be required, since the methane-to-olefins process uses different equipment from existing crackers.

The emissions profile of these approaches varies significantly but is estimated to be lower overall than using fossil-fuel feedstocks.[4]

1 Pyrolysis is the heating of an organic material, such as biomass, in the absence of oxygen.
2 The source of the captured carbon would influence the overall footprint of methanol. To maximize the abatement potential of e-methanol, biogenic CO_2 point-sources (CO_2 released as a result of combustion or decomposition of biomass and its derivatives) or direct air capture would be needed.
3 *Renewable methanol*, Methanol Institute, accessed May 2024.
4 "Sustainable feedstocks: Accelerating recarbonization in chemicals," McKinsey, October 26, 2023.

The availability of bio and synthetic feedstocks may be constrained given that there will be competition for them during the energy transition.[463] Using biobased feedstock would entail balancing competing uses for land and water. Synthetic feedstock production may offer higher output per unit of land than biomass, and it could be an option over the long term.[464] However, technological maturity is lower, and securing the required inputs (both captured carbon and hydrogen) requires cracking interdependencies with the hard challenges of carbon capture and hydrogen. Currently, synthetic feedstock production, which can be energy-intensive and require advanced technologies, can also be far more expensive than traditional fossil-fuel-based feedstocks.[465] Finally, a large amount of asset reconfiguration could be needed in both biobased feedstocks and synthetic feedstocks, given the different processes and equipment used—for instance, replacing the cracker process with a dehydration process in the case of bioethanol.

Recycling plastics would cut the need for fossil-fuel feedstocks, but scale would rely on additional infrastructure and innovation

Recycling involves breaking down plastic end products, either mechanically into polymer resin or chemically into the base monomer.[466] Both can be used to create more plastic products or even the chemical feedstock for new plastics production, and therefore reduce the need for new fossil-fuel feedstock.

Today, less than 10 percent of the plastics produced uses recycled plastics, and increasing that share would require overcoming a number of hurdles.[467] For example, additional investment would be needed to improve the collection and separation of goods to minimize waste contamination, thus improving the quality of recycled materials. Behavioral change among consumers (which is beyond the scope of this research) is also important. If consumers increased their collection and sorting of plastic waste, the availability of that waste for recycling would accelerate.

There are two main plastic recycling approaches, which have different advantages and drawbacks in how mature they are and the performance of the resulting products.

— *Mechanical recycling.* This uses mechanical processes to convert plastic waste into new plastics without changing the chemical structure of the material. It is a mature and common process, having initially been scaled in the 1970s.[468] Furthermore, the process of mechanically recycling plastics is relatively easy to decarbonize, because it relies on low-temperature heat and mechanical power, both of which can be electrified.[469] The main physical issue with this process pertains to constraints on its scale-up, given that sufficient feedstock may not be available and that recycled plastics can currently be used only in limited ways. Mechanical recycling relies on high-quality, relatively clean, sorted waste to be effective. Yet today it is still difficult to separate components of multilaminated products, such as some food and beverage packaging, plastic pipes, automotive parts, and medical devices. Furthermore, the properties of plastic waste being recycled and the recycling process itself limit the number of times a plastic can be mechanically recycled and limit potential use cases. Recycled plastics don't exhibit the same performance as new ones. For example, using mechanically recycled plastics in food-grade materials is likely to remain difficult because of safety concerns about contaminants. As a result, while mechanical recycling rates could scale up significantly, there are limits to how large a share of total plastics production recycling could ever reach.[470]

— *Chemical recycling.* Chemical recycling converts a wide range of mixed materials into hydrocarbons and precursors that can later be used as chemical feedstocks for plastics production. Processes include gasification and pyrolysis. Chemical recycling has an advantage over mechanical recycling because it offers more flexibility in which plastics can be recycled. It can be an option for plastics that are not suitable for mechanical recycling, such as mixed polymer flows, aged or contaminated plastics, and thermosets or fiber-reinforced plastics.[471] Moreover, it does not limit the number of times the plastic can be recycled, since the recycled plastic is equivalent to virgin plastic and delivers identical performance.

However, chemical recycling is less technologically mature than the mechanical route. Large-scale trials have been undertaken since the 1990s, and many, largely proven technologies exist, including gasification and pyrolysis, but deployment on a commercial scale has been limited. One consideration is that chemical recycling requires more inputs than mechanical recycling, including power (with large variation in how much is used, from one to seven megawatt-hours per tonne, depending on the plastic) and low-emissions hydrogen in the case of gasification technology.[472] Further research is needed to ascertain the environmental impact and toxicity of hazardous chemicals used in the process.[473]

Overall, then, almost all plastics recycling is still done mechanically rather than chemically.[474] That being said, some commercial-scale facilities do operate, including, for instance, the production of PEX pipes in Finland using plastics chemically recycled via pyrolysis.[475] New capacity has increased substantially, from 200,000 tonnes per year in 2020 to one million in 2023. Projects that could add eight million tonnes per year by 2027 are ongoing.[476]

Substituting plastics with other materials in products is an option, but the feasibility and abatement potential vary by use case

In some cases, it may be feasible to substitute plastic with metal, wood, ceramics, glass, paper, or fabric in a wide variety of end markets from construction to packaging. In the EU, for instance, it is estimated that up to 25 percent of plastics currently used in packaging could be substituted with fiber-based alternatives without compromising functionality.[477]

In some cases, biobased replacement materials could be used that do not rely on fossil fuels, such as biodegradable polyhydroxyalkanoates and polyhydroxybutyrates.[478] These materials are inherently different from conventional plastics, display different physical properties, and are produced in a different way. This means that producing them entails large asset reconfigurations. Deploying new equipment and processes would be needed, and supply chains would have to be reconfigured. In this way, deploying these materials goes well beyond simply replacing feedstocks in existing processes.

How much emissions abatement these materials might offer also differs by application, production route, downstream processing considerations, and their duration or lifetime in use relative to conventional plastics. Overall, substitutes for plastics should be assessed case by case.[479] In many applications, substitutes could result in higher emissions than plastics, taking into account both direct and indirect emissions throughout the life cycle.[480]

▪ ▪ ▪

This is a Level 3 challenge. Decarbonizing plastics is hard because fossil fuels are integral to their production, both as their primary feedstock and as a source of the high-temperature heat required. Almost no low-emissions primary plastic production exists today. Decarbonizing plastics would require deploying several currently available technologies that could reduce emissions, including increasing mechanical recycling and using biobased feedstocks, plastics substitutes, or alternative fuels. However, these approaches are limited in how much they can scale. Additional innovation of other required low-emissions technologies would be needed. Examples include e-crackers, which are still not deployed on a commercial scale, and chemical recycling. Furthermore, decarbonizing plastics would require a large asset transformation to retrofit existing sites as well as the scaling of access to important inputs such as biobased feedstocks, hydrogen, and low-emissions power.

Challenge 16

Challenge 16: Heating other industries (Level 2)

Coauthored with Ken Somers

Decarbonizing industrial heat is central to reducing the emissions of the entire industry sector. Heat represents about 55 percent of industrial energy demand and 20 percent of overall final energy demand globally.[481]

For the big four materials discussed earlier in this chapter, high-temperature heat is key, and delivering it using low-emissions processes often requires extensive reconfigurations of existing assets and deploying technologies that have not yet been proven at scale. But a large number of other industries require relatively lower-temperature heat, broadly speaking, and may therefore be comparatively easier to decarbonize. These include food processing, papermaking, and other general manufacturing sectors. These other industries account for more than half of total industrial energy demand and generate about 12 percent of the total global CO_2 emissions of the energy system.

Across industries (including the big four), where low- or medium-temperature heat is needed, efficient and widespread low-emissions heating technologies are already commercially available today. Therefore, the major physical challenge is not a lack of technological options but the sheer scale of deployment that would be required. The big issue is the extent to which existing assets would need to be overhauled across economies. In the EU alone, there are more than two million manufacturing enterprises, giving a sense of the breadth of the effort that would need to be undertaken.[482]

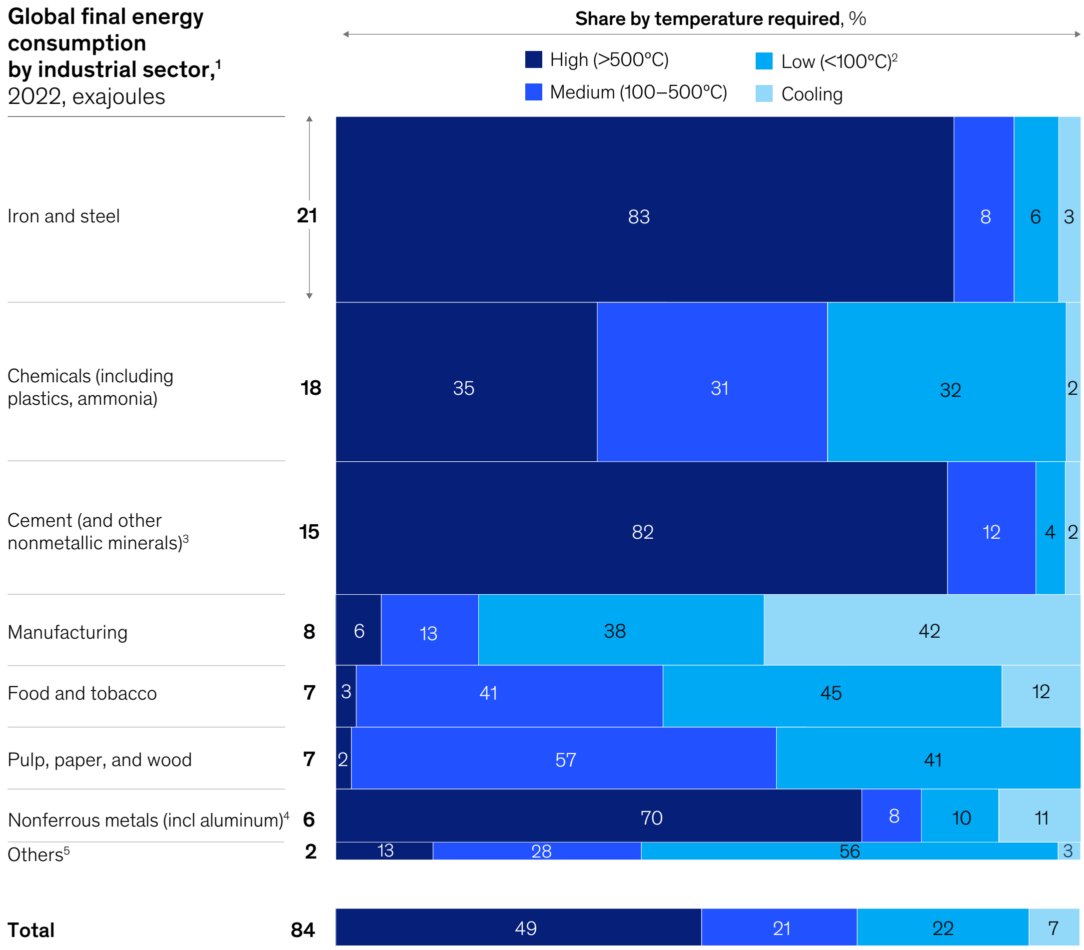
Decarbonizing industrial heat in other industries requires broader deployment of mature technologies

Around 50 percent of the heat used in these other industries relies directly on the combustion of fossil fuels, with the rest coming from electricity or alternative fuels.[483] Decarbonizing these industries would thus require replacing the use of fossil fuels by electrification or alternative fuels.

Electrification of these industries could be easier, because they rely on comparatively lower temperatures than is the case in the large industrial materials discussed. Some 90 percent of the heat demanded by these other industries is of low to medium temperatures (below 500°C). For example, 86 percent of energy consumption for heating in food processing, and 98 percent in paper, wood, and pulp production, requires temperatures below 500°C. The one exception is nonferrous metals, such as aluminum (Exhibit 33).[484] In comparison, the clinkerization process in cement requires heat of above 1,500°C.

Heat represents about 55 percent of industrial energy demand and 20 percent of overall final energy demand globally.

Exhibit 33



[1]Excludes ~18 EJ of final energy consumption with insufficient reporting; excludes agriculture and forestry (~5 EJ). Across all industries, industrial energy consumption is categorized by the temperature requirements for both thermal and mechanical energy. High-temperature heat supports processes like smelting and chemical reactions, medium-temperature heat is used in drying and other moderate-temperature processes and often for mechanical energy demands, and low-temperature heat is applied for pre-heating or maintaining specific conditions. Mechanical energy demands, such as compression work, are typically met by steam turbines or electric motors.
[2]Includes hot water and space heating.
[3]Also includes ceramics and glass.
[4]The production of aluminum requires temperatures of over 1,000°C. However, unlike the big four industrial materials, most of this high-temperature energy demand is already delivered through electricity.
[5]Includes oil and gas, construction, mining, and fishing industries.
Source: McKinsey Energy Solutions and McKinsey Global Institute analysis

McKinsey & Company

Electrification of heat sources could abate emissions and is already feasible

Significant decarbonization of these other industries would require the current source of heat to be replaced, including by direct electrification of low- to medium-temperature heat processes. This is already feasible because the relevant technologies are mature and available. Electric heat pumps for low- and medium- temperature heat are already used on industrial sites, such as for food processing and drying lumber in sawmills. Mechanical vapor recompression evaporators, which are used to separate liquids from solutions, are more efficient than their predecessors and are now standard for new evaporators in China.[485] And for areas where heat energy is being used not to raise temperatures, but to produce steam that is in turn used to perform mechanical tasks, electric drives could be used instead.

These technologies would enable a considerable share of heating demand in other industries—the 90 percent that uses low to medium heat—to be electrified, but deployment would need to be stepped up. In the food and tobacco industry, for instance, electricity accounts for 29 percent of total final energy consumption, but in McKinsey's Achieved Commitments scenario, this would need to increase to 53 percent by 2050.[486]

The remaining 10 percent of heat demand that requires very high temperatures in other industries—for instance, glass and ceramics production—may require more innovation. It is potentially promising that, over time, electrification technologies have been deployed successfully for an ever-widening range of temperatures (see Sidebar 11, "Electrifying industrial high-temperature heat—the next frontier").

Alternative heat sources could complement electrification

Other sources of heat could be deployed alongside electrification, including nuclear, geothermal, concentrated solar power, and biomass. Many of these alternative heat sources build on existing technologies, and some reuse waste heat that is already being produced for other goals such as power generation.[487]

Nuclear-based heat generation is being used as a heat source in chemical complexes in China.[488] New approaches are emerging in nuclear-generated heat, including the use of spent fuel rods that can no longer function in reactors to produce medium-temperature heat for a couple of years and low-temperature heat thereafter.[489] Geothermal is an option capable of generating heat up to 200°C.[490] A startup in Germany is working on deep geothermal closed-loop systems that can provide both heating and electrical power with full operational capacity and are expected in 2026.[491] Concentrated solar power is also being used to generate low-temperature heat alongside electrical power. One example of the successful implementation of this technology for industrial heat demand is in Oman. The primary obstacle to deploying these alternative heat sources has to do with the reconfiguration needed to reorient industrial processes to leverage them. Biomass is the exception, in that it would require the least amount of asset reconfiguration, but it faces competition for its use, as discussed in other sections of this chapter.

Some new technologies could also play a role but are less mature. They include steam explosion processing, which could turn cellulosic biomass into a material similar to coal, which could, in turn, be used in existing coal infrastructure or be further processed into syngas.[492]

Sidebar 11. Electrifying industrial high-temperature heat—the next frontier

The range of electric technologies that can produce heat for industrial production is expanding. Four main groups of technologies are being developed: (1) heat pumps; (2) resistive heating; (3) electromagnetic heating; and (4) arc-based technologies. All of these can convert electricity into heat at efficiencies of 90 to 99 percent—300 percent plus in the case of heat pumps—at a wide range of temperatures.[1] In the case of low- and medium-temperature applications, deployment of electric-based technologies is already widespread.

Electric technologies had long been considered unsuitable for producing high-temperature heat, but new applications have been emerging, albeit mostly nascent and deployed only at small scale. McKinsey analysis suggests that about 80 percent of the heat demand for temperatures above 1,000°C could be met by electric-based technologies.[2] However, the majority of this demand would rely on technologies that are only in early development—in the R&D, prototype, or pilot project phase.[3] Example technologies include electric furnaces used in float glass manufacturing. Other examples of high-temperature heat being generated with electric technologies include e-crackers used in petrochemical manufacturing (as discussed in the plastics section) and electric kilns (as discussed in the cement section).

1 *Electrifying industrial heat: A trillion euro opportunity hiding in plain sight*, Ambienta, February 2023.
2 Joris van Niel, Ken Somers, Chiara Magni, and Marcin Hajłasz, "Net-zero heat: A turning point in feasibility," McKinsey, July 2024.
3 Ibid.

Electrification of heat could create additional flexibility in power systems
Beyond helping to decarbonize industrial processes, electrification could contribute to making the entire energy system more stable. Electrifying heat production in industry creates a new source of power demand that could be used to enhance demand-side flexibility in the power system. Such flexibility could, in some cases, be achieved by pairing electrification with backup sources that can provide heat at times when demand on the grid is higher. One example could be dual-fuel heating systems in which heating can switch to be provided by a backup gas furnace. Another example is TES, which stores excess heat to use later. When demand for electricity is high, industrial plants could scale down their call on the power system by leveraging either stored heat or alternative heating sources.

A particular advantage of TES is its efficiency. Storing heat can have round-trip efficiencies of more than 90 percent. In comparison, storing power often results in round-trip efficiency of less than 60 percent.[493]

Scaling TES could rely in part on technologies that are already commercially available and could relatively easily be deployed and integrated with existing systems—for example, providing heat for medium-pressure steam generation—among the most common forms of heat used in industrial processes in, say, the chemicals and food and beverage industries. Other forms of TES, such as chemical reaction storage and absorption, are still in the early stages of deployment.

...

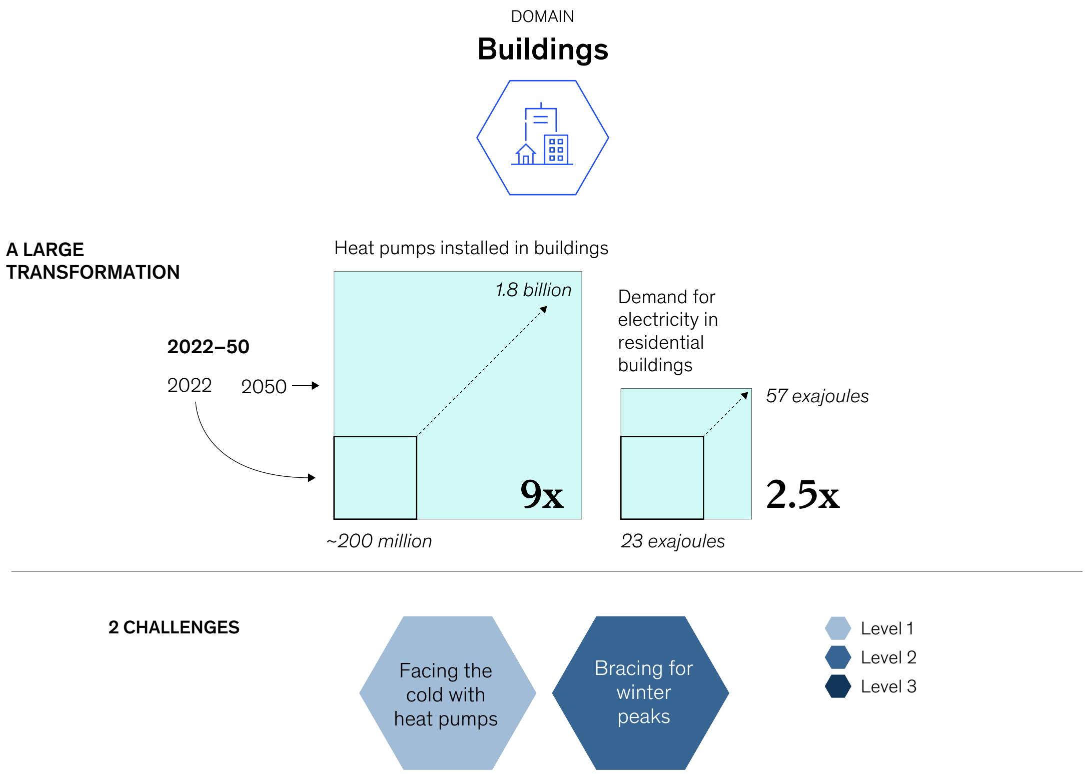
This is a Level 2 challenge. Decarbonizing other industries would require broader deployment of mature technologies, namely low- and medium-temperature heating, both electric (such as industrial heat pumps) and based on other fuels (such as biomass). This would require a large asset transformation, given the millions of individual manufacturing sites spread globally. Despite overall technological approaches being mature, some additional innovation will still be needed to address the tail end of high-temperature use cases. While these challenges are hard to overcome, this transformation could also bring about new opportunities. Electrification can often be cost-effective. Electrifying industrial processes can also open up new forms of flexible demand, for example, when used with thermal energy storage.

Heat storage can have round-trip efficiencies of more than 90 percent, compared to less than 60 percent for power storage.

A heat pump in a family house in winter
© gutesk7/Getty Images

8. Buildings

Coauthored with Daniel Cramer



Note: This research examines 25 significant physical challenges in seven domains at the core of the energy transition, categorized in three levels. Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning. The focus is on physical realities because they influence the ability to design an interdependent system that has performance comparable to that of the current system and to reduce emissions feasibly. These factors influence cost and affordability. Nonphysical factors—notably cost—are important but are not the focus of this research. Assessment of required deployment of technologies primarily draws on McKinsey's 2023 Achieved Commitments scenario, which assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and in which warming reaches 1.6°C relative to preindustrial levels by 2100. This scenario is used because it provides sufficient regional and sectoral granularity for assessing required deployment. In some instances, this research also uses scenarios from other sources for reasons of data availability.
Source: *Global energy perspective 2023,* McKinsey; International Energy Agency; McKinsey Global Institute analysis

The heating and cooling needs of buildings—the focus of this chapter—account for almost 85 percent of total CO_2 emitted from buildings, with space heating and water heating responsible for more than 75 percent.[494] The vast majority of buildings emissions are produced on-site through the combustion of fossil fuels, for example in gas boilers.[495] The rest of buildings emissions come from electricity that is used for lighting, powering appliances, and, to a lesser extent, cooking.[496]

Decarbonizing heating and cooling in buildings would entail deploying a variety of low-emissions technologies. Electrification is the main approach being considered, and heat pumps are the primary tool for heating and, to some extent, cooling spaces as well as heating water.[497]

Overall, about 10 percent of the deployment of heat pumps required in the IEA's Net Zero scenario by 2050 has been achieved.[498] By 2050, the number of heat pumps installed in buildings would have to scale by around 9 times, from about 200 million today to around 1.8 billion. Sales of heat pumps have reached about 10 percent of the annual sales that would be required in 2050 in McKinsey's 2023 Achieved Commitments scenario. In this scenario, the global share of heat provided by electricity in households would increase from about 15 percent today to 65 percent by 2050.[499]

Some of the heating buildings need could come from other low-emissions solutions, such as electric resistance heaters, district heating, solar thermal technology, and electric or hydrogen boilers.[500] The size of the overall need for heating could also be reduced by improving energy efficiency through better insulation, for instance. Expanding energy efficiency is Challenge 23.

This chapter focuses on heat pumps because they are expected to play the largest role of any technology in decarbonizing heating in buildings. The two key physical challenges analyzed relating to the future deployment of heat pumps are (1) facing the cold with heat pumps; and (2) managing peaks in electricity demand in winter.

The first is a Level 1 challenge, defined as requiring progress in deploying established technologies with the least hurdles. It involves ensuring that heat pumps perform sufficiently to meet use cases even where temperatures are coldest and average heat pump efficiency declines. The second is characterized as a Level 2 challenge that requires that the deployment of known technologies accelerates and that associated infrastructure and inputs scale. As heat pump penetration rises, more people would turn on their heat pumps at the same time, and peaks in the use of electricity in the winter would become more pronounced. Transformation would therefore be needed in the way the power system works, and managing demand peaks would require new technologies.

The 1.8 billion heat pumps that would be needed for all buildings in 2050 would have other operational challenges that are not discussed in this research. They include the need to scale up manufacturing capacity for heat pumps, whether sufficient skilled labor is available to install them, whether consumers adopt them given their associated costs, and the large turnover that their installation would entail.[501]

Challenge 17

Challenge 17: Facing the cold with heat pumps (Level 1)

Heat pumps can be a highly energy-efficient way to heat buildings.[502] They work by extracting heat from the air, the ground, or water bodies such as rivers and ponds, and then moving it to the areas that need it. There are different varieties, but air-source heat pumps (ASHPs), which transfer heat from outside air to the interior of buildings, are the most common.[503] Different types of ASHPs are used globally, and their sales have been rising.[504] Globally, sales of heat pumps have grown 30 percent per year since 2020.[505] In Europe, for example, sales of air-to-water heat pumps jumped by almost 50 percent in 2022. Such heat pumps can more readily be integrated with existing water-circulation-based heating systems, such as radiators and underfloor heating systems. In the United States, heat pump sales overtook gas furnace sales in 2022. Most US residential units are air-to-air models in ducted air systems. Nonetheless, in 2023 global sales of heat pumps decreased by 3 percent, although not uniformly. In the US sales declined by about 15 percent and in the European Union by about 5 percent, while in China they increased by 12 percent.[506]

The efficiency of a heat pump is measured by the coefficient of performance (COP), which typically ranges from two to five for heat pumps, meaning that for every unit of electrical energy consumed, the heat pump is able to deliver two to five units of heat.[507] In comparison, the energy efficiency of a natural gas furnace is about 80 to 97 percent, and 95 to 100 percent in the case of electric resistance heating (meaning that for a unit of energy consumed, they deliver less than a unit of energy in the form of heat).[508]

In cold temperatures, more heat is needed, but heat pumps have to work harder to deliver it

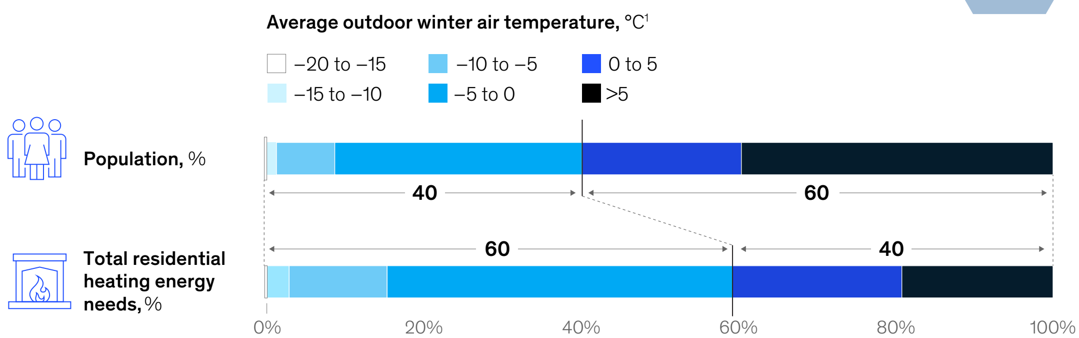
Demand for heating is naturally higher in regions that experience colder temperatures. In the United States, for instance, the 40 percent of people living in regions where average winter temperatures are below freezing account for 60 percent of residential heating energy consumed (Exhibit 34).[509]

Exhibit 34

Forty percent of the population accounts for a majority of heating needs in the United States.

CHALLENGE
17 Facing the cold with heat pumps

Share of US population and associated heating needs in winter



[1]Average winter (Dec-Feb) temperature, 1901–2000.
Source: Waite and Modi (2020); US Census Bureau; McKinsey Global Institute analysis

It is critical to understand the ability of heat pumps to supply heat to populations living in colder climates given that they require the most heat. ASHPs in particular can struggle to meet higher demand for heat in colder climates for the following two reasons:

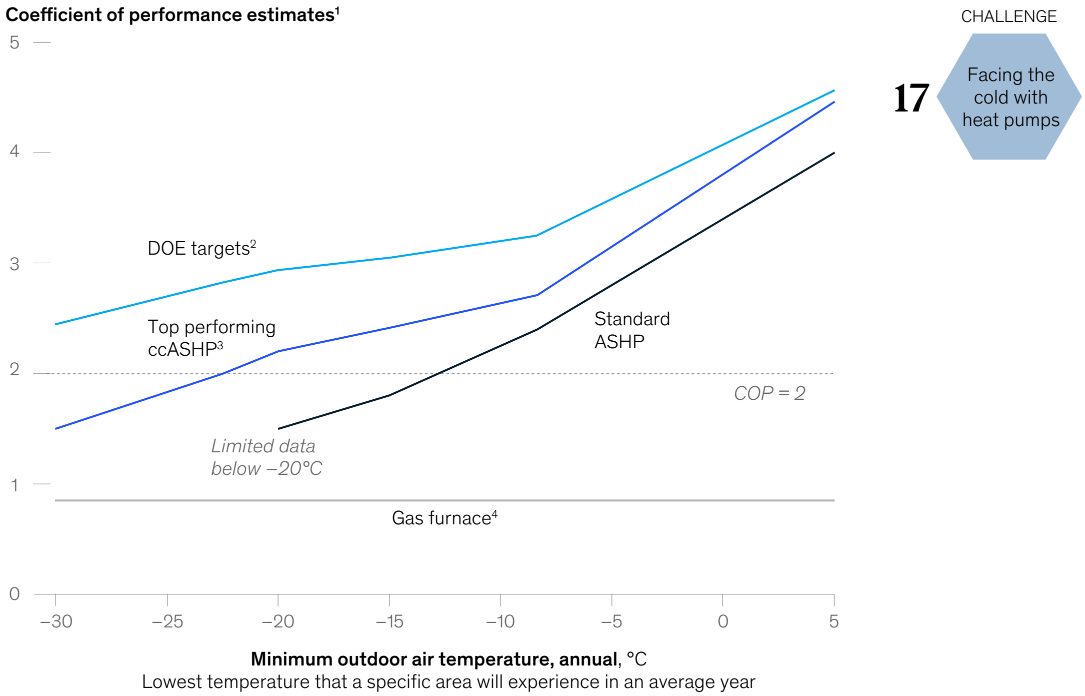
— *Lower heating capacity.* As it gets colder and there is less heat in the air outside the building, the total amount of heat an ASHP can deliver drops. This is also true for ground-source heat pumps (GSHPs) when the ground cools, although underground temperatures fluctuate only slightly during the year.[510] As temperatures fall below freezing, most ASHPs currently on the market start operating at less than their full capacity.[511] As temperatures continue to drop, they may be unable to deliver enough heat to meet households' needs.[512]

— *Lower heating efficiency.* When it is cold and, by definition, there is less heat in the air, ASHPs have to work harder to deliver the same amount of heat, and their efficiency can decline. For example, when temperatures drop from 5°C to minus 10°C, the COP of standard heat pumps almost halves.[513] At temperatures of around minus 10°C and minus 15°C, the COP of a standard ASHP may drop below two (Exhibit 35).[514] In such cases, the efficiency of heat pumps could be roughly equivalent to that of gas furnaces.[515] Heating efficiency is all the more important because some regions and economies have high electricity costs, and such efficiency declines could mean that the economic business case for heat pumps in comparison with gas furnaces is more difficult to make.

Of course, the extent to which heating capacity and efficiency drop depends on a specific heat pump's model and size, as well as the conditions of the home where it is installed (such as floor area and insulation). In general, research finds that at temperatures of between minus 10°C and minus 15°C, the performance of many standard ASHPs drops substantially. In some cases, heating capacity may even fall below needed levels.[516] At such temperatures, studies find that specialized cold-climate ASHPs could offer an alternative. As temperatures continue to drop and reach below minus 20°C to minus 25°C, even specialized heat pumps may be unable to deliver heat effectively.

Exhibit 35

Coefficient of performance drops below 2 at –10 to –15°C for standard heat pumps, and at –20 to –25°C for top-performing cold climate heat pumps.



[1]Coefficient of performance (COP) measures the efficiency of heating or cooling, excluding upstream losses. For heat pumps, COP typically ranges from two to five (for every unit of electrical energy consumed, the heat pump is able to deliver two to five units of heat energy). COP may vary depending on the types of heat pumps.
[2]The US Department of Energy (DOE) sets technology targets to guide research, development, and deployment efforts in various fields, including energy. These targets are typically aimed at advancing technologies to achieve specific performance, cost, or efficiency goals.
[3]Cold climate air-source heat pump.
[4]Value for gas furnace indicates the direct energy efficiency of a standard gas furnace.
Source: Waite and Modi (2020); Austin Selvig (2015); Gibb et al. (2023); McKinsey Climate Analytics; McKinsey Global Institute analysis

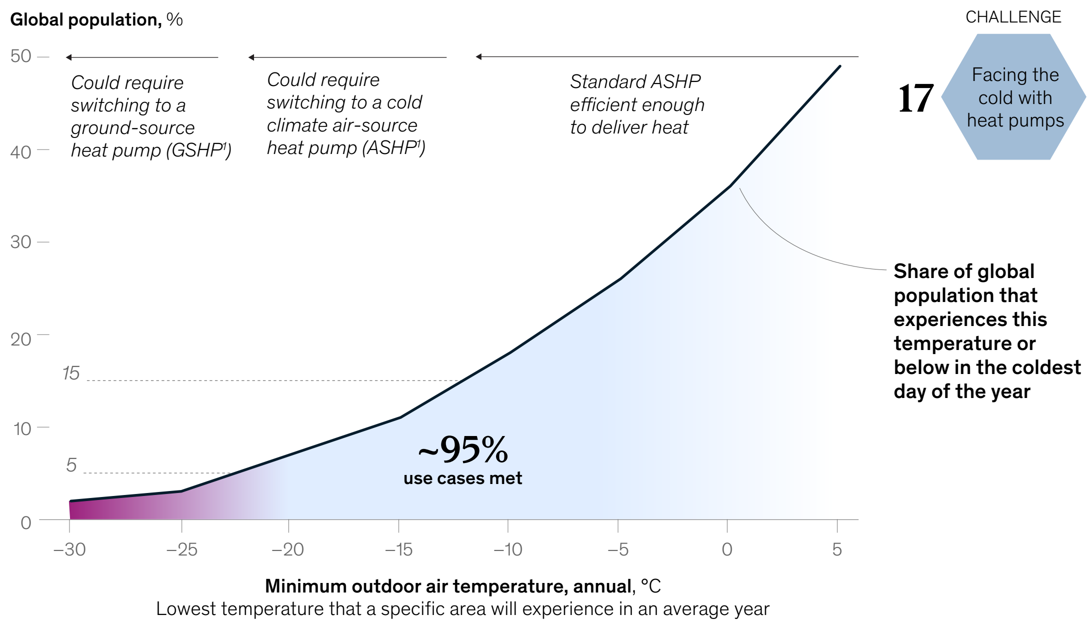
Standard heat pumps deliver most of the heating needed but are currently not suitable for the most extreme use cases

Populations that regularly experience extremely cold winter temperatures may have issues with standard heat pumps and may need specialized cold-climate ASHPs to ensure more efficient heating at these low temperatures. To understand the degree to which this is an issue, this research considers the minimum outdoor temperatures that different people experience on the coldest day of the year.

This analysis finds that about 1.2 billion people—some 15 percent of the global population—live in regions that experience minimum temperatures below about minus 10°C to minus 15°C at least once per year. About 400 million people, or some 5 percent of the world's population, experience minimum daily temperatures below about minus 20°C to minus 25°C at least once a year (Exhibit 36).[517] Overall, therefore, most people live in regions with minimum temperatures above about minus 10°C to minus 15°C, where standard ASHPs are able to meet heating needs and deliver high performance. However, for those experiencing minimum temperatures below that range, standard heat pumps alone may not suffice.

Exhibit 36

Although cold weather reduces performance of heat pumps, >95 percent of use cases can be served by today's cold temperature heat pumps.



[1]Precise temperature threshold at which a switch to a different model of heat pump is required would depend on many conditions, including insulation of the home and sizing of the heat pump.
Source: Waite and Modi (2020); Austin Selvig (2015); Gibb et al. (2023); McKinsey Climate Analytics; McKinsey Global Institute analysis

Innovation and alternative technologies could help address the most demanding use cases
Even with today's technologies, it is possible to meet the heating needs of regions with extreme cold climates effectively—with top-performing, rather than standard, cold-climate ASHPs. New generations of top-performing cold-climate ASHPs have COPs greater than two at temperatures far below freezing and can even provide uninterrupted heat at temperatures below minus 20°C to minus 25°C.[518] While this is not yet the case for most ASHPs on the market today, recent initiatives have been launched to further improve ASHP performance at these lower temperatures. For instance, the US Department of Energy's Residential Cold Climate Heat Pump Technology Challenge encourages industrial players to develop higher-performance heat pumps.[519] As part of this initiative, the department set target specifications for residential cold-climate heat pumps to be operational at minus 26°C and have a COP of 2.1 to 2.4 at minus 15°C.[520]

Other heat pump technologies could also provide heat efficiently where temperatures are extremely low, although they have some challenges to overcome. For instance, GSHPs could be more effective than ASHPs; they use established technologies that can have COPs of four even at the very lowest temperatures.[521] However, GSHPs are more difficult to install, it takes longer to do so, and they require more-specialized labor and more space because land needs to be dug up to install them.[522] Another option would be to have a source of backup heat on the coldest days, such as backup electric resistance heating or a dual-fuel system, which is a hybrid heat pump that retains a gas furnace in parallel with a heat pump. Of course, this option would add to the cost and the space needed and could lead to residual emissions.[523]

The performance of heat pumps has already been increasing by about 2 percent a year, and further improvements are likely.[524] Overall, penetration of different types of heat pumps is rising, especially in cold climates. Norway, one of the coldest economies in the world, has an overall penetration rate of about 60 percent of the stock of all buildings, one of the highest rates in the world.[525] Penetration of heat pumps in buildings in Finland, which regularly sees winter temperatures as low as minus 35°C, has reached more than 40 percent.[526] Adoption of heat pumps in Finland has significant momentum, with heat pump sales increasing by 50 percent year over year in 2022.[527]

■ ■ ■

Ensuring that heat pumps can cover use cases at extremely cold temperatures effectively and efficiently is a Level 1 challenge. The vast majority of use cases can already be met by today's typical heat pumps. However, average heat pumps have lower efficiencies at low temperatures, and as a result, there are still some use cases not served by typical ASHPs. Additional technological innovations would be needed, including innovation related to alternative heat pumps, such as specialized cold-climate heat pumps, as well as deploying GSHPs, which is not as easy operationally as deploying ASHPs. Nevertheless, rapid progress has been made in delivering low-emissions heating in buildings and improving performance. Even in extremely cold temperatures, heat pump penetration is increasing.

Challenge 18

Challenge 18: Bracing for winter peaks (Level 2)

As heating in buildings electrifies with the use of heat pumps and other technologies, demand for electricity will, of course, increase (together with increased demand from other parts of the energy system, including industry and mobility). But higher demand for electricity is only part of the story. Peaks in that demand at specific times of the year (or day) create a distinct physical challenge. People in a particular region tend to want heat at the same time, during the coldest hours of the coldest days of the year. Meeting that peak demand necessarily involves a system that has plenty of spare capacity—like a passenger train that needs to be large enough to accommodate busy rush hours but may be nearly empty for much of the day. The world needs a larger power system not only to support the electrification of heating in buildings and other domains but also because it needs to have flexibility built in for these peaks. This is not a new problem—the same challenge regarding peak usage appeared in the case of air conditioning during summers in the United States in the 1950s.[528] Now the system needs to adjust again as use of heat pumps rises.

Power systems need to scale up significantly to meet winter peaks in demand

In the United States, about 30 percent of space heating energy is electrified today, and some estimates suggest that this share could rise to about 50 percent without exceeding the current peak loads of the existing grid.[529] This is partly because the current system already has spare capacity to cope with existing peaks in demand, which today occur in the summer mostly due to the use of air conditioning in many states.[530] It is also because legacy systems across the United States are moving from less-efficient resistance heaters to heat pumps. However, if heat pumps spread, at some point peak power demand would be higher than today and would shift from typically occurring in the summer to happening in the winter.

External research has estimated that, in a hypothetical scenario in which heat for buildings is fully electrified, every other source of demand is held constant, and no additional measures to balance supply and demand are put in place, the US power system peak demand could be 1.7 times today's peaks (Exhibit 37).[531] In colder parts of the country, such as New England, peak demand could be about three times today's peaks.[532] Other analyses, including studies by McKinsey, ISO–NE, and others, have found similar values of potential growth in peak demand of about two to three times in colder states in a range of different potential decarbonization scenarios.[533]

Exhibit 37

As heating electrifies, peak electricity demand could triple in some US states if not managed.

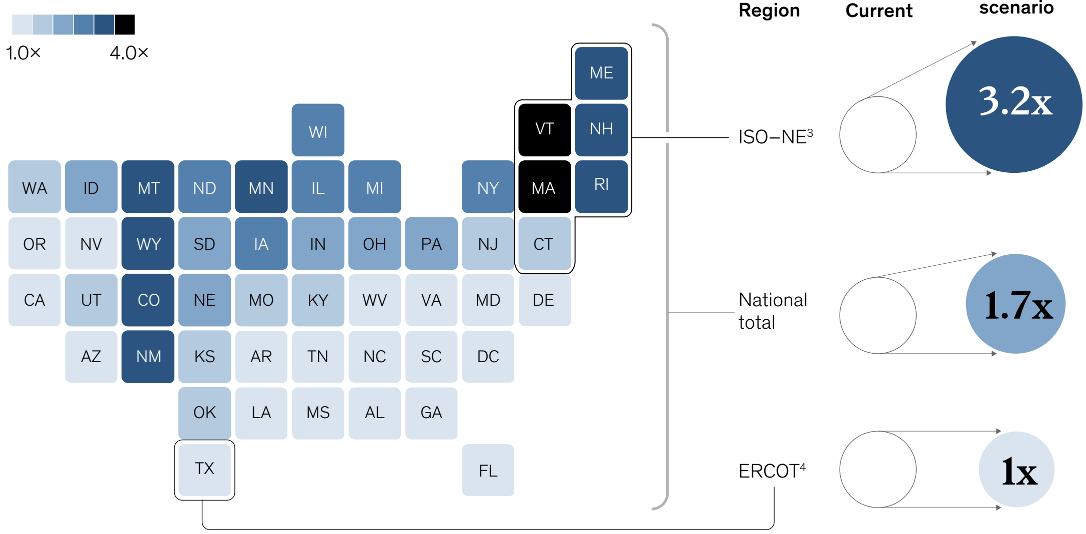
CHALLENGE

18 Bracing for winter peaks

Projected peak electricity demand in 100% electrified heat scenario in the US vs current, without additional demand management measures[1]

Peak electricity demand in an electrified scenario vs current peak by state, in ISO,[2] and at the national level

PEAK ELECTRICITY IN ELECTRIFIED SCENARIO VS CURRENT PEAK



[1]Based on analysis by Waite and Modi (2020) comparing current electricity demand to a scenario with 100% electrification of current building heat demand in the US. Assumes top-performing heat pump (90th percentile) is used. This analysis does not consider the potential growth of energy demand and electrification in other domains, such as mobility and industry. Peak loads refer to noncoincidental loads. Alaska and Hawaii not included in analysis.
[2]In the US, independent system operators (ISOs) are split into different regions, such as ISO-NE and ERCOT.
[3]ISO-New England (NE) serves Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont.
[4]Electric Reliability Council of Texas (ERCOT) serves most, but not all, of Texas.
Source: Waite and Modi (2020); McKinsey Global Institute analysis

The key challenge, then, would be to transform the energy system so that it can manage such increases in peak demand while avoiding building a massively oversize and often underutilized power system. This would entail transforming how, and how much, energy is delivered to heat buildings, addressing interdependences involved in scaling up the power system, and implementing new technological solutions.

Various measures are being explored to reduce the extent to which peak capacity load needs to increase

Part of the solution to these demand peaks could, of course, be to increase the capacity of the power system. However, doing so could lead to an oversize power system—able to accommodate peaks, but at the cost of keeping significant unused capacity sitting idle for most of the year.

Four levers could be used to reduce the peak demand the power system has to accommodate, and the mix of the four could well shift over time. Many of them come with their own implementation issues, such as required asset retrofits and effective integration of different technologies, which would need to be overcome if the peak demand challenge is to be addressed.

— *Continuing to innovate technology of heat pumps.* Improving the COP of heat pumps, particularly at lower temperatures, would reduce the amount of power needed, especially in cold-climate systems. If the US Department of Energy targets for the improvement of heat pump performance (noted earlier) were met, research estimates that the United States could potentially electrify up to 75 percent of heating without having to increase the current peak capacity of the power system.[534] Some manufacturers have already succeeded in prototyping models that meet the department's challenge.[535]

— *Creating efficiency and flexibility in managing demand.* More-efficient buildings would reduce overall demand for heating, for example through improved insulation and reducing energy loss from windows. Technologies like smart thermostats can also help to better manage and adjust heating demand. But the potential extends beyond energy efficiency. Demand-management strategies could also reduce the peak (coincidental) load—by nearly 40 percent, according to some estimates (for a discussion on options for demand-side flexibility, see chapter 5 on the power domain).[536] In particular, some technologies are developing that could smooth demand for power for heating throughout the day and manage peak periods better. For example thermal energy storage (TES) is a promising form of long-duration energy storage that could complement the electrification of heating. These technologies involve capturing and storing excess heat generated during periods of low heating demand and releasing it during periods when demand for heating is higher. For instance, heat pumps could generate heat that is stored in TES during the warmer part of the day when COPs are higher and power demand is lower; that heat could then be used by homes in the coldest parts of the day, thereby alleviating peak demand for power.[537] One major heat pump manufacturer has announced a heating system that uses an air-to-water heat pump and water-based TES.[538] However, with little deployment to date, the path forward for TES would rely on continued innovation and effective integration into the broader energy system—and on consumers to respond positively by changing their behavior.

— *Deploying alternative low-emissions heating solutions.* Alternative heating sources that do not draw on the power system, such as district heating and solar thermal, could also meet some demand. However, these solutions cannot be rolled out in all circumstances.[539] For instance, district heating requires a central heating source, such as a thermal power plant or surplus heat from industry. Solar thermal may not be efficient for geographies with low solar irradiance.

— *Backing up heat pumps with dual-fuel systems.* Targeted use of dual-fuel systems for the coldest days of the year would lower electricity requirements while still significantly reducing emissions in comparison with existing fossil-fuel furnaces. The most common dual-fuel systems have a heat pump and a gas furnace; the latter can be used when demand for electricity is high or on very cold days when a heat pump alone may struggle to meet demand. Some utilities are starting to explore and promote dual-fuel systems. For example, utilities in Quebec have partnered with one another to convert customers to dual-fuel systems, and they plan to use heat pumps for more than 70 percent of heating needs by 2030.[540] Dual-fuel systems could be particularly relevant in the short term because they use existing infrastructure. Research cited previously in this chapter suggests that in the United States, growth in peak power demand could be avoided with a combination of top-performing heat pumps and a very small share of fossil-fuel use in dual-use systems—as little as 1 to 3 percent of annual heating energy demand deployed on the coldest days.[541] In the longer term, as TES and other technologies mature, dual-fuel systems could be phased out. While dual-fuel systems could be beneficial, they could complicate installations. This is because multiple heating units would need to be installed, which would mean maintaining the fossil-fuel infrastructure despite it experiencing limited use.

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Managing winter peaks is a Level 2 challenge. A world in which the majority of heat for buildings is provided by electricity would increase demand for power on the coldest days. The power system would need to be scaled up to accommodate new winter peaks, but accelerating the deployment of other technologies and approaches could manage the extent of that scale-up. This includes improving the energy efficiency of buildings to reduce energy loss, using TES to smooth demand, deploying dual-source heating systems, and upgrading heat pumps to be more effective in colder environments. While these come with some implementation challenges, such as retrofitting assets and integrating new (often mature) technologies, they present opportunities to reduce the peak capacity load on the power system and manage the extent of scale-up needed.

A world in which the majority of heat for buildings is provided by electricity would increase demand for power on the coldest days.

A gloved hand holds traces of lithium concentrate

© Bloomberg Creative/ Getty Images

9. Raw materials

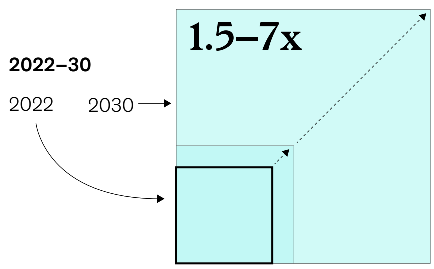
Coauthored with Michel Foucart, Michel Van Hoey, and Patricia Bingoto

DOMAIN

Raw materials

A LARGE TRANSFORMATION

Increase in demand across critical minerals[1]



1 CHALLENGE

Note: This research examines 25 significant physical challenges in seven domains at the core of the energy transition, categorized in three levels. Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning. The focus is on physical realities because they influence the ability to design an interdependent system that has performance comparable to that of the current system and to reduce emissions feasibly. These factors influence cost and affordability. Nonphysical factors—notably cost—are important but are not the focus of this research. Assessment of required deployment of technologies primarily draws on McKinsey's 2023 Achieved Commitments scenario, which assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and in which warming reaches 1.6°C relative to preindustrial levels by 2100. This scenario is used because it provides sufficient regional and sectoral granularity for assessing required deployment. In some instances, this research also uses scenarios from other sources for reasons of data availability.

[1]Across eight critical minerals. The low ends of 1.5 times refers to the minimum value across minerals, while the high end of 7 times refers to the maximum value across minerals. For reference, the average value is around 3 times.

Source: *Global energy perspective 2023*, McKinsey; McKinsey Global Institute analysis

Deploying the billions of low-emissions assets required for the energy transition, from electric cars to wind turbines to electrolyzers, would require access to the raw materials that make up their components. Many of those raw materials already move around the world in substantial amounts, examples being iron ore in the manufacture of steel, limestone for making cement, and wood for alternative construction materials.[542] However, some materials, notably certain minerals that are critical for the low-emissions technologies that will be required to decarbonize many domains, will play a disproportionately important role in the transition. Securing these critical minerals is the main physical challenge—a Level 2 one—in the raw materials domain and is the focus of this chapter.

Challenge 19

Challenge 19: Unearthing critical minerals (Level 2)

Ensuring that sufficient critical minerals are available to support the deployment of low-emissions technologies would require a large scale-up of their extraction and refining. These minerals will be needed, for instance, to produce batteries, wind turbines, electric motors, and electrolyzers. They are a vital enabler of decarbonization across domains.[543]

The many critical minerals required by the energy transition fall into four major categories related to how they are used.

— *Batteries.* Cobalt, graphite, lithium, and nickel, for instance, are used in batteries, such as those that power EVs, and for grid-level storage.

— *Permanent magnets.* Many rare earth elements are used in permanent magnets, which are key components of, for example, EV motors and wind turbines.

— *Electrification and infrastructure.* Copper and aluminum are used in electrical wiring, transmission lines, and transformers, for example.

— *Other applications.* Among other critical minerals are iridium, used in electrolyzers that enable the production of hydrogen, and silicon for the manufacture of solar panels.

The scale-up of critical minerals is still in its early stages. Current supply of critical minerals is only about 10 to 35 percent of what would be needed by 2050 under McKinsey's 2023 Achieved Commitments scenario. Both supply expansion and demand management would be needed to bridge the gap.

The key factors that make this challenge difficult are whether sufficient critical minerals will be available, and quickly enough, to support the deployment of low-emissions technologies. A potential input constraint could arise if the expansion of supply does not occur sufficiently fast. Moreover, demand-management approaches, such as technological substitution, remain somewhat uncertain, and the implications of these approaches for technological performance must be carefully considered.

Demand for critical minerals is expected to soar as the energy transition progresses
Under McKinsey's 2023 Achieved Commitments scenario, demand for seven of the eight critical minerals investigated—lithium, cobalt, nickel, dysprosium, terbium, neodymium, and praseodymium—could at least double by 2030.[544] For example, demand for nickel could double, demand for dysprosium and terbium could quadruple, and demand for lithium could increase sevenfold. This projected surge in demand is largely related to the needs of the energy transition. By 2030, in the Achieved Commitments scenario, low-emissions technologies are expected to drive more than 50 percent of demand for many critical minerals, and as much as 80 or 90 percent of demand for lithium and rare earth elements like dysprosium, praseodymium, neodymium, and terbium.[545]

The spike in demand is likely to be particularly pronounced in the years to 2030, because this is when most new low-emissions technologies would be likely to experience the fastest growth in deployment in typical net-zero scenarios. After 2030, demand for these critical minerals is expected to continue to grow, but at a slower pace.[546]

Supply is not projected to grow as fast as demand under the transition, potentially leading to imbalances
Considering potential demand and supply across various scenarios, the supply of critical minerals is not expected to increase quickly enough to keep pace with the surging demand needs of the transition, particularly in the period to 2030.

McKinsey MineSpans' base-case supply scenario, which includes operating mines and potential new projects (based, for example, on the development stage among other criteria), sees significant imbalances between projected supply and the demand that would be required in the Achieved Commitments scenario.[547] For example, the amount of dysprosium and terbium required could be 75 percent higher than expected supply by 2030. In the case of lithium, it could be 40 percent higher (Exhibit 38). Even when considering potential additional supply sources from announced projects in a high-case scenario, there could still be a medium to high supply-demand imbalance in four of the eight critical minerals examined.[548] This high case includes projects still in the feasibility stage without confirmed financing (and where potential delays could also occur and are accounted for in the scenario). Reaching this high case of supply is by no means guaranteed, and would rely on many conditions being met, including securing the required financing and managing the concurrent execution of multiple projects in parallel. Historically, this has not always been achieved.

Exhibit 38

Demand for critical minerals is expected to grow by up to seven times, with a risk of demand-supply imbalances.

CHALLENGE 19 Unearthing critical materials

MCKINSEY 2023 ACHIEVED COMMITMENTS SCENARIO

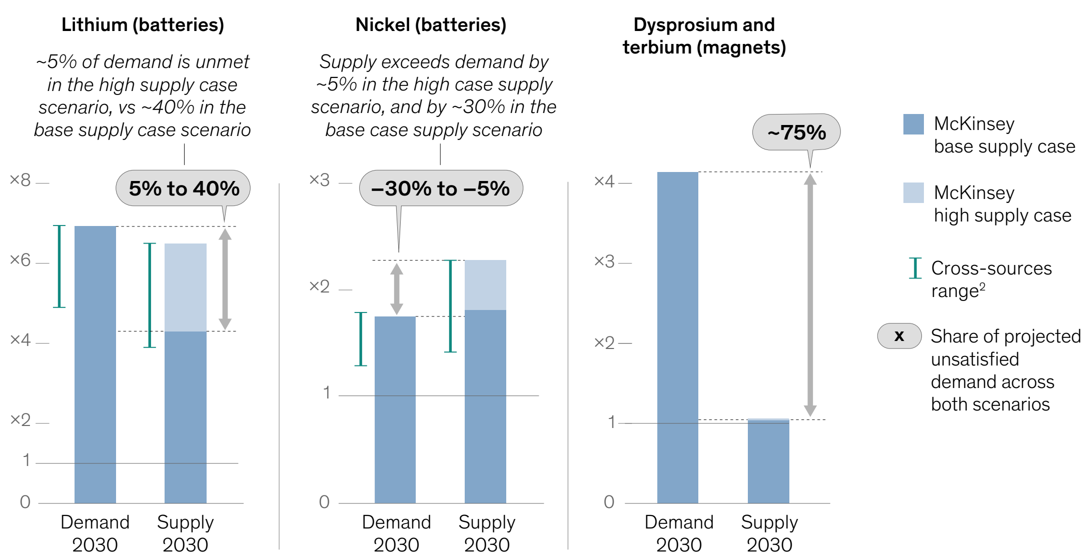
2030 demand increase scenario, index demand 2022=1

Applications	Critical minerals	2030 vs 2022 demand	Supply-demand balance[1] Base supply case	High supply case
Batteries	Lithium	×7	Medium imbalance	No or low imbalance
	Cobalt	×2	No or low imbalance	No or low imbalance
	Nickel	×2	No or low imbalance	No or low imbalance
Permanent magnets	Dysprosium and terbium	×4	High imbalance	High imbalance
	Neodymium and praseodymium	×2.5	Medium imbalance	Medium imbalance
Electrification and infrastructure	Copper	×1.5	Medium imbalance	No or low imbalance

×1

High imbalance
Medium imbalance
No or low imbalance

2030 demand and supply, index demand 2022=1



[1]McKinsey MineSpans' base-case of supply includes all operating mines (corrected for depletion and expected closure where relevant), and a selection of projects currently under construction or at the feasibility stage, and in most cases with financing confirmed. The high-case of supply includes, for example, some projects in feasibility stage and no financing confirmed, with adjustments for potential delays. Note that reaching this high-case of supply is by no means guaranteed, and would rely on many conditions being met, including the required financing and concurrent execution of multiple projects in parallel, which has not historically always been the case. Potential imbalances between required demand and projected supply are classified into three categories. "High imbalance" corresponds to cases in which demand is more than 50% higher than projected supply. "Medium imbalance" corresponds to cases where demand is more than 10% higher than supply, but less than 50%. "No or low imbalance" corresponds to cases where demand is less than 10% higher or even lower than supply.
[2]Ranges from McKinsey and other external sources.
Source: McKinsey MineSpans; International Energy Agency; Energy Transitions Commission; McKinsey Global Institute analysis

A meta review (as of early 2024) of studies of the supply-demand balance in net-zero scenarios, including those from the International Energy Agency, the Energy Transitions Commission, and the International Renewable Energy Agency, also reveals that most expect demand-supply imbalances.[549] The exact size of those imbalances depends on assumptions about how quickly low-emissions technologies are deployed, the specific mix of technologies assumed (for example, different battery chemistries), and how quickly supply ramps up. Imbalances are expected to be more pronounced in the period to 2030 when demand is seen growing fastest, and supply is expected to take time to catch up. Thereafter, as demand growth stabilizes and supply has time to come online, imbalances could ease.

This is not to say that imbalances are inevitable, particularly because there are rapid developments on both the supply and demand sides. For example, in 2023, the output of some critical minerals like lithium, cobalt, and nickel scaled rapidly, by 10 to about 25 percent.[550] China's contribution was notable. It scaled lithium mining output with an increase in production between 2022 and 2023 of almost 50 percent.

Moreover, the knock-on dynamics are far from certain. At the same time that supply scaled up over the past year, EV adoption was slower than expected, reining in demand growth.[551] This change in the supply and demand landscape in 2023 in turn led to drops in prices of some of these critical minerals, which in turn prompted the postponement of some previously announced projects.[552]

Therefore, uncertainty about the evolution of supply and demand remains, and potential imbalances between supply and demand need to be anticipated and managed to ensure that the transition continues apace.[553]

There is no shortage of raw materials, but questions surround how quickly they can be accessed
The physical challenge of expanding the supply of critical minerals is not that there are insufficient critical minerals in the ground, but rather that it takes time for new extraction projects to come online. In fact, resources and reserves of metals and materials such as copper, lithium, and nickel have been increasing as more exploration has been undertaken and, indeed, are at an all-time high.[554] However, lead times to access these reserves can be very long and uncertain. The IEA has estimated that, on average, it has taken 17 years for critical minerals projects to go from discovery to production over the past decade.[555] Copper and nickel projects tend to have the longest lead times at 13 to 19 years. Lithium projects become operational quicker, at about five years.

A number of factors explain these large variations in lead times. Physical factors such as the complexity of accessing the ore can play a large role. Other physical factors can also have a bearing on, for instance, the need to scale up (or even build from scratch) the infrastructure, such as access to power, water, and roads, rail, and ports, needed to support higher supply. This is not easy when mines are in remote locations.

Nonphysical factors, such as the time it takes to get permits and financing, as well as whether enough people with the right skills are available, also determine lead times.[556] Scarcity of available workers such as engineers has been particularly pronounced in many OECD countries. In Australia, for instance, job vacancies in mining have more than doubled since 2020.[557] And fewer people are studying mining. The number of mining engineers graduating has fallen by 60 percent in Australia since 2014 and by 40 percent in the United States since 2016.

Bottlenecks may be present beyond the extraction stage, during the refining of some minerals. Cobalt and lithium are relatively simple to refine, and therefore expanding refining capacity is less likely to be an issue; it can be done in as little as two years in economies where know-how and infrastructure are already strong.[558] But other minerals, including rare earth elements and battery-grade graphite, are more complex to refine, and refining capacity may be trickier to add.[559]

Another pertinent issue is that the extraction and, even more so, the refining of critical minerals are highly concentrated in a few countries around the globe. Therefore, sufficient access to refined minerals relies on the stability of global trade flows.[560]

Diversification would require new regions to ramp up their capacity quickly. For regions that would have to build refining capacity from scratch, for example, and would lack experience and expertise, this would be hard. In some cases, it could take decades (see Sidebar 12, "Critical minerals extraction and refining are highly concentrated, and diversification would take time and effort").[561]

A combination of additional supply and demand levers would be required to alleviate imbalances
Imbalances between projected supply and expected demand for critical minerals would need to be addressed at both ends.

Accelerating supply
There are a number of options for increasing the pace at which supply of critical minerals comes online. One option would be to accelerate lead times of new projects through, for instance, streamlining permitting and planning processes.[562] Innovation in how projects are developed is another way to cut lead times. In the Democratic Republic of Congo, new copper and cobalt assets are being developed faster than ever through a mix of leveraging exploratory work undertaken from the 1960s to 1980s, and using modular construction to accelerate the design, planning, and construction phase.[563]

New technologies could also accelerate the time it takes to develop new projects. For example, direct lithium extraction could help ramp up supply more quickly. This process extracts lithium directly from brine without the need for extensive evaporation ponds. Some projects aim for recovery rates of about 90 percent, compared with 40 to 50 percent for the conventional process, and in only one week compared with 18 months when conventional evaporation ponds are used.[564]

Exploration, too, could be accelerated through the use of new technologies. For example, AI is being used to make exploration techniques more effective by improving estimates of prospective deposits and site selection.[565] Other new technologies being explored, in the case of copper, for example, include bulk-ore sorting, coarse particle recovery, and digital twins of processing flow.[566]

Improving the efficiency of existing assets could also support supply increases.[567] One way to increase efficiency is by ensuring that adequate and high-quality talent is available, for example through effective talent management and worker training.[568]

Recycled supply could also be used to supplement primary supply. End-of-life recycling rates for many critical minerals are relatively low.[569] The EU's Critical Raw Minerals Act has set a target of at least 25 percent of EU annual consumption of each strategic raw material to be met through recycling by 2030.[570] Such measures to increase recycling can scale up the volume of supply, but their impact will not be immediate. This is because, in the short term at least, only a limited volume of materials is available to be recycled because comparatively few low-emissions assets have reached the end of their life.[571]

Reducing demand
Unlocking supply would need to be complemented with action on the demand side. In many cases, it may be possible to reduce the amount of critical minerals needed. Material intensity has fallen in many use cases. For example, the amount of lithium per unit used in EVs dropped by 30 percent, and the amount of polysilicon and silver used in solar panels by 60 to 80 percent, between 2010 and 2022.[572]

Substitutions for some critical minerals could be possible if technological innovation allows. However, even if innovation pans out, there could be trade-offs; some substitutions could result in lower technological performance. In the case of hydrogen electrolyzers, for instance, a shift from proton exchange membrane to other technologies such as alkaline water electrolysis or, later on, solid oxide electrolyzer cells could reduce use of iridium.[573] While it is less expensive than proton exchange membrane, alkaline water electrolysis is not capable of producing high-purity hydrogen gas required for fuel-cell vehicles.[574]

Sidebar 12. Critical minerals extraction and refining are highly concentrated, and diversification would take time and effort

Mining and refining of critical minerals today tend to be largely concentrated in a few economies. This can deliver high efficiency based on specialization and know-how but also poses risks of supply-chain disruptions that, if significant, could even have the potential to delay the energy transition. This reality has come increasingly into focus given recent trade tensions and supply disruptions. In several instances, these tensions and disruptions have affected global flows of critical minerals.[1]

Many of the critical minerals required for the energy transition, including cobalt, lithium, natural graphite, nickel, and rare earth elements, rely on the three largest supplying economies for more than 50 percent of their extraction, and more than 80 percent in the most extreme cases. For instance, Australia, Chile, and China together account for about 90 percent of the global supply of lithium. The Democratic Republic of Congo accounts for more than 75 percent of cobalt extraction, and China for more than 60 percent and 80 percent, respectively, of global extraction of rare earth elements and natural graphite.[2]

Refining of minerals tends to be even more geographically concentrated, with China being far and away the world leader.[3] China accounts for more than 60 percent of the refining of cobalt, lithium, natural graphite, and rare earth elements.

Some diversification is under way in both extraction and refining. By 2030, 35 percent of global lithium production is expected to be sourced in regions that were not mining it in 2020.[4] However, diversification may come up against constraints. One hurdle is environmental concerns. Chile, Serbia, and the United States have all experienced pushback against new mining projects from local communities in recent years.[5] Such concerns relate, for instance, to energy and water requirements in the production and processing of critical minerals. Another issue is that critical minerals often lead to more waste rock than other more commonly extracted ores such as iron, and some of the waste rock and tailings generated in the extraction and processing can contain dangerous substances and damage the environment.[6] The metal content in iron ore is typically 50 to 70 percent, compared to an average of less than 1 percent for copper.[7] By 2050, up to 13 billion tonnes of waste rock with limited applications could be created to produce 300 million tonnes of materials for clean energy technologies.[8]

In addition, some mineral resources occur in places where mining is particularly difficult, for example because they are only accessible at some times of the year due to weather conditions, or because there are concerns whether there is sufficient water.[9]

There are ways to mitigate some of the environmental impact of mineral extraction. One potential approach is to increase the efficiency of the extraction process through technological innovation. For example, reprocessing copper tailings with new solvents and reagents to extract more copper ore would reduce the amount of material moved from new mining operations and use less water.[10] Direct lithium extraction could unlock new supplies while using less water.[11]

Another significant constraint is a shortage of skills, especially in refining. Many processing and refining stages of some critical minerals rely on know-how that is present in only a few economies and companies for specific steps, which makes it hard to replicate in other geographies or firms. It would take years or even decades to fully establish new capabilities.[12]

Potential solutions rely on international collaboration to develop and expand capabilities in new locations. In 2023, the Malaysian government renewed its partnership with the Australian mining company Lynas, creating the biggest refinery of rare earth elements outside China.[13] In 2023, 14 countries and the EU announced the Minerals Security Partnership with the aim of developing a more diversified mineral supply, including both extraction and processing, and announced new projects to diversify processing of minerals such as nickel and natural graphite.[14]

1 For some examples, see Lily Kuo, "The next front in the tech war with China: Graphite (and clean energy)," *Washington Post*, November 29, 2023; *Prohibition of the export of nickel ore*, IEA, December 2023; Matthew Chye, "Chile lithium move latest in global resource nationalism trend," Reuters, April 21, 2023. Also see *Geopolitics and the geometry of global trade*, McKinsey Global Institute, January 2024.
2 McKinsey MineSpans.
3 Ibid.
4 Based on announcements of public projects. See Marcelo Azevedo, Magdalena Baczyńska, Ken Hoffman, and Aleksandra Krauze, "Lithium mining: How new production technologies could fuel the global EV revolution," McKinsey, April 2022.
5 *Latin America's opportunity in critical minerals for the clean energy transition*, IEA, April 2023; Jennifer Mayerie, "Local groups push back against mining near BWCWA: 'This would be a pretty major assault of our ecosystem,'" CBS News, October 19, 2023; and Ivana Sekularac, "Serbia revokes Rio Tinto lithium project licenses amid protests," Reuters, January 20, 2022.
6 Mining waste can contain large quantities of dangerous substances, such as heavy metals. See *Mining waste*, European Commission, accessed May 2024; and *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.
7 *The role of critical minerals in clean energy transitions*, IEA, March 2022.
8 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.
9 *Global critical minerals outlook 2024*, IEA, May 2024.
10 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.
11 Marcelo Azevedo, Magdalena Baczyńska, Ken Hoffman, and Aleksandra Krauze, "Lithium mining: How new production technologies could fuel the global EV revolution," McKinsey, April 2022.
12 Karl Tsuji, *Global value chains: Graphite in lithium-ion batteries for electric vehicles*, Office of Industries working paper ID-090, US International Trade Commission, May 2022.
13 Elouise Fowler, "Malaysian government gives Lynas Rare Earths green light on refinery," *Financial Review*, October 24, 2023.
14 The 14 countries are Australia, Canada, Estonia, Finland, France, Germany, India, Italy, Japan, Norway, South Korea, Sweden, the United Kingdom, and the United States. See *Minerals Security Partnership*, US Department of State, accessed May 2024.

Another example is the fact that some automakers plan to shift toward electric motors that are free of rare earth elements.[575] However, EVs that do not use rare earths could have lower performance, such as lower torque (capacity to do work) and power (ability to do work quickly).[576] Finally, copper wiring can be replaced in many instances with aluminum, whose ore (bauxite) is more abundant. However, the properties of aluminum can be less suitable for some use cases; for example, it can be more prone to heat expansion than copper.[577]

These performance differences mean that alternative technologies may be suitable for some, but not all, use cases. For example, increasing the use of lithium iron phosphate batteries, which are already deployed in about 40 percent of new EVs, could help ease pressure on the supply of cobalt and nickel.[578] These batteries also have lower energy density than the NMC (lithium nickel manganese cobalt) models that are currently most common, but they are still suitable for many mobility use cases when lower ranges are not an issue, an example being relatively small urban cars.

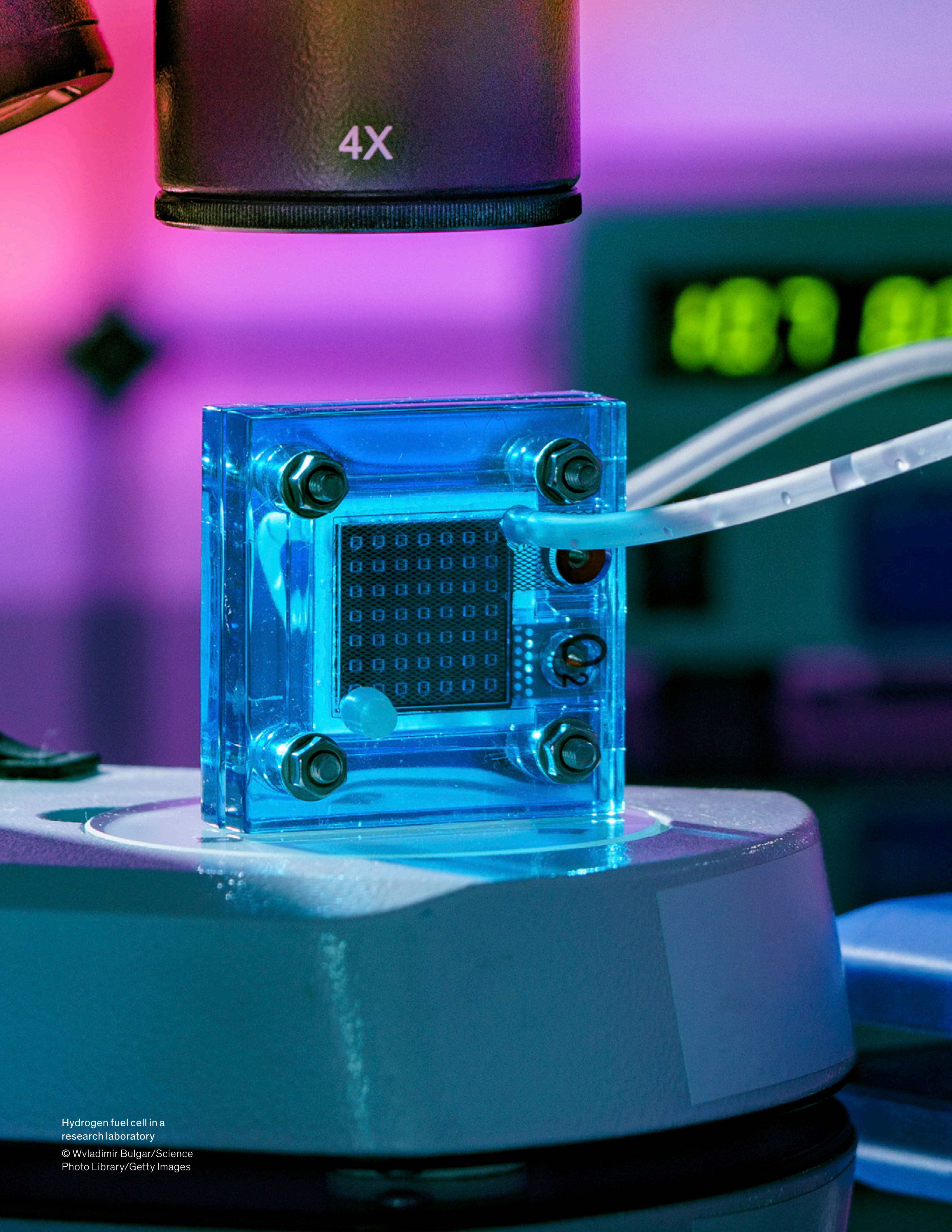
To take another example, sodium-ion batteries are developing. These batteries could become an alternative to lithium-ion batteries, thereby reducing lithium demand. Their lower energy density means they can be particularly suited for use cases where density is less important, such as stationary grid-level storage.[579] In 2023 and 2024, the first stationary projects using sodium-ion batteries were announced, and some EV makers are also planning on launching them for shorter-range vehicles.[580]

Overall, while deployments of new technologies that require smaller quantities of critical minerals are starting to emerge, many of them would need to see much larger scaling. For instance, rare-earth-free motors could scale from less than 10 percent of total supply to making up the majority of new supply by 2030.[581]

...

The energy transition would require growing volumes of critical minerals, especially in the period to 2030. However, even with a surge in new projects that is currently anticipated, expected supply would not keep pace with demand in typical decarbonization scenarios. More effort would be needed to scale supply and manage demand, and therefore this is a Level 2 challenge. To scale extraction and refining capacity, constraints related to lead times, know-how, and other factors would need to be addressed. On the demand side, reducing material intensity and deploying new technologies that use alternative materials could be required. Recycling of end-of-life low-emissions technologies such as batteries could also play a large role. While some of these technologies are mature and already being deployed, others would require further innovation to narrow performance gaps, and many would require further scaling.

The use of LFP batteries, already deployed in 40 percent of new EVs, could help ease pressure on the supply of cobalt and nickel.



Hydrogen fuel cell in a research laboratory

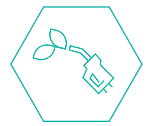
© Wvladimir Bulgar/Science Photo Library/Getty Images

10. Hydrogen and other energy carriers

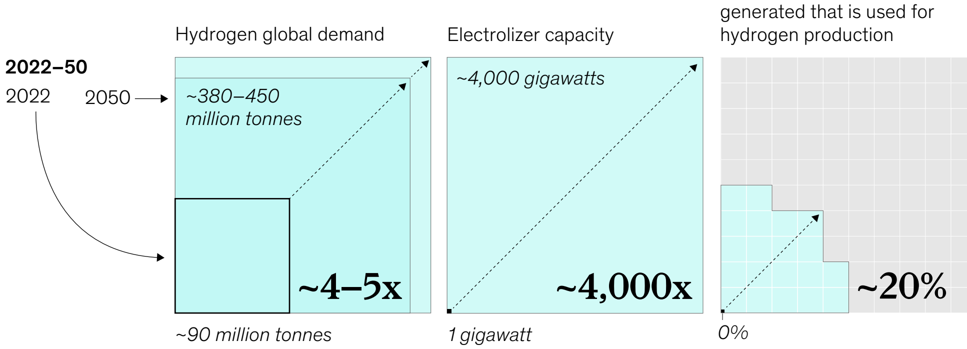
Coauthored with Rory Clune

DOMAIN

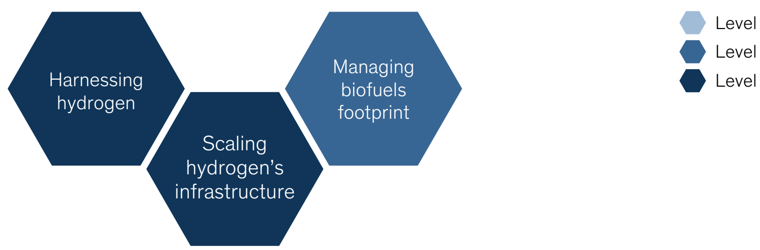
Hydrogen and other energy carriers



A LARGE TRANSFORMATION



3 CHALLENGES



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Source: *Global energy perspective 2023*, McKinsey; International Energy Agency; *New energy outlook 2024*, BloombergNEF, 2024; McKinsey Global Institute analysis

Today's energy system relies on fossil fuels to serve as energy carriers (fuels that enable storing and transporting energy that can be used when and where needed) and as feedstocks for many industrial processes. The energy transition would require new low-emissions alternatives that could serve these functions, since not all use cases would be feasible, or desirable, to electrify.

Hydrogen is being discussed as an important option, especially given its versatility. It has been described as the "Swiss Army knife of decarbonization."[582]

Today, hydrogen is predominantly used for refining fossil fuels (for example, to reduce the sulfur content of oil) and producing fertilizer (ammonia). About 90 million tonnes of hydrogen are consumed every year, and about 99 percent of current production results in high emissions, because it uses fossil fuels as an input and does not use carbon capture to abate resulting emissions.[583]

In a low-emissions energy system, hydrogen use could shift in two key ways. First, its production for current uses would have to be decarbonized. The share of low-emissions production would increase from about 1 percent today to more than 95 percent in 2050 under McKinsey's 2023 Achieved Commitments scenario.[584] In this scenario, about two-thirds of this production would be of electrolytic hydrogen (that is, produced from the electrolysis of water using electricity), with the remainder mostly from fossil fuels combined with carbon capture (see Sidebar 13, "Hydrogen: From production to use").[585]

Second, hydrogen could potentially play a much broader role than today in a low-emissions energy system, serving new use cases, but this would require scaling hydrogen production and doing so in a low-emissions way. Potential applications range from replacing fossil fuels as industrial feedstock in new use cases like steelmaking and plastics, to serving as an energy carrier by converting, transporting, and storing energy that can then fuel power generation, vehicles, and the production of high-temperature heat.

These roles could be enabled by hydrogen's unique physical properties. First, hydrogen can be produced in low-emissions processes such as electrolysis, and it can also be used to provide low-emissions energy. For example, using hydrogen in fuel cells produces electricity and releases water rather than CO_2. Second, hydrogen has a high gravimetric energy density (by unit of mass) that is about three times larger than oil's.[586] Third, burning hydrogen can produce high-temperature heat of more than 2,000°C.[587] Fourth, it can be a low-emissions input to produce low-emissions steel as well as many chemicals and synthetic fuels (when combined with carbon).

At the same time, other physical properties of hydrogen can be tricky to manage. First, hydrogen is hard to store, transport, and use. Its volumetric energy density is about one-half to two-thirds lower than that of natural gas.[588] This means hydrogen needs to be transformed before being stored or transported, for example by being compressed or converted into other molecules in order to reduce the space it takes up.[589] Furthermore, hydrogen is leaky. It is a very small molecule, and leakage can occur during transportation, especially when it is transported in gaseous form. Hydrogen can also permeate pipelines and storage tanks, affecting their structural integrity. Safety considerations are relevant, too. Hydrogen is highly flammable and can ignite more easily than gasoline and natural gas. Its flame is almost invisible, requiring special detection systems.[590]

Second, the processes involved in hydrogen's production, conversion, and use entail substantial energy losses, for example, in the form of waste heat.

Two physical challenges emerge from these physical properties, and both are Level 3. The first is harnessing hydrogen's potential in new use cases by making the most of its advantageous properties, while also managing energy losses. The second is scaling the specialized infrastructure associated with the production, transportation, and use of hydrogen that would be needed to manage hydrogen's tricky physical properties. Both would be hard to address and this leaves considerable uncertainty about how large a role hydrogen could play in a future energy system, and how much of it would be required by 2050.[591] Total hydrogen production may have to scale by as much as four to five times from today according to McKinsey's 2023 Achieved Commitments scenario, the IEA's 2023 Net Zero scenario, and Bloomberg NEF's New Energy Outlook's 2024 Net Zero scenario. In these scenarios, between 380 and 450 million tonnes of hydrogen would need to be produced by 2050.[592] Considerable scaling of production capacity of low-emissions hydrogen would be required, including scaling of associated capacity of electrolyzers (equipment used to produce hydrogen), from about one gigawatt today to about 4,000 gigawatts in 2050 in McKinsey's 2023 Achieved Commitments scenario. And in this scenario, about 20 percent of total electricity consumption in 2050 could be used to power them.[593]

Sidebar 13. Hydrogen: From production to use

Hydrogen is produced, often transported and stored, and then finally used. For each phase of the hydrogen life cycle, different options exist.

Production. There are several ways to produce hydrogen, each of which has a different emissions footprint. These different options are often referred to as hydrogen of different colors:

— *Using unabated fossil fuels.* Hydrogen is produced by separating hydrocarbon molecules into their constituent parts. Hydrogen produced this way is often referred to as gray, black, or brown.[1] The process most frequently employed today is steam methane reforming, which uses natural gas to produce a mixture of CO_2 and hydrogen.[2] More than 99 percent of current hydrogen production uses unabated fossil fuels as feedstocks. This is currently the lower-cost option, but has relatively high carbon emissions at eight to more than 20 tonnes of CO_2 equivalent per tonne of hydrogen produced.[3]

— *Using fossil fuels with carbon capture.* Hydrogen is produced through the same processes as before, but some of the resulting emissions are captured through carbon-capture technologies. Hydrogen produced this way is often referred to as blue. Hydrogen production with carbon capture is currently infrequent—less than 1 percent of hydrogen production currently uses carbon capture.[4] It is also more costly than producing hydrogen through unabated fossil fuels, because of the addition of a carbon capture step. However, it could result in as much as 90 to 95 percent lower emissions per tonne of hydrogen produced.[5]

— *Electrolysis.* Hydrogen can be produced with no direct emissions by electrolyzing water (splitting hydrogen from oxygen in water molecules) through technologies such as alkaline water electrolysis (AWE), proton exchange membrane (PEM), and solid oxide electrolysis cell (SOEC) among others. Very little hydrogen—less than 0.5 percent of global production in 2022—is currently produced through electrolysis.[6] Nonetheless, electrolyzer technologies are mature and proven; AWE and PEM electrolyzers are currently the most commonly used.[7] Today, hydrogen production with electrolysis using renewable electricity costs more than hydrogen production with carbon capture.[8] Hydrogen produced using electrolysis is often referred to as green, pink, or yellow.[9]

— *Other options.* Pyrolysis of natural gas produces hydrogen and solid carbon rather than CO_2 emissions. Hydrogen produced through this route is often called turquoise hydrogen. Only small demonstration projects have been undertaken to date.[10] Naturally occurring hydrogen—often referred to as white hydrogen—could potentially be extracted in a similar way to natural gas. This source of hydrogen is at an early stage of exploration.

Transportation and storage. There are several options for transporting and storing hydrogen:

— *Short-distance transportation.* For transportation over shorter distances, hydrogen is usually compressed. Hydrogen can then be carried by trucks, usually for up to 500 kilometers, or by pipelines over a few thousand kilometers.

— *Long-distance transportation.* For transporting hydrogen across longer distances, other means are needed beyond pipelines and for this to occur would require hydrogen's volume to be reduced by more than compression can achieve. One option for reducing its volume would be to liquefy hydrogen by cooling it to minus 253°C. Hydrogen can also be converted into intermediary chemicals (hydrogen carriers) such as ammonia and liquid organic hydrogen carriers.[11] These carriers are more energy-dense and enable larger amounts of energy to be stored by unit of volume. The liquefied hydrogen or its carriers can then be transported, usually by ship. One main alternative to the transportation of hydrogen itself is the transportation of products that are made using hydrogen, such as direct reduced iron and synthetic fuels.

1 Gray refers to hydrogen produced from natural gas. Black and brown refer to hydrogen produced from different varieties of coal. For all color references in this section see "What is hydrogen energy?" McKinsey, September 27, 2023; and *Hydrogen colours codes*, H2 Bulletin, accessed June 2024.
2 In this process, natural gas (methane) reacts with steam in the presence of a catalyst to produce hydrogen and carbon monoxide (CO). The CO produced is then converted into CO_2 in a water-gas shift reaction. Another common way of producing hydrogen today using fossil fuels is coal gasification.
3 The upper end of this range corresponds to coal gasification, while the lower end corresponds to steam methane reforming, without carbon capture but with best available technologies. See *Comparison of the emissions intensity of different hydrogen production routes*, IEA, 2021, updated June 2023.
4 *Global hydrogen review 2023*, IEA, revised September and December 2023.
5 Kamala Schelling, *Green hydrogen to undercut gray sibling by end of decade*, BloombergNEF, August 9, 2023; *Comparison of the emissions intensity of different hydrogen production routes*, IEA, 2021, updated June 2023.
6 *Global hydrogen review 2023*, IEA, revised September and December 2023.
7 *McKinsey Hydrogen insights 2023*, Hydrogen Council and McKinsey, December 2023.
8 Kamala Schelling, *Green hydrogen to undercut gray sibling by end of decade*, BloombergNEF, August 9, 2023.
9 Green hydrogen is produced using electricity from renewable energy sources. Hydrogen is called yellow when the electricity used in its production is produced from solar power. When the electricity is produced using nuclear power, the hydrogen is called pink.
10 *Global hydrogen review 2023*, IEA, revised September and December 2023.
11 Liquid organic hydrogen carriers (LOHC) are organic compounds that can absorb hydrogen gas and form stable chemical compounds.

Sidebar 13. Hydrogen: From production to use (continued)

— *Storage.* A number of different storage options exist depending on duration and type of discharge (that is, access to the stored hydrogen) needed. For smaller-scale applications, compressed and liquefied hydrogen can be stored in tanks, which enable fast discharge of the stored hydrogen when it is required. For long-term and large-scale storage, a number of options are possible, including salt caverns, depleted oil and gas reservoirs, and water aquifers. Salt caverns are suitable for frequent use, and this approach is mature, with a proven track record of hydrogen storage over five decades.[12] But they are not available at all locations. Porous reservoirs, such as aquifers and depleted oil and gas fields, could be used to store hydrogen. However, their exploration has progressed more slowly and this approach has only been used for mixes of methane and hydrogen, and is not yet proven for pure hydrogen storage.[13]

Use. Hydrogen has several potential use cases. While it is being explored for many applications, its ultimate attractiveness in comparison with alternative technologies is still often debated (see the discussion later in this chapter as part of Challenge 20). Potential uses include ways in which hydrogen is already deployed in industrial settings as well as new use cases in the power, mobility, and industry domains.

— *Industry feedstock.* Hydrogen can be used as an input for many industrial processes. Some of them, including using hydrogen in the production of ammonia and oil refining, are already widely deployed. More nascent use cases—with first projects ramping up in the mid-2020s—include using hydrogen as a reducing agent for stripping oxygen from iron ore in the steel industry and the use of hydrogen and captured carbon to create feedstock for plastics production, such as e-methanol (see chapter 7 on the industry domain).[14]

— *Power storage and generation.* Hydrogen can be used to store energy. Low-emissions power can be used to create hydrogen (known as power-to-gas). When and where the energy is needed, the hydrogen (or a hydrogen derivative) that is produced can then be used in turbines or fuel cells to generate electricity. Today, there are already gas turbines that can be fitted to run on pure hydrogen or a mixture of hydrogen and other gases such as natural gas or syngas—a synthetic gas produced from hydrogen and a mixture of other gases, including carbon monoxide.[15] However, currently essentially no hydrogen is used to generate power at scale—although many utilities companies have demonstrated co-firing of hydrogen and natural gas in initial trials in recent years.[16]

— *Mobility.* Hydrogen can be used as a fuel for road vehicles powered by fuel cells where electrification with batteries may be challenging due to the need for extended ranges and heavy loads, such as long-haul trucks. A small number—about 80,000—of FCEVs (including passenger cars, buses, and trucks) are currently on the road (see chapter 6 on the mobility domain).[17] Hydrogen is also being considered for use in the aviation and maritime sectors, mostly in the form of hydrogen-derivate fuels, such as ammonia and methanol in maritime, and sustainable aviation fuel in aviation. While planes and ships that are technically able to run on some of these fuels are already available today, barely any of such fuels have yet been used. Fossil fuels still provide more than 99 percent of energy used in shipping and aviation.[18]

— *High-temperature heat.* Hydrogen burns at temperatures of more than 2,000°C and could be used to provide high-temperature heat for industrial processes. Multiple pilots are exploring this use—although, in most cases, the hydrogen has been deployed in a mixture with natural gas rather being used by itself.[19] In some markets, hydrogen has also been discussed as a potential option for residential heating, either in isolation or blended with natural gas.[20]

12 *Global hydrogen review 2023*, IEA, revised September and December 2023.
13 Aquifers are underground layers of permeable rock or sediment that can hold and transmit water, and depleted gas fields are reservoirs that have been emptied of natural gas. See *Global hydrogen review 2023*, IEA, revised September and December 2023.
14 "Sustainable feedstocks: Accelerating recarbonization in chemicals," McKinsey, October 2023; *Decarbonization challenge for steel: Hydrogen as a solution in Europe*, McKinsey, April 2020.
15 Mariano Martín Martín, "Syngas," in *Industrial chemical process analysis and design*, Elsevier, 2016; *Hydrogen boiler trials*, Worcester and Bosch, accessed May 2024.
16 *Global hydrogen review 2023*, IEA, revised September and December 2023.
17 "Preparing the world for zero-emission trucks," McKinsey, November 2022.
18 "Global energy perspective 2023: Sustainable fuels outlook," McKinsey, January 2024.
19 *About HyInHeat*, HyInHeat, accessed June 2024; and *Global hydrogen review 2023*, IEA, revised September and December 2023.
20 Chelsea Baldino et al., *Hydrogen for heating? Decarbonization options for households in the European Union in 2050*, ICCT working paper, March 2021.

This massive scale-up of hydrogen production and infrastructure is still in its early stages. While announcements of new low-emissions hydrogen projects have accelerated across the globe, thus far, only a small fraction of all of the announced capacity to date—about 5 percent—has reached a final investment decision. This leaves a lot of uncertainty about the potential for scaling up the projects.[594]

Of course, hydrogen is not the only low-emissions energy carrier that could play a useful role in the energy transition. Energy carriers could be derived from biomass, and could also be pivotal in use cases ranging from industry, such as providing high-temperature heat in the manufacture of cement, to aviation, where they could be an input for sustainable fuel. Challenge 22, a Level 2 challenge related to managing the footprint of biofuels, is summarized in chapter 2 of this report but not explored further here.[595] Under the IEA's Net Zero scenario, use of modern forms of bioenergy (excluding traditional biomass use) would grow by about 8 percent a year between 2022 and 2030, more than double the rate at which it is currently increasing.[596] Continuing to scale production of biofuels would require managing competition for the land they would need. Developing new, more efficient biofuels could help, as would increasing the use of biomass sources such as waste, which does not increase competition for land.

Challenge 20

Challenge 20: Harnessing hydrogen (Level 3)

Hydrogen has significant potential to be an enabler in many domains of the energy transition, including power, mobility, and industry—well beyond today's use cases. However, harnessing hydrogen's potential in new use cases to complement other low-emissions solutions would require balancing a range of advantageous properties with the substantial physical challenges associated with its production, transportation and storage, and use.

Hydrogen is being considered for new use cases, some of which have other low-emissions alternatives

In a scenario where countries meet their stated climate commitments, the majority of potential hydrogen use by 2050 could come from new use cases that have so far not been deployed at scale. Of total potential hydrogen demand in 2050 in McKinsey's 2023 Achieved Commitments scenario, only about one-quarter could come from use cases where hydrogen is already deployed. These use cases are mostly in industry and relate to the refining of fossil fuels and the production of ammonia (fertilizer) and other chemicals.[597] The remaining demand would come from new use cases where uptake of hydrogen has not yet ramped up.

However, in these new use cases, there are often low-emissions alternatives to hydrogen. In some applications, the beneficial properties of hydrogen could eventually enable it to play a leading role in, for instance, steelmaking, as well as in shipping and long-haul aviation, where hydrogen could be used to make synthetic fuel.[598] Such use cases could represent about 35 percent of potential demand for hydrogen under McKinsey's 2023 Achieved Commitments scenario. In other use cases, which account for the remaining 40 percent of potential hydrogen demand by 2050, strong low-emissions alternatives exist, for example in the form of direct electrification. The extent to which hydrogen or other approaches could be used is still uncertain. For example, in power storage a range of technologies, including Li-ion batteries, pumped-hydro storage, novel LDES, and biogas could be used to provide needed storage of different durations. In road mobility, BEVs and vehicles that run on other low-emissions fuels, such as biofuels, can serve different use cases. In industrial heat production, electric heating and low-emissions fuels, such as biomass, are being developed to produce high-temperature heat.

Given that there are alternatives to hydrogen in many use cases, which could either complement hydrogen or be used instead of it, it is important to compare the relative performance of hydrogen and these other options.

Using hydrogen involves energy losses, but offers other advantages

At every stage of hydrogen's journey, from production to transportation, storage, and use, energy is lost. The physical processes that take place during this journey consume energy, and after each step, less energy is available for use (for example, due to losses in the chemical reactions that occur in the step or the production of waste heat).

It is important to take a close look at hydrogen's energy losses because they can influence whether using hydrogen is cost-effective and therefore whether hydrogen is adopted. A large share—as high as 70 percent in some cases—of the total cost of producing hydrogen relates to the energy inputted.[599] More energy is needed when hydrogen is compressed, converted, and transported, and this adds to cost. Furthermore, the sheer amount of energy that hydrogen may require matters for the design of a new energy system, because the higher the energy losses, the more additional electricity generation capacity would need to be built to power hydrogen production. By 2050, 20 percent of total electricity consumption could be used to produce hydrogen—more than total low-emissions electricity currently being generated.[600]

Because energy losses occur at each step, the end-to-end energy efficiency of hydrogen can be low. Energy efficiency is expressed as a ratio of the energy output at the end of each stage to the energy input at the beginning of that stage. In simple terms, it describes the amount of energy that is available for an intended end-use after a given step, divided by the amount of energy that went into that step. For example, during the production stage, efficiency compares the output (energy contained in the hydrogen produced) with the input provided (such as the electricity used to produce that hydrogen). In the use stage, energy efficiency compares the output (for example, the energy delivered from the motor of a car to its wheels) with the input provided (the energy contained in the hydrogen in the fuel tank). Values referenced below are based on the higher heating value (HHV) of hydrogen.[601] In sequence, the efficiency of each step is as follows:

— *Production.* A large amount of energy is needed when hydrogen is produced in order to break chemical bonds and convert inputs, such as natural gas or water, into hydrogen. The energy efficiency of the most common production methods ranges from 75 to 80 percent. This means that about 20 to 25 percent of the energy that was used to produce hydrogen (for example, electricity) is lost, with the rest being contained in hydrogen (in HHV terms) and available for the next step of the process. The exact efficiency figure depends on the specific production method. When hydrogen is produced from unabated fossil fuels, as it is in steam-methane reforming, energy efficiency is about 80 percent.[602] When a carbon capture step is used, efficiency drops to about 75 percent. And energy efficiency when hydrogen is produced through electrolysis currently ranges from about 75 to 80 percent when using AWE and PEM electrolyzers. Nascent solid oxide electrolysis cell (SOEC) electrolyzers, which can make use of waste heat, can deliver efficiency of more than 90 percent.[603]

— *Transportation and storage.* In its raw gaseous form, hydrogen has very low volumetric density and therefore, to be transported and stored, it needs to be either compressed, liquefied, or converted into other molecules. These transformations can also entail significant energy losses incurred during the process. These losses could come from energy spent in compressors or in the reactions to convert hydrogen into another energy carrier. Overall, the energy efficiency of these conversions ranges from 65 to 95 percent. Efficiency is highest when hydrogen is carried over short distances and used without needing to be stored or transformed into other molecules. Efficiency is lowest when it is converted into a different energy carrier and then reconverted into hydrogen. Compressed hydrogen (that remains in gaseous form) transported through pipelines can lead to efficiencies of about 90 to 95 percent. In the case of liquid hydrogen transportation, energy efficiency drops to 65 to 75 percent, because a large amount of energy is spent in the liquefaction process.[604] Additional losses can occur, their magnitude depending on how long the hydrogen is stored and transported. Liquid hydrogen may lose around 0.2 to 0.5 percent of its value every day through boil-off (essentially, evaporation) when being transported by ship, and close to 0.05 percent when kept in stationary storage.[605] The efficiency of the conversion of hydrogen into ammonia is about 80 to 90 percent. However, if ammonia is then reconverted to hydrogen, the total efficiency drops to roughly 65 to 75 percent, given that losses occur in both stages of the transformation. Finally, in the case of liquid organic hydrogen carriers (LOHCs), energy efficiency is about 65 percent, including the reconversion back to hydrogen.[606]

— *Use.* Energy efficiency for the hydrogen use step ranges from 40 to 80 percent (or even 90 percent if released heat is reused). This value corresponds to the energy that is actually converted into useful work (such as movement or power), compared with the energy contained in the hydrogen that is consumed. The remaining energy is lost, for example as waste heat. When hydrogen is used for heating, such as being burned in a boiler, it can reach 75 to 80 percent efficiency, which is similar to the efficiency of natural gas boilers.[607] In road mobility use cases, the energy efficiency of fuel cells is typically 40 to 50 percent; the remaining energy is lost largely as waste heat.[608] In power, it ranges between 40 and 50 percent in the case of peaking power plants when energy is generated, using fuel cells or turbines.[609] Again, efficiencies are similar to those of existing natural gas turbines.[610] Options that reuse released heat to, for instance, heat spaces or water can raise energy efficiency. For example, combined heat and power plants can have energy efficiencies of about 85 to 90 percent.[611]

Hydrogen can be less energy-efficient than electrification in specific use cases
Energy losses at each stage compound. For example, if efficiencies are 80 percent in production, 90 percent in transportation, and 50 percent in use, end-to-end hydrogen efficiency would be around 35 percent.[612]

The result is that hydrogen use would generally lead to lower energy efficiency than direct electrification—when the latter is available. Consider a scenario in which electricity powers an electrolyzer to produce hydrogen that is then compressed and used locally, and compare this with a scenario in which the same electricity is instead used directly.

If hydrogen is used in a FCEV, only about 25 to 35 percent of the energy originally available in the form of electricity is converted into actually running the vehicle. By comparison, a BEV may have 80 to 90 percent energy efficiency, or up to quadruple that of a hydrogen-powered FCEV (Exhibit 39).

When hydrogen is used to produce heat in industrial processes, it delivers end-to-end efficiencies of around 50 to 60 percent. In comparison, direct electrification can have energy efficiency of 90 to 99 percent if resistance-based heating is used, and as much as 150 to 400 percent if heat pumps are used (although they can only reach relatively lower temperatures).[613] All in all, electrification of industrial heat can have from close to twice to up to eight times the efficiency of hydrogen. And when hydrogen is used to store power, only about 25 to 40 percent of the energy drawn from the grid is converted back into power (round-trip efficiency) while the remaining 60 to 75 percent is lost. In comparison, using novel LDES can result in about 40 to 70 percent round-trip energy efficiency—it can range from matching the efficiency of hydrogen to having three times the efficiency.[614] Li-ion batteries and pumped-hydro storage can have even higher round-trip efficiencies of 75 to 90 percent.[615]

These results assume that hydrogen and electricity are produced and used locally. In a scenario where additional transportation losses were incurred (for example, if hydrogen were converted to ammonia and then back to hydrogen), overall energy efficiencies would be even lower. Of course, depending on how and when hydrogen is produced, the impacts on overall system efficiency can differ, which is discussed in the next section (see also Sidebar 14, "Limitations on and assumptions about energy-efficiency calculations").

Exhibit 39

Despite being less efficient than direct electrification, hydrogen has distinctive features for a set of specific use cases.

CHALLENGE

20 Harnessing hydrogen

Technologies

Hydrogen (electrolytic) | Electrification

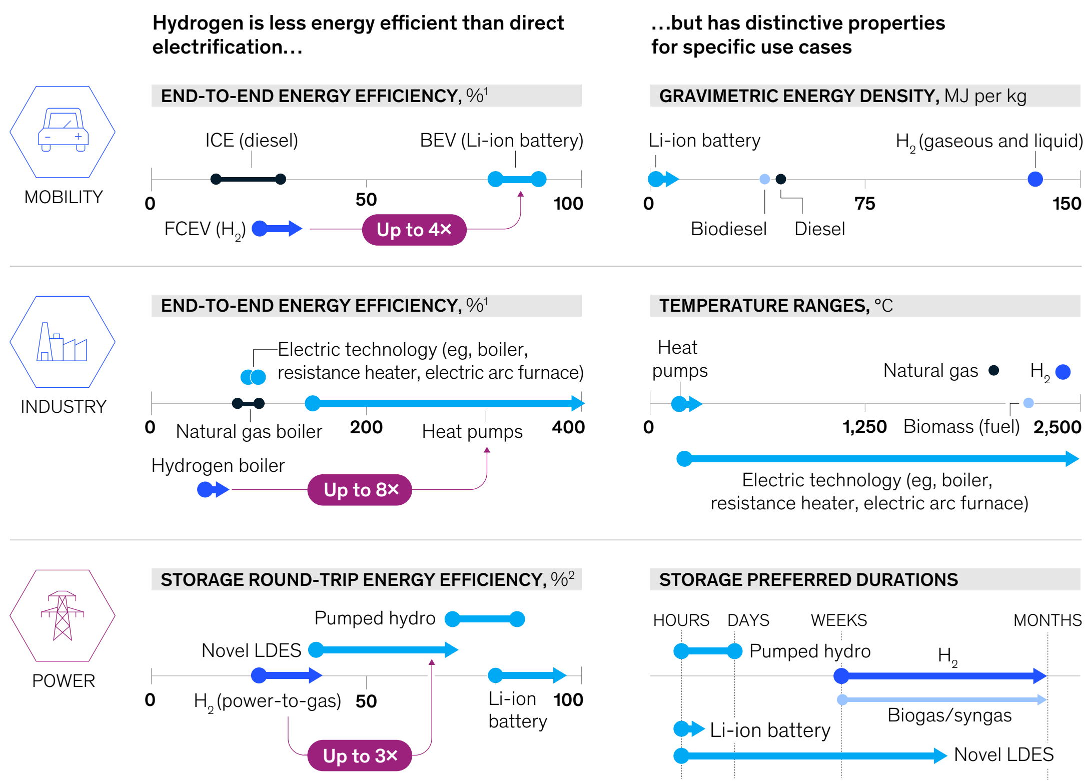
FOR REFERENCE

Other low-emissions | Higher-emissions

Current and potential evolution

Current range

Potential evolution



Note: Efficiency calculations assume electrolytic hydrogen produced from alkaline water electrolysis/proton exchange membrane electrolysis, and transported only for a short distance—the most common scenario. Efficiencies displayed start from the point of final energy—in the case of hydrogen, from the power used to produce it. In that way, efficiencies between hydrogen and electric use cases are directly comparable since they have the same starting point (electricity). Other cases—fossil fuels or biomass—entail other forms of final energy and, as such, are not directly comparable and shown only for reference.

[1]In mobility and industry, all hydrogen and electrification cases consider efficiency from electricity to the fulfillment of useful work (movement and heat, respectively).

[2]Efficiency from storing power and converting it back into power.

Source: Long Duration Energy Storage (LDES) Council; Fraunhofer ISI; US Department of Energy; National Renewable Energy Laboratory; International Energy Agency; Energy Transitions Commission; Hydrogen Council; International Council on Clean Transportation; Hydrogen Science Coalition; Agora Industry; Paschchenko (2024); McKinsey Global Institute analysis

Sidebar 14. Limitations on and assumptions about energy-efficiency calculations

For purposes of comparison, this research looks at the relative efficiency of direct electrification and electrolytic hydrogen, since both start from the same form of energy (electricity). This enables an apples-to-apples comparison of the most efficient use for a given amount of electricity. The efficiencies of use cases involving other sources of energy, such as fossil-fuel-based ICEs and biomass-based boilers, are not directly comparable and displayed only for reference.

Because of the multiple steps and transformations of the hydrogen journey with energy losses at every stage, assumptions made about the precise way that hydrogen is produced are highly relevant to its energy efficiency. This analysis assumes that hydrogen is produced in the most common ways: from alkaline water electrolysis/proton exchange membrane electrolyzers, and then compressed and used locally. To compare hydrogen-based use cases and direct electrification, energy efficiency was calculated starting from the point of use of electricity onward. In the case of hydrogen, this point is the electrolyzer; in the case of direct electrification, it is the point of intake of electricity, such as the charging of an electric vehicle.

Importantly, this comparison assumes that hydrogen and electricity are used locally and at the time of production of electricity, and excludes losses related to the upstream production, storage, or distribution of that electricity. Such considerations could change relative efficiency in specific use cases.

A final caveat is that this analysis is a direct comparison of hydrogen and electrification to help dimensionalize the energy-efficiency implications of using hydrogen. It does not consider other potential upsides of producing and using hydrogen (or electricity) in different locations or at different times from where it was originally produced, which could affect overall system efficiency. We discuss this issue separately later in the chapter.

While it can be less energy-efficient than electrification, hydrogen offers other advantages

Given these efficiency losses, why use hydrogen? Energy efficiency is an important performance parameter when comparing technologies, but it is only one of many factors determining which technology is appropriate for a given use. Consider, for instance, that fossil fuels also have large energy losses—passenger cars convert as little as 15 to at most 30 percent of the energy in diesel into propelling their movement.[616] The fact that fossil fuels are relatively affordable and energy dense has enabled them to be the key fuels for most transportation over the past century despite energy losses.

It is therefore also important to consider hydrogen's other physical properties when comparing it with other low-emissions alternatives. Other physical properties of hydrogen could offer distinct advantages and complement electrification in specific use cases, including the following:

— *Producing high-temperature heat while limiting the retrofitting needed.* Several industrial processes require very high-temperature heat and currently rely on burning fossil fuels, such as natural gas and coal. While different electrification technologies may be able to deliver the temperatures required, deploying them usually entails large retrofits of existing assets (see chapter 7 on the industry domain). Using hydrogen (or hydrogen combined with natural gas) in existing furnaces or boilers could be possible with more limited retrofitting.

— *Storing power for very long durations.* Hydrogen could provide flexibility in power systems by being used to store energy over weeks, months, or even seasons and making the power available when generation from renewables is low due to, say, a lack of wind or sun (see chapter 5 on the power domain). Using hydrogen in this way could also enable more renewable power that would otherwise not be utilized to be stored and used at a later date. Compared with Li-ion batteries, using hydrogen for storage leads to comparatively lower fixed capital costs, but higher operational costs, because energy efficiency is lower.[617] As such, hydrogen could be particularly well suited for use cases where power needs to be stored for very long durations and where bursts of large amounts of power are needed only intermittently or sporadically. Hydrogen could complement Li-ion batteries, which are efficient for use cases that require more frequent and short-discharge durations, such as in the case of intraday storage. Other forms of storage over long periods are possible but have different limitations. There are limited suitable sites for pumped-hydro storage. Biogas used as a fuel in power generation could be limited by whether sufficient biomass is available (see chapter 5 on the power domain). And while novel long-duration energy storage systems, such as compressed air energy storage, are emerging that could play a role similar to that of hydrogen in long-term storage, most of those being tested today are less suitable for the very longest (seasonal shifting) storage purposes over the course of months. The longest-duration storage options currently being tested are designed for heat storage rather than power storage, although this could change with further innovation.[618]

— *Fueling vehicles that need to carry large payloads over long ranges.* Hydrogen and fuels derived from hydrogen can be more than 100 times more energy dense by weight than current batteries (about one megajoule per kilogram in the case of Li-ion batteries, compared with about 140 for hydrogen).[619] The lower energy density of batteries means electric vehicles face trade-offs between range and payload, which affects their performance in use cases such as trucking, shipping, and aviation. Vehicles powered by hydrogen or hydrogen-derived fuels could carry larger payloads without sacrificing so much range. Furthermore, battery electric vehicles take longer to recharge than hydrogen-based vehicles and may face more challenges operating under extremely cold temperatures. In the case of trucking, hydrogen-powered trucks could be one option to meet some of the trickiest routes that demand the highest payloads and ranges. In the case of aviation and shipping, electrification is expected to play a smaller role in the overall energy mix by 2050 than alternative fuels, such as ones based on hydrogen.[620] Of course, using hydrogen in these cases comes with its own caveats. In volumetric terms (that is, by unit of volume), hydrogen's energy density is comparatively less attractive, which means that liquefaction or compression would be needed. Furthermore, refueling infrastructure would need to be developed. Finally, there are alternative fuels beyond hydrogen that have high energy density, notably biofuels, and could also be considered.

— *Substituting fossil-fuel feedstocks for industrial processes.* Hydrogen could be used as a feedstock for many new industrial processes. In steelmaking, for instance, hydrogen can be a low-emissions feedstock as a reductant that replaces coke. While direct electrification (molten ore electrolysis) could also be possible, hydrogen-based approaches are further along the innovation track, with large projects already in place.[621] In other industries, hydrogen combined with captured carbon could provide synthetic feedstocks. For example, it can be used to produce e-methanol, which could, in turn, be used as an alternative feedstock for plastics production. As in the case of fuels, alternative approaches to hydrogen could include bio-based feedstocks and could also be considered (see chapter 7 on the industry domain).

For use cases where both hydrogen and other-low emissions alternatives are available, they could play a complementary role by being suited for slightly different use cases within a given application. For example, while battery electric trucks could cover the majority of freight routes, hydrogen-based trucks could be used for specific routes that require the very longest ranges and largest payloads (see chapter 6 on the mobility domain for further discussion). And while Li-ion and novel LDES could be used for the majority of intraday and intraweek needs, hydrogen could play a complementary role in the very longest seasonal duration storage use cases.

To harness hydrogen's advantages would require innovation, system reconfiguration, and matching it to the right use cases

To leverage hydrogen's advantageous properties, a combination of approaches would be needed, including innovation, the reconfiguration of the energy system, and ensuring that those properties are deployed in the right use cases.

— *Innovation could improve hydrogen energy efficiency to an extent.* Technological advances already under way could lower energy losses during hydrogen's life cycle. In production, SOECs have higher production efficiencies than current AWE/PEM models.[622] SOECs operate at high temperatures (typically over 500°C) and convert water in steam into hydrogen and oxygen, separating the two using an electrolyte.[623] The heat needed to produce the steam could be supplied from alternative sources, such as waste heat from industry, and enhance overall efficiency. Two large SOEC demonstration projects began in 2023. Other electrolyzer technologies could offer 95 percent efficiency and are expected to be commercialized by 2025.[624] Innovation in end uses, such as combined heat and power plants, could deliver higher energy efficiency, too.

— *The energy system could be reconfigured to minimize the impact of energy losses.* Two routes to achieving this are the following:

- *Hydrogen production could be configured to happen where and when it is most beneficial for the efficiency of the overall system.* It makes sense to produce hydrogen when and where it is most efficient to do so. Hydrogen can be used to store large amounts of energy over time. As electrolyzers can be run flexibly, hydrogen can absorb excess renewables production that would otherwise not be utilized—in short, hydrogen can be produced at times when VRE generation exceeds demand.[625] Hydrogen can also be produced in areas where renewables deployment is most efficient. For example, on average, solar power in Spain has double the capacity factors as Germany.[626] Of course, the relative merits of using hydrogen to store and move energy would need to be compared with other forms of storage and energy transportation, such as electric storage and transmission infrastructure. In the case of storage, hydrogen may be particularly suitable for very-long-duration storage in comparison with other options. Generally speaking, transporting hydrogen would be most efficient when the final demand is in the form of hydrogen, while transporting the electricity itself would be most efficient when the final demand is for power. The same logic would apply to hydrogen carriers. Consider ammonia. The efficiency of the system would be highest if ammonia is produced through hydrogen when and where renewables are more plentiful, and if the ammonia is then used in a location directly (say as an input for fertilizer production). Efficiency would be comparatively lower if the ammonia is reconverted back to hydrogen or electricity.

- *Moving intermediate goods with embedded energy could lead to lower energy losses than transporting hydrogen itself.* One of the ways to reduce transportation losses would be to use hydrogen locally to produce intermediate products such as HBI (hot briquetted iron from the DRI process), ethylene, or urea, which could then be transported over longer distances, instead of moving the hydrogen itself.[627] This has the potential to minimize the compounded losses that accrue through production, transportation, storage, and use today. While promising, this approach would necessitate a transformation of our material production system. For example, using HBI as a form of transporting embedded energy would lead to a decoupling of ironmaking and steelmaking steps into different regions.[628]

— *Hydrogen can be prioritized for use cases where it could offer the highest value and complement other approaches.* It makes sense to employ hydrogen in use cases that can make the most of its advantageous properties and in a way that complements electrification and other low-emissions alternatives. Priority could be given to using low-emissions hydrogen where there is no feasible alternative for decarbonization and to use cases where hydrogen offers a clear benefit over low-emissions alternatives. Making sure hydrogen is used optimally would require careful consideration of its physical properties on a case-by-case basis. For instance, hydrogen's chemical flexibility and high energy density could potentially be particularly useful in the production of low-emissions steel and in mobility use cases with the highest payload or range requirements, while hydrogen usage in cases with established high-performing electric-based alternatives (such as low- and medium-temperature heating through heat pumps) would be less clear-cut.

...

Harnessing hydrogen for new use cases is a Level 3 challenge. Some of hydrogen's physical properties make it difficult to deploy, and can result in energy losses during its production, conversion, and use. As a result, using hydrogen is generally less energy efficient than direct electrification when the latter is available. Importantly, hydrogen does have beneficial physical properties. Careful assessment of where those properties could be most useful would help to clarify where hydrogen could most advantageously be deployed. Furthermore, losses would have to be managed, which would require both more innovation of individual technologies—such as new, more efficient electrolyzers—and configuring the energy system to ensure that hydrogen is produced when and where it enables the system to be more efficient overall.

Challenge 21

Challenge 21: Scaling hydrogen's infrastructure (Level 3)

For hydrogen to play a larger role in a low-emissions energy system, a significant scale-up of low-emissions production, transportation, and storage infrastructure would be needed. This, in turn, would require developing supporting supply chains and inputs as well as resolving associated interdependencies.

Hydrogen production would require scaling of capacity, and large-scale power and inputs
More than 1,000 low-emissions hydrogen production projects have been announced globally. Europe has the largest share of announced projects, followed by North America. Despite these developments, actual deployment has been slow. For example, only about 5 percent of planned low-emissions hydrogen production capacity globally has been committed and passed final investment decisions.[629] Today, about one gigawatt of installed electrolysis capacity has been built globally. That would rise by many thousand-fold to about 4,000 gigawatts by 2050 under McKinsey's 2023 Achieved Commitments scenario.

Two key inputs could make expanding hydrogen production capacity harder. First, electrolytic hydrogen production would need a great deal of power. Hydrogen production currently accounts for a very small share of total electricity use. However, by 2030, 3 to 5 percent of total electricity generated could be dedicated to producing low-emissions hydrogen, a figure that climbs to about 20 percent by 2050 under McKinsey's 2023 Achieved Commitment scenario.[630] Second, one of the most common electrolyzer models today—PEM, which accounts for about 30 percent of current electrolyzer installed capacity—relies on critical inputs that could be in short supply, such as iridium and other platinum group metals.[631]

Scaling the capacity for hydrogen production while using fossil fuels in combination with carbon capture would also pose challenges, notably scaling CCUS technologies and transportation, storage, and use options for the carbon captured (see chapter 11 on carbon and energy reduction).

Scaling hydrogen production could be aided by an acceleration in the development of projects and innovation of electrolyzers
To scale hydrogen production capacity, acceleration would be needed in both closing financial commitments and scaling up supply chains and manufacturing. In some regions, this is starting to happen. China is outpacing others on the volume deployed after final investment decisions, and it accounts for about 50 percent of electrolyzer capacity globally.[632]

To provide the necessary expansion of low-emissions power to enable a ramp-up in hydrogen production would necessitate the building of additional dedicated renewable capacity. This is happening in some cases, an example being the construction of an electrolysis plant in Saudi Arabia with a capacity of more than two gigawatts, which is to be powered by four gigawatts of renewable power from onshore solar, wind, and storage. When commissioned in 2026, the plant could produce up to 600 tons of low-emissions hydrogen a day.[633] Such investments are promising, but many more would be needed to achieve the magnitude of the scale-up required.

Innovation could also be instrumental in addressing some of the key input constraints on scale-ups. Different electrolyzer models could alleviate the pressure on critical mineral supplies. The first deployment of iridium-free PEM electrolyzers was announced in 2023.[634] Other technologies, such as SOEC electrolyzers, could also help manage critical mineral and power needs because they can be more energy-efficient than currently used electrolyzer models.[635]

Transportation and storage infrastructure would also need to be scaled up, requiring innovation, new projects, and retrofits

Hydrogen's low volumetric density, potential for leakage, and safety considerations can make it hard to transport. Specialized infrastructure would therefore be needed on a large scale, alongside innovation in cases where technology is less mature, to make its transportation viable.

In the case of short-distance transportation, the cumulative length of hydrogen pipelines could have to scale by about 40 times by 2050, from about 5,000 kilometers today to more than 200,000 by 2050, under the IEA's Net Zero scenario.[636] One way to achieve a scale-up of this magnitude would be through retrofitting to repurpose the extensive network of natural gas pipelines that spans more than one million kilometers today.[637] For example, in July 2023, Germany's gas system operators presented a draft of a hydrogen-transportation network that would include about 9,700 kilometers of repurposed gas pipelines.[638] One concern about developing hydrogen-fit pipelines is embrittlement in the steel and welds caused by the absorption of hydrogen atoms or molecules by the pipe material. As a result, some pipelines, especially older or damaged ones, would need to undergo more extensive retrofitting, such as using pipe coatings or alternative materials like fiber-reinforced plastics.[639]

Transporting hydrogen over long distances would be even harder because it would require approaches other than pipelines, alongside converting hydrogen into other states or other derivatives. Many approaches for long-distance transportation are already mature. For example, transportation of hydrogen carriers such as ammonia and methanol already occurs on a large scale.[640] However, some potential approaches still require further innovation. Ammonia crackers used to reconvert ammonia back to hydrogen are not yet available commercially. In the case of LOHC, while first pilot shipments occurred in 2020 and 2022, experimentation is still under way with different organic carriers to improve the efficiency of the conversion process.[641]

Where needed, shipping would be the most likely option for long-distance transportation of hydrogen, derivatives, or byproducts. Shipping would need about a tenfold scale-up by 2050 under McKinsey's 2023 Achieved Commitments scenario; today, fewer than 100 ships are able to transport these products. Their number could potentially increase to about 1,000 by 2050, split roughly equally into liquefied hydrogen ships, green iron carriers, and hydrogen-derivative carriers.[642] In addition to increasing the number of suitable ships, significant loading and unloading facilities as well as ammonia crackers to transform ammonia back into hydrogen would be required in ports. Here, too, using existing infrastructure could help, although this would necessitate extensive retrofitting. For instance, the European Union has approved financing for the conversion of the Hamburg LNG terminal in Germany so that it can support hydrogen carriers such as ammonia.[643]

Additional scale-up in storage options for hydrogen would also be required, from about 0.5 terawatt-hour today to more than 1,000 terawatt-hours by 2050 under the IEA's Net Zero scenario.[644] Salt caverns are a mature option for storage that has been used since the 1970s, but there are limited numbers of them, and more forms of storage would be needed by 2050. Innovation could help. Trials are under way to test different storage options, including porous reservoirs, such as depleted oil and gas reservoirs, and water aquifers. However, these have not yet been demonstrated for pure hydrogen storage. Multiple projects in Europe and the United States have been launched to test the viability of different sites. Announced storage projects offer capacity of 30 terawatt-hours, split almost equally between salt caverns and depleted gas fields.[645] Other new forms of storage, such as absorption and adsorption, are also promising because they have high densities of volumetric storage and higher efficiency than existing options. However, they are still nascent.[646]

Finally, the assets that use hydrogen would also need to scale significantly. Retrofitting could be an important part of this. Existing assets running on natural gas, including gas turbines for power generation and gas boilers for heat, could be retrofitted to take either pure hydrogen or a blend of hydrogen and natural gas. Current gas turbines are subject to regulatory limits on allowable hydrogen content (typically 1 to 5 percent of volume). However, manufacturers are working on designing combustors retrofitted from existing gas turbines that could run on mixed fuels made up of 100 percent hydrogen. EU turbine manufacturers have committed to delivering standard gas turbines that can handle pure hydrogen by 2030.[647] Likewise, while the use of hydrogen in industrial heating contexts has proven feasible using existing burners, it would require some retrofitting to accommodate the properties of hydrogen gas.[648]

...

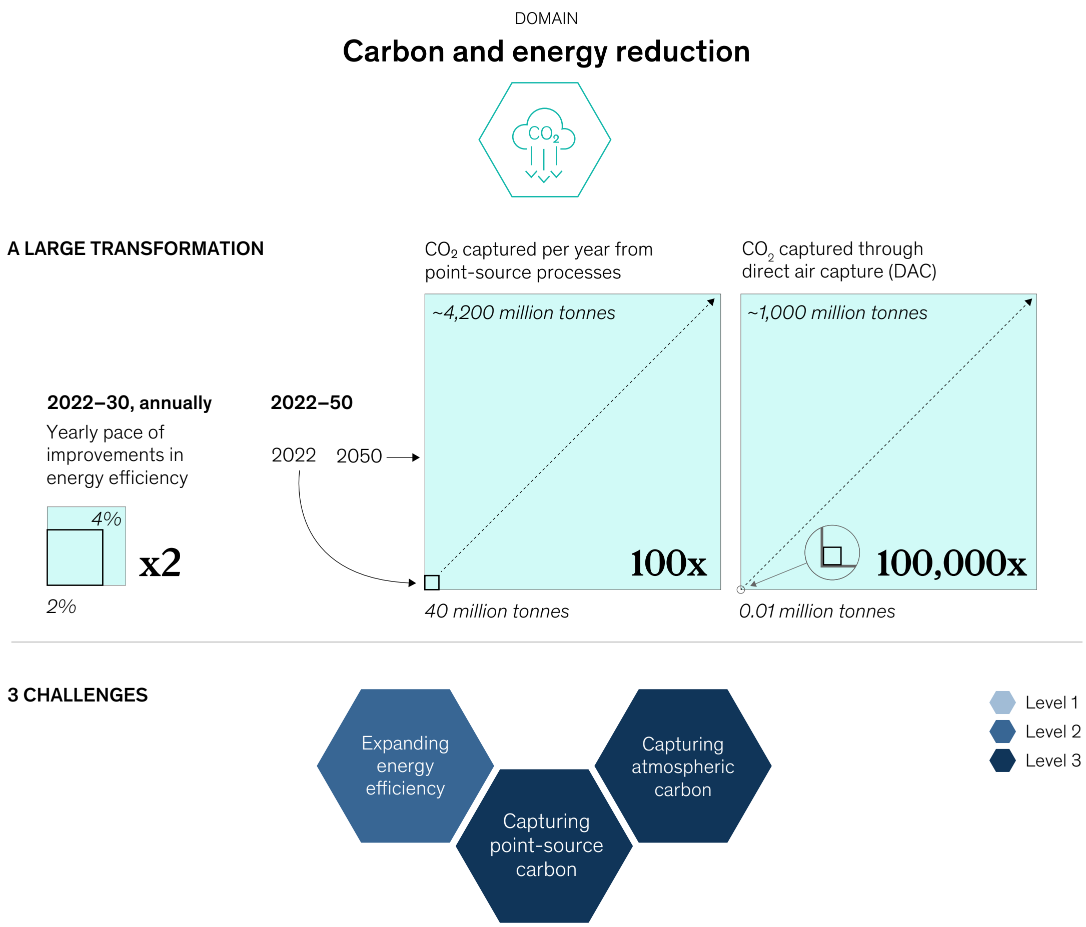
Scaling up hydrogen's infrastructure is a Level 3 challenge. The scale-up of hydrogen production capacity and support infrastructure is nascent. Scaling hydrogen is hard given the amount of specialized infrastructure and inputs required. Production capacity would need to scale up thousands of times, and many of the required technologies (such as some forms of long-distance transportation of hydrogen derivatives and reconversion to hydrogen) have not been developed at scale. More innovation could help manage tricky input needs (power and critical minerals) and unlock new approaches to transportation, storage, and use. Retrofitting existing assets could help scale hydrogen-ready infrastructure more rapidly, but comes with its own challenges and substantial dedicated infrastructure would still have to be built.

Scaling hydrogen is hard given the amount of specialized infrastructure and inputs required.

Carbon capture and
sequestration machine
under construction

11. Carbon and energy reduction

Coauthored with Clint Wood and Santhosh Shankar



Note: This research examines 25 significant physical challenges in seven domains at the core of the energy transition, categorized in three levels. Level 1 challenges require progress in deploying established technologies and face the least physical hurdles. Level 2 challenges require the deployment of known technologies to accelerate, and associated infrastructure and inputs to be scaled. Level 3 challenges occur when there are gaps in technological performance (often with demanding use cases), large interdependencies exist, and the transformation is just beginning. The focus is on physical realities because they influence the ability to design an interdependent system that has performance comparable to that of the current system and to reduce emissions feasibly. These factors influence cost and affordability. Nonphysical factors—notably cost—are important but are not the focus of this research. Assessment of required deployment of technologies primarily draws on McKinsey's 2023 Achieved Commitments scenario, which assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and in which warming reaches 1.6°C relative to preindustrial levels by 2100. This scenario is used because it provides sufficient regional and sectoral granularity for assessing required deployment. In some instances, this research also uses scenarios from other sources for reasons of data availability.
Source: *Global energy perspective 2023,* McKinsey; International Energy Agency; McKinsey Global Institute analysis

Under typical decarbonization scenarios, most of the CO_2 abatement required to achieve stated climate commitments is expected to come from replacing high-emissions technologies with new low-emissions ones, including, for instance, replacing cars running on gasoline with electric vehicles and replacing gas furnaces with heat pumps. But another opportunity comes from managing the emissions footprint of high-emissions assets to reduce overall CO_2 emissions.

This goal could be achieved in three ways, each of which is important to consider. First, energy efficiency can be a cheap and relatively quick measure to implement in order to reduce the emissions of many energy uses, including power generation, transportation, buildings, and industry.[649] Second, high-emissions assets could be transformed into low-emissions ones through the use of carbon capture technologies. Finally, any emissions that continue to occur could be directly removed from the atmosphere through carbon dioxide removal (CDR) and, in particular, direct air capture (DAC). Each of the three presents a physical challenge.

— *Challenge 23: Expanding energy efficiency (Level 2).* The first approach is to ensure greater energy efficiency, so that less energy is used overall for a given process. This could include more efficient lighting and equipment, improved vehicle fuel efficiency, and industrial-process improvements. The Intergovernmental Panel on Climate Change finds that energy efficiency mitigation options could contribute more than five gigatonnes of CO_2-equivalent to net emissions reduction by 2030.[650] The pace of energy efficiency improvements would have to grow in most net-zero scenarios. For example, in the IEA's Net Zero scenario, improvements in energy efficiency would need to double, from 2 percent a year currently to just above 4 percent on average in the period to 2030.[651] This challenge is classified as Level 2 because the technologies are mature, but a large transformation would be needed to retrofit many millions or even billions of assets, such as industrial sites and buildings. This would take time and effort and would come with deployment challenges and upfront costs. This challenge is summarized in chapter 2 but not explored further in this chapter.[652]

— *Challenge 24: Capturing point-source carbon (Level 3).* The second approach is capturing any residual CO_2 that is emitted at point sources, by using carbon capture, utilization, and storage (CCUS) technologies. But CCUS is harder to deploy in processes where CO_2 is present at lower concentrations in flue gases, which is true for the majority of emissions today. Moreover, the captured CO_2 would need to be transported and stored. Ramping up the use of CCUS would require resolving these issues. This is a particularly difficult, Level 3, challenge, defined as having a hard use case and a transformation that is only just beginning. That challenge is the focus of this chapter.

— *Challenge 25: Capturing atmospheric carbon (Level 3).* The third approach is developing and deploying a second distinct but related set of technologies, which include CDR, by capturing carbon directly from the atmosphere.[653] DAC removes CO_2 directly from the atmosphere and could play a role alongside nature-based carbon removal (the latter is not explored in this report). DAC currently captures only about 0.01 million tonnes of CO_2.[654] Under the IEA's Net Zero scenario, the scale-up would need to be tremendous—by as much as 1,000 million tonnes by 2050.[655] Overall, carbon removal technologies are nascent, and their high energy intensity makes their use challenging. This challenge is also classified as Level 3, since deployment would have to start from a negligible base today, and atmospheric capture could prove to be even harder than point-source capture. Again, this challenge is summarized in chapter 2 but is not discussed further in this chapter.

Challenge 24

Challenge 24: Capturing point-source carbon (Level 3)

CCUS refers to a group of technologies that, as the name suggests, capture CO_2 from industrial and power processes—point sources—to prevent it from entering the atmosphere, and then use or store it. These technologies have been around for decades. One is amine-based scrubbing, which has been used in industrial processes since the 1930s.[656]

CCUS could be an important tool for advancing the energy transition. In several use cases across the energy system, low-emissions technologies may have limitations that prevent them from delivering full decarbonization. In industry, for example, deploying technologies to capture carbon could be particularly important for reducing process emissions generated in the production of cement (Challenge 13), since those emissions would continue to be created even if the use of fossil fuels to generate heat in cement production were to be replaced completely. Furthermore, carbon capture technologies, if successfully applied, could be used to enable the decarbonization of existing infrastructure, avoiding the need for full replacement. Capture units deployed on existing industrial emitting equipment, such as hydrogen steam methane reformers, would lower the overall emissions intensity of the production processes. The captured CO_2 could potentially be deployed for other uses, for instance to manufacture synthetic fuels and chemicals such as e-methanol (see Sidebar 15, "The three stages of the CCUS life cycle").[657]

However, various difficulties exist. Despite the fact that many CCUS technologies have been around for decades, widespread adoption has been limited. One important reason is that high costs have made the business case challenging.[658] Fundamental physical challenges remain that relate to the effectiveness of technologies and to the storage and use of captured CO_2, outlined later. As of 2022, only about 30 commercial CCUS facilities were operating around the world, mostly in specific industrial processes, such as gas processing and ethanol production.[659] In all, carbon capture totaled about 40 million tonnes of CO_2 a year, or only some 0.1 percent of global emissions from the energy system.[660] Existing facilities include the RasGas CO_2 Injection Project in Qatar and the Boundary Dam 3 in Canada, which could capture 2.2 million and 1.0 million tonnes a year, respectively.[661]

Overall, then, the use of CCUS remains in its early stages, and its deployment would need to expand by a much more significant degree under typical decarbonization scenarios.[662] By 2050, the use of CCUS would be at least 100 times larger than today's in McKinsey's 2023 Achieved Commitments scenario. More than 4,200 million tonnes of CO_2 would potentially need to be captured. However, the extent to which CCUS would scale is subject to a considerable degree of uncertainty.[663] For CCUS to achieve large scale-ups, it would need to overcome physical challenges—most critically, being deployed in new processes with lower concentrations of CO_2, which would be harder to do.

Sidebar 15. The three stages of the CCUS life cycle

The CCUS life cycle includes capturing carbon, transporting it, and finally storing or using it.

Capture. Carbon capture from point-source emissions separates CO_2 from the rest of the gases in a flue stream emitted by an industrial (or power generation) process. There are four main methods for achieving this today. Each can be capital-intensive to deploy and would require significant amounts of energy to run.

Absorption. CO_2 emissions are captured through a chemical reaction of the CO_2 gas with a liquid solvent, such as an amine-based solvent. This results in a solution that contains the absorbed CO_2.[1] Amine scrubbing is a mature technology that has been used commercially for more than 40 years. However, liquid amine-based solvents do not perform as well as solid sorbents at low CO_2 concentrations: the mass of CO_2 transported is lower, and thus there are smaller effects than with solid-sorbent-based technologies.[2]

Membranes. Permeable or semipermeable membranes allow CO_2 to pass through while blocking other components, thus reducing energy consumption, with a lower physical and chemical footprint.[3] These technologies have been used in processes such as natural-gas sweetening.[4] However, they are mostly applicable only when the concentration of CO_2 in the flue gas is high.

Adsorption. Capture no longer occurs using a liquid solvent, but rather with a solid compound that has a CO_2-reactive agent fixed to it. In this approach, CO_2 passes over the solid sorbent, which separates CO_2 from flue gases when the gas comes into contact with the solid surface.[5] This technology has not yet been deployed on a large scale, but it has the potential to perform better at lower CO_2 concentrations.[6]

Oxy-fuel combustion. Fossil fuels are burned with pure oxygen instead of air (oxygen is

1 Examples include monoethanolamine, diethanolamine, and alkaloamines. See David Kearns, Harry Liu, and Chris Consoli, *Technology readiness and costs of CCS*, Global CCS Institute, March 2021.

2 "Appendix E: Mature CO_2 capture technologies," in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use and storage*, National Petroleum Council, March 2021.

3 Rujing Hou et al., "Current state and advances in membrane technology for carbon capture," Separation and Purification Technology, volume 300, November 2, 2022.

4 Natural-gas sweetening removes all or part of acid gases to meet natural-gas specifications on toxicity and corrosion. See *Carbon dioxide capture approaches*, National Energy Technology Laboratory, US Department of Energy, February 2019; Rujing Hou et al., "Current state and advances in membrane technology for carbon capture," *Separation and Purification Technology*, volume 300, November 2, 2022; and Sebastien Duval, "Natural gas sweetening," in Qiwei Wang, ed., *Surface process, transportation, and storage*, Oil and Gas Chemistry Management series, 2022.

5 David Kearns, Harry Liu, and Chris Consoli, *Technology readiness and costs of CCS*, Global CCS Institute, March 2021.

6 "CO_2 capture," in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use and storage*, National Petroleum Council, March 2021; Sander van Paasen et al., "Development of the solid sorbent technology for post combustion CO_2 capture towards commercial prototype," *International Journal of Greenhouse Gas Control*, volume 109, July 2021.

Sidebar 15. The three stages of the CCUS life cycle (continued)

produced from air using an air separation unit).[7] Combusting fuels in this way results in a flue stream that is purer than one burned with air and has a higher concentration of CO_2, making its capture easier. The CO_2 typically can be separated from the flue gas stream using a dehydrator. This technology is in its early stages of development, and R&D efforts are under way to improve performance and system design.[8]

Several other technologies are in the early research and testing phases, including cryogenic distillation, ceramic autothermal reactors, and chemical looping systems.[9]

Compression and transportation. Captured carbon can be used on site or compressed, liquefied, or both in order to be transported and stored.[10] Pipelines to transport CO_2 have been operating for a long time in the oil and gas sector, mainly in the United States. Pipelines are the primary and least expensive mode of transporting CO_2. The shipping of liquid and supercritical compressed CO_2 is an emerging technology depending on the new generation of tankers, which can expand access to storage locations over longer distances.[11] Transportation by rail and truck is generally limited to low volumes and short-distance applications, given high per-unit costs.[12]

Storage. CO_2 is generally stored by injecting compressed CO_2 into geological formations, such as saline aquifers, depleted oil and gas reservoirs, and coal seams.[13] It is typically stored in a supercritical state, reducing the overall volume of CO_2 in storage.[14] Other storage options are being explored, such as storage in concrete and in basaltic rock formations, where CO_2 tends to mineralize when in contact with the chemicals in the rock.[15] Selecting and monitoring storage sites is critical for safety and to avoid the risk of leakage; large-scale CO_2 storage facilities have shown that the risk can be mitigated if storage is managed effectively.[16]

Use. Captured CO_2 can be employed in many ways. Today it is most commonly used in enhanced oil recovery (EOR), where it is injected into oil reservoirs to increase production. About half of the 30 large-scale CCUS facilities operating today provide CO_2 for use in EOR. However, EOR use goes hand in hand with continued emissions. Moreover, demand for EOR would likely not meet demand for CO_2 captured under typical decarbonization scenarios. Therefore, other use cases for captured CO_2 would need to scale. With the potential to support decarbonization in other domains too, new approaches have started to take off, including producing synthetic fuels; producing materials such as CO_2-cured cement and concrete, plastics, chemicals, and new materials, including polyethylene and polypropylene; and other uses, such as urea production, with applications in agriculture and food production.[17] Additional uses matter because they could help with the economics of capture and strengthen its business case, increasing adoption.

7 Hamidreza Gohari Darabkhani, Hirbod Varasteh, and Bahamin Bazooyar, "Oxygen production and air separation units," in *Carbon capture technologies for gas-turbine-based power plants*, Elsevier, 2022.
8 *Oxy-combustion*, National Energy Technology Laboratory, US Department of Energy, accessed June 2024.
9 Y. Zeng et al., "A novel cyclic process for synthesis gas production," *Chemical Engineering Science*, volume 48, issues 3–6, February–March 2003; and Anuj Joshi et al., "Chemical looping: A perspective on the next-gen technology for efficient fossil fuel utilization," *Advances in Applied Energy*, volume 25, August 2021.
10 *Pathways to commercial liftoff: Carbon capture*, US Department of Energy, April 2023.
11 Supercritical CO_2 remains in a fluid state when it is held above its critical temperature and pressure. See *CCUS around the world in 2021: Northern Lights*, IEA, April 2021; *Mitsubishi Shipbuilding holds launch ceremony in Shimonoseki for demonstration test ship for liquefied CO_2 transport*, Mitsubishi Heavy Industries, March 2023; *CO_2 transport and storage*, IEA, accessed June 2024; and *CO_2 compression: Stranger things?* Thunder Said Energy, February 2023.
12 *Transporting CO_2, fact sheet*, CCS Institute, accessed June 2024.
13 *Commercial carbon dioxide uses: Carbon dioxide enhanced oil recovery*, National Energy Technology Laboratory, US Department of Energy, accessed June 2024; and Christophe McGlade, "Can CO_2-EOR really provide carbon-negative oil?," IEA, April 2019.
14 *What is carbon capture and storage? Carbon storage FAQs*, National Energy Technology Laboratory, US Department of Energy, accessed June 2024.
15 Mineralization is the process that converts CO_2 into a solid mineral, thus preventing its release into the atmosphere. See *Making minerals—how growing rocks can help reduce carbon emissions*, USGS, March 2019; Wan Yun Hong, "A techno-economic review on carbon capture, utilisation and storage systems for achieving a net zero CO_2 emissions future," *Carbon Capture Science and Technology*, volume 3, June 2022; and "Ocean storage," in *IPCC special report on carbon dioxide capture and storage*, IPCC, 2018.
16 Raimund Malischek and Samantha McCulloch, *The world has vast capacity to store CO_2: Net zero means we'll need it*, IEA, April 2021.
17 "A new era for CCUS," in *Energy perspectives 2020*, IEA, September 2020; and *Maersk secures green e-methanol for the world's first container vessel operating on carbon neutral fuel*, Maersk, August 19, 2021.

It is harder to deploy CCUS in lower-concentration use cases, but they are the source of most emissions

A key physical challenge in scaling the deployment of CCUS is that capturing carbon from flue gases with low CO_2 concentrations and higher levels of impurities is harder, is more energy-intensive, and costs more than capturing carbon from flue gases with high CO_2 concentrations and lower levels of impurities.

In this report, emissions from industrial and power generation sources fall into three main categories, according to concentration levels (Exhibit 40).[664] They are (1) high concentrations of CO_2, with more than 50 percent CO_2 concentrations in the flue stream—for instance, in natural gas processing and ammonia and ethanol production; (2) intermediate concentrations of 15 to 50 percent in the flue stream—for example, in heavy industrial processes such as steel and cement manufacture; and (3) low concentrations of less than 15 percent in the flue stream—for example, in coal-fired and natural gas–fired power plants.[665]

All else being equal, the effectiveness of any carbon capture system is inversely related to the concentration of CO_2 in flue gases. Concentration affects the amount of energy needed, the type of technology that can be deployed, and the equipment required to capture CO_2.[666] Ultimately, these factors also affect costs; capturing CO_2 in lower concentrations is more expensive. For example, capturing emissions during the production of steel, with concentrations between 20 and 30 percent, could be three to four times more costly than it is during chemical processing, where concentrations are relatively high, at 80 to 90 percent.

Consider energy use. More dilute concentrations require more energy.[667] In the case of amine-based solutions, for example, lower concentrations of CO_2 mean that more heat (and therefore more energy) is needed for the separation and recovery of the CO_2 from the solution.[668]

Moreover, the type of technology deployed is also influenced by the concentration of CO_2 and affects energy consumption. Chemical reactions are often employed to capture CO_2 in lower concentrations, whereas at higher concentrations the capture could take place via “physical” mechanisms. The CO_2 captured via a chemical reaction is bound more strongly, which would require more energy to undo and release the CO_2 for use and storage.[669]

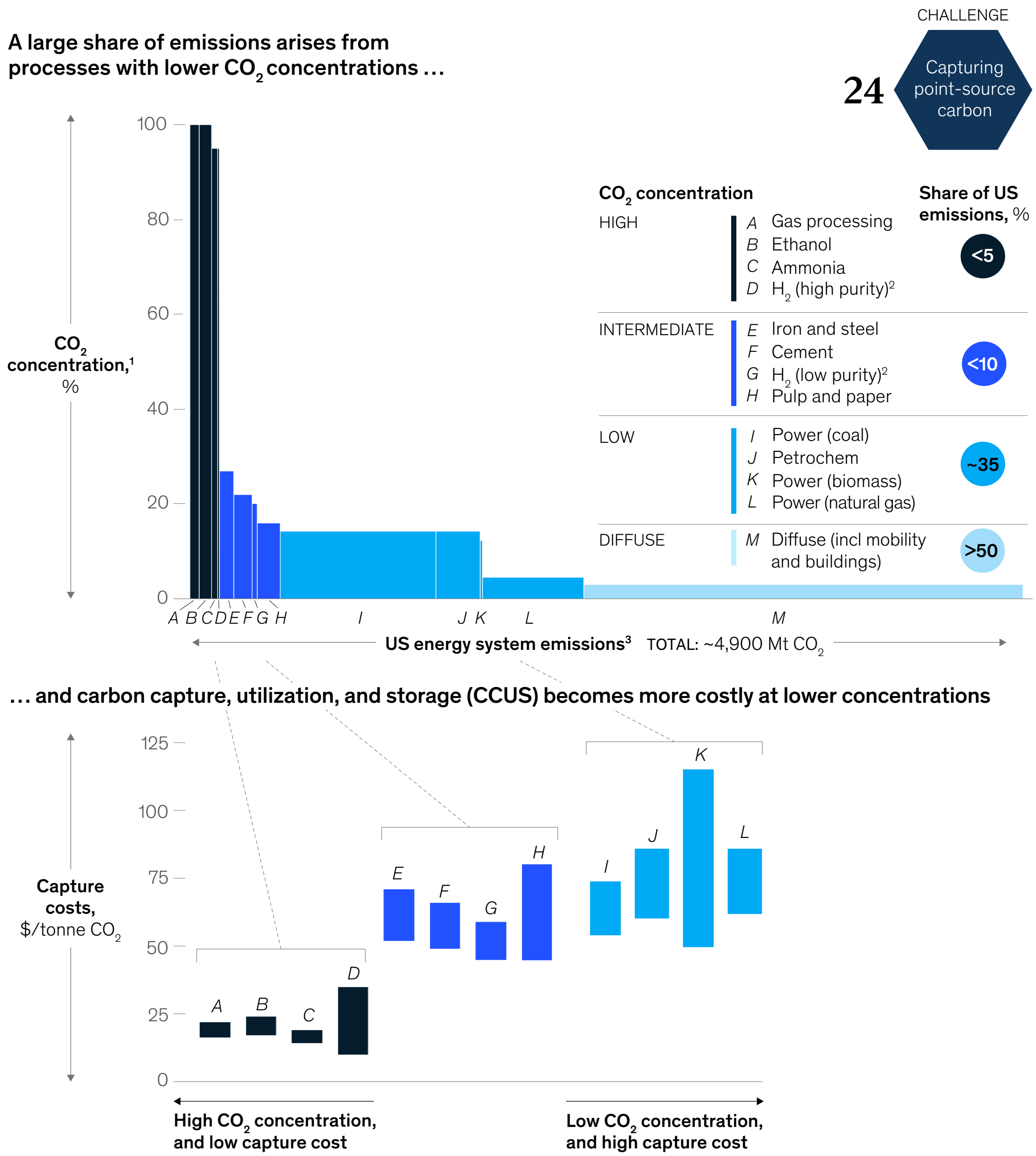
Last, lower concentrations also often require the processing of a larger amount of flue gases to obtain the same amount of CO_2 captured, which creates the need for larger or more units of equipment.[670] For example, at lower concentrations, larger assets, such as taller scrubbing columns, are required. Lower concentrations also mean more stages, more time, and more packing and can require other enhancements in the capture equipment.[671] This may also involve ancillary equipment, such as multiple heat exchangers, coolers, pumps, and blowers—all raising capital and operating costs.

So far, CCUS has been deployed almost exclusively where high concentrations are present, such as in the processing of natural gas, ammonia, and ethanol.[672] The issue is that high-concentration processes account for less than 5 percent of CO_2 emissions, with emissions today in the United States as an example.

To deploy CCUS on a larger scale would require applications in emissions streams with intermediate and low concentrations.[673] As discussed, in 2050 about 4,200 million tonnes of CO_2 would need to be captured in the 2023 McKinsey Achieved Commitments scenario. Of the total that would be captured in 2050, more than 60 percent could come from low- and intermediate-concentration point sources. The rest is projected to come from high-concentration point sources, mostly the production of low-emissions hydrogen (which would grow significantly in comparison with today’s production), as well as from other high-concentration use cases where CCUS technologies are already mature today.[674]

Exhibit 40

Most emissions arise from processes with low CO_2 concentration, where carbon capture, utilization, and storage is harder and more costly to deploy.



[1] CO_2 concentration refers to the degree of concentration of CO_2 in the flue gas, also associated with the level of purity, with high purity referring to high CO_2 concentration. Note that all values denote averages for the US only.
[2] Hydrogen emissions can range from isolated high-purity streams (lower cost) to lower-purity combined streams (higher cost).
[3] Globally the emissions mix differs from that of the US.
Source: US Environmental Protection Agency; Global CCS Institute; National Petroleum Council; Santos et al. (2021); Lagnholtz et al. (2020); National Energy Technology Laboratory; US Energy Information Administration; McKinsey Global Institute analysis

CCUS technologies have other operational challenges

The vast majority of carbon capture processes are not aimed at capturing 100 percent of the CO_2 in point-source flue gases, because targeting higher capture rates is proportionately more costly. One of the reasons for this problem is that many industrial processes have multiple sources of emissions, each with its own distinct profile, and this makes it difficult to aggregate these emissions into a single stream to be captured. For these reasons, carbon capture is often being considered only for some sources of flue gas emissions and not others. In steel, where emissions happen at many points in the process, most target capture rates being considered range from about 50 to 90 percent.[675]

Moreover, operational challenges and risks surrounding first-of-their-kind plants—for instance, risks such as a lack of operational experience—often prevent CCUS facilities from achieving target capture rates and mean that effective capture rates are lower. For example, effective capture rates in some projects have been about 30 percentage points lower than expected when the projects were designed.[676] Other operational issues that have an impact on effective capture include unscheduled downtime: the amount of time that the operating facility is not capturing carbon.

Issues that arise in the storage stage can affect capture rates, too. They include clogging of injection wells, issues with monitoring instrumentation, and leakage of storage sites.

Advances in CCUS technologies could address capture issues

A number of advances in CCUS technologies address issues in the capture stage, including capture at low concentrations and establishing operational best practices. A number of developing CCUS industry consortia share experience and best practices.[677]

To tackle the issue of capture in lower concentrations, several projects are under way from R&D to pilot, with plans to launch over the next five years.[678] In the case of absorption processes, improvements are in the works to reduce the energy consumption of recovering captured CO_2—for example, using sterically hindered amines that form weaker bonds with the captured CO_2 and therefore require less energy to break them.[679] In adsorption processes, innovations in solid sorbents are promising. Solid sorbents have been used since the 1990s on the International Space Station to remove CO_2 at very low concentrations from the ambient air.[680] The level of focus has also increased on new approaches to capture CO_2—for example, oxy-fuel processes that result in higher-concentration CO_2 streams, where the carbon is easier to capture. Industrial-process reengineering to create purer CO_2 streams is also happening in cement production, where the LEILAC project aims to electrify part of the heating process, thereby creating a pure CO_2 stream that arises from process emissions, which would be easier to capture (see chapter 7).[681] While these approaches are promising, additional exploration through more and higher-scale applications is needed to determine their efficacy.

R&D investment in CCUS technologies and project deployment can accelerate advances in capture rates at low concentrations and help to address operational issues. The United Kingdom announced a £20 billion investment to strengthen its CCUS market.[682] In the United States, the Energy Act of 2020, the Bipartisan Infrastructure Law of 2021, and the Inflation Reduction Act of 2022 included investments in research and offered deployment incentives for CCUS technologies.[683] This program includes authorization for various carbon management and removal programs, such as large-scale pilot projects and commercial-scale demonstrations in heavy industry, the development of large-scale storage projects, and the establishment of a carbon utilization program.

Once captured, a massive amount of carbon needs to be transported and used or stored
If carbon capture scaled up, the carbon would have to be transported and used or stored. A large scale-up of supporting infrastructure would be needed.

— *Transportation.* CO_2 can be transported by pipeline, ship, truck, and rail, and the technology to transport gases or liquids via these methods is fairly mature. However, transportation infrastructure needs to scale up enormously to support CCUS technologies by 2050, and this effort remains at an early stage, especially in the case of shipping and rail.[684] According to the IEA's Net Zero scenario, between 30,000 and 50,000 kilometers of pipelines would be needed to transport CO_2 by 2030, which is a 2.0 to 3.5 times increase from the 14,500 kilometers now under development.[685] Today, 85 percent of CO_2 pipelines are located in the United States.[686] More pipeline infrastructure would be needed elsewhere to support global growth in CCUS applications. Similarly, shipping is emerging for large-scale transportation but remains limited.[687]

— *Use.* The most mature use case for captured carbon thus far, as noted, is enhanced oil recovery, or EOR. However, as also noted, use of EOR continues to produce emissions. Together with the fact that demand for EOR would not be likely to match demand for CO_2 captured under typical decarbonization scenarios, this means that other use cases for captured CO_2 would need to scale. Additional uses that have started to take off could increase the business case for CCUS and help with the economics of capture. They could further reduce emissions if the captured carbon was used to displace fossil fuels. These applications would range from use in construction materials, such as cement and plastics, to the creation of synthetic fuels for aviation or shipping.[688] While their development would accelerate adoption of CCUS by strengthening the business case, today their high manufacturing cost and power intensity often limit feasibility (absent a market premium or regulatory support), as is the case with synthetic fuel.

— *Storage.* High-level geological analysis suggests that the world has ample CO_2 storage capacity—even accounting for accessibility, commercial viability, land use, and public acceptance—mostly in deep saline formations and depleted oil and gas fields. Current estimates of available storage capacity range between 8,000 gigatonnes and 55,000 gigatonnes.[689] This by far exceeds the estimates of what is required from today to 2050 in McKinsey's 2023 Achieved Commitments scenario.[690] However, further study is required to ensure the long-term durability and permanence of the storage sites.

Different implementation models could address transportation, use, and storage challenges
With a few exceptions, most CCUS projects to date have been developed and operated by a single entity, which transports CO_2 from one capture facility to a single injection site. An alternative approach would be to share infrastructure between emitters and those who provide CCUS services. In such business models, separate entities would deal with carbon capture, transportation, and storage.[691] This approach could be effective because it would expand opportunities for CCUS and unlock scale benefits by aggregating a larger stable volume of CO_2. New projects that have been announced attempt to do this. In total, more than 140 CCUS hubs were in development as of 2023—more than three times as many as in 2021—with most of the activity concentrated in Europe and North America.[692]

Increased collaboration could also support the expansion of carbon capture. Projects are now relying on partnerships between private and public entities. For example, Porthos (the Port of Rotterdam CO_2 Transport Hub and Offshore Storage project) aims to capture CO_2 emitted by industrial facilities located in the port of Rotterdam and to transport and sequester the CO_2 by injecting it into a depleted natural-gas reservoir in the North Sea. Porthos, a partnership between the Port of Rotterdam Authority and energy companies Gasunie and EBN, is enabled with EU funding.[693] Similarly, the Northern Lights project, a partnership among Equinor, Shell, and Total, is the first cross-border CO_2 transportation and storage infrastructure network. It complements Longship, which is the government of Norway's large-scale carbon capture and storage project at a cement factory.[694] Together, such joint efforts and their sharing of risks and costs (as well as streamlining of interdependencies) could support investments in these technologies. Learning from operations and sharing the know-how developed by executing large-scale CCUS projects can help to accelerate successful deployment in the future.

...

Capturing point-source carbon is a Level 3 challenge. If CCUS is to serve as an important decarbonization lever, physical challenges in applying it to use cases with lower concentrations of CO_2 must be overcome. Carbon capture would potentially need to scale up more than 100 times by 2050, and even more than that in lower-concentration streams. New capture technologies and processes could help to deliver the performance required by these use cases, but many of them remain in the early stages of deployment. Moreover, a high degree of transformation (in the form of a significant scale-up of CCUS facilities and supporting infrastructure, such as pipelines and ports) would be required.

If CCUS is to serve as an important decarbonization lever, physical challenges in applying it to use cases with lower concentrations of CO_2 must be overcome.

Water engineer at a riverside sustainable power station

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Endnotes

Introduction

1 *How the world really works: The science behind how we got here and where we're going*, Vaclav Smil, May 2022.

2 McKinsey EMIT database, 2023.

3 *Primary energy consumption as of 2022*, Energy Institute, accessed May 2024.

4 *The Paris Agreement*, United Nations, 2015.

5 The Intergovernmental Panel on Climate Change (IPCC) has found that to limit global warming to 1.5°C with no, or limited, overshoot (with a greater than 50 percent probability), greenhouse gas emissions would have to be reduced by 43 percent by 2030, and CO_2 emissions by about 100 percent by 2050, in relation to modeled 2019 emissions levels. (Each of those values is the median of the estimates in various scenarios). See *Climate change 2022: Mitigation of climate change*, IPCC, 2022.

6 "ChatGPT witnesses massive rise, Chatbot gains 100 million users in two months," *Economic Times*, March 2023.

7 Vaclav Smil, *Halfway between Kyoto and 2050: Zero carbon is a highly unlikely outcome*, 2024; and Daniel Yergin, "Bumps in the energy transition," Finance & Development, International Monetary Fund, December 2022.

8 Vaclav Smil, *Energy transitions: Global and national perspectives*, second expanded and updated edition, Praeger, 2016; and *Statistical review of world energy*, Energy Institute, 2023.

9 Roger Fouquet, "Historical energy transitions: Speed, prices and system transformation," *Energy Research & Social Science*, volume 22, December 2016. Fouquet defines a transition as the diffusion of energy sources and technologies from 5 to 80 percent of the energy consumption of a particular service in a particular sector.

10 See, for example, *ETP Clean energy technology guide*, updated September 14, 2023; *The state of clean technology manufacturing*, International Energy Agency (IEA), May 2023; *Global critical minerals outlook 2024*, IEA, May 2024; *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach 2023 update*, IEA, September 2023; *World energy transitions outlook 2023: 1.5°C pathway*, International Renewable Energy Agency, 2023; *New energy outlook 2023*, BloombergNEF, 2023; *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023; and *Better, faster, cleaner: Securing clean energy technology supply chains*, Energy Transitions Commission, June 2023.

11 *An affordable, reliable, competitive path to net zero*, McKinsey Sustainability, November 2023.

12 *Solving the net-zero equation: Nine requirements for a more orderly transition*, McKinsey Sustainability, October 2021; *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.

13 Nell Derick Debevoise, "The third critical step in problem solving that Einstein missed," *Forbes*, January 26, 2021.

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14 *Number of people lacking access to reliable electricity services*, United Nations Development Programme, 2022.

15 Clemens Forman et al., "Estimating the global waste heat potential," *Renewable and Sustainable Energy Reviews*, volume 57, May 2016; *Energy flow charts: Charting the complex relationships among energy, water, and carbon*, Flowcharts, Lawrence Livermore National Laboratory and Department of Energy, accessed July 2024; Paul Martin, *The primary energy fallacy—or, committest thou NOT the 2nd sin of thermodynamics!*, June 2024.

16 McKinsey EMIT database, 2023. Global CO_2 emissions from energy combustion and industrial processes total about 37 gigatons, with about five gigatons in agriculture, forestry, and other land use. In the case of methane, more than approximately 35 percent of global emissions arise from the energy system, from combustion and industrial processes, with the remaining 65 percent divided between agriculture, at about 40 percent, and waste and other sectors, at about 25 percent (data for 2021).

17 See also *An affordable, reliable, competitive path to net zero*, McKinsey Sustainability, November 2023. It is also important to take a holistic view of the socioeconomic impacts of different transition pathways and to use this perspective to help inform decision making. See *Climate Transition Impact Framework: Essential elements for an equitable and inclusive transition*, McKinsey Sustainability, December 2023; and "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey Sustainability, October 2021.

18 This report typically uses the 2023 McKinsey Achieved Commitments scenario to define progress made to date and the magnitude of the transformation needed. This scenario provides detail across different economies and types of assets about the deployment levels that would be required for those economies to meet the climate commitments they have made. This scenario assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments and that warming reaches 1.6°C relative to preindustrial levels by 2100. See *Global energy perspective 2023*, McKinsey, October 2023. Other net-zero scenarios may contain slightly different combinations of technologies and rates of deployment, but the broad trends and themes described in this research would still apply. This report is based on analysis as of September 2023. Subsequent developments in the energy system may lead to different outcomes, which will be covered in forthcoming McKinsey research.

19 *Global EV Data Explorer*, IEA, April 23, 2024; and *Renewable capacity statistics 2023*, International Renewable Energy Agency, 2023.

20 Simulations are based on the McKinsey Power Model using the McKinsey 2023 Achieved Commitments scenario.

21 A range of nonphysical factors, notably cost and consumer preferences, could also be important in determining EV adoption, but these are not the focus of this research.

22 Vaclav Smil, "The modern world can't exist without these four ingredients. They all require fossil fuels," *Time*, May 12, 2022; and *Global energy perspective 2023*, McKinsey, October 2023.

23 Other operational challenges related to the scale-up of heat pumps are not discussed in this research. They include the need to scale up manufacturing capacity for heat pumps, whether sufficient skilled labor is available to install them, whether consumers adopt them given their associated costs, and the large turnover and retrofits that the installation of heat pumps would entail so that they can perform effectively.

24 Under a scenario in which all heating of buildings is electrified. See Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, February 2020. Other McKinsey and external research found similar increases of two to three times for colder states. *The role of natural gas in the move to cleaner, more reliable power*, McKinsey, September 2023; and *2050 transition study*, ISO New England Inc. Transmission Planning, February 2024.

25 *Hydrogen insights 2023*, Hydrogen Council and McKinsey, May 2023, updated December 2023.

Chapter 1

26 This research includes the nonenergy uses of energy resources in materials production, namely as feedstocks (for example, the use of oil as a feedstock for the production of plastics). For comprehensive definitions relating to the energy system, see "Glossary" in *Climate change 2014: Mitigation of climate change*, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2014.

27 *The world's nine largest operating power plants are hydroelectric facilities*, Today in Energy, US Energy Information Administration, October 2016; *Number of people lacking access to reliable electricity services*, United Nations Development Programme, 2022; Population data, World Bank, accessed July 2024; and Logan Byers et al., Global database of power plants, World Resources Institute, March 2018.

28 Global gas infrastructure tracker and Global oil infrastructure tracker, Global Energy Monitor, accessed July 2024.

29 McKinsey Basic Materials Institute; Plastic Collective, "Plastic pollution facts, data and statistics," blog entry, December 11, 2023; and *Ammonia technology roadmap: Towards more sustainable nitrogen fertilizer production*, IEA, October 2021.

30 Vehicle parc, also known as vehicle fleet or vehicle stock, refers to the total number of registered vehicles that are in active use within a particular geographic area at a given time. Numbers on vehicle parc include passenger vehicles, trucks, light commercial vehicles, and buses, which collectively account for 95 percent of road transportation emissions. The figures exclude two- and three-wheelers for data availability reasons. See *Global energy perspective 2023*, McKinsey, October 2023.

31 *Liquefied natural gas: Understanding the basic facts*, US Department of Energy, 2005.

32 *Flexibility in thermal power plants, With a focus on existing coal-fired power plants*, Agora Energiewende, June 2017.

33 In the case of fertilizer, natural gas is a feedstock for most of today's production of ammonia, which is in turn used in nitrogen-based fertilizers. In the case of steel, while coking coal is the most commonly used fossil fuel, natural gas can also be used as a reductant in direct iron reduction processes. In the case of plastics, natural gas is used as feedstock in many regions, as a source of ethane.

34 Among the other important issues that relate to the current energy system are energy security risks, in particular for economies that lack domestic energy supply; and the system's contribution to air pollution and other pollution. While important, these issues are not highlighted in this report whose focus is the energy transition arising from the system's production of greenhouse gas emissions. Estimates of impact of air pollution vary widely, but many studies cite five million to ten million premature deaths per year as a result. See "Fossil fuel air pollution responsible for 1 in 5 deaths worldwide," Harvard T. H. Chan School of Public Health, February 9, 2021; and Max Roser, *Data review: How many people die from air pollution?* Our World in Data, November 25, 2021.

35 Clemens Forman et al., "Estimating the global waste heat potential," *Renewable and Sustainable Energy Reviews*, volume 57, May 3016; *Energy flow charts*, Flowcharts, Lawrence Livermore National Laboratory and Department of Energy, accessed July 2024; and Paul Martin, *The primary energy fallacy—or, committest thou NOT the 2nd sin of thermodynamics!*, June 2024.

36 Global CO_2 emissions from energy combustion and industrial processes total about 37 gigatonnes, with about five gigatonnes in agriculture, forestry, and other land use. In the case of methane, more than approximately 35 percent of global emissions arise from the energy system, from combustion and industrial processes, with the remaining 65 percent divided between agriculture, at about 40 percent, and waste and other sectors at about 25 percent (data for 2021); McKinsey EMIT database, 2023.

37 This is based solely on tailpipe emissions; if upstream emissions were included, the figure could be closer to three kilograms of CO_2. See *Comparison: Your car vs. an electric vehicle*, US Environmental Protection Agency; and *Forests, health and climate change*, European Environment Agency, July 2023.

38 Vaclav Smil, *Halfway between Kyoto and 2050: Zero carbon is a highly unlikely outcome*, 2024; Roger Fouquet, "Historical energy transitions: Speed, prices and system transformation," *Energy Research & Social Science*, volume 22, December 2016; and Daniel Yergin, "Bumps in the energy transition," *Finance & Development*, International Monetary Fund, December 2022.

39 In many countries, and for specific communities, energy and associated sectors are also a source of jobs and economic activity. Transforming the current system therefore also has the potential to affect these parts of the world disproportionately, and stakeholders will need to consider how to manage the transition for these regions. For further detail, see *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.

40 Total final consumption per capita for 2021. Consumption data come from the IEA and population data from the World Bank. In useful energy terms (accounting for different levels of wasted energy), per capita consumption in Thailand is roughly half that in Germany. See *Energy flow charts*, Lawrence Livermore National Laboratory, 2017.

41 Laura Cozzi et al., *Access to electricity improves slightly in 2023, but still far from the pace needed to meet SDG7*, IEA, September 2023.

42 Gravimetric energy density is expressed in megajoules per kilogram. *See Assessment of the extra capacity required of alternative energy electrical power systems to completely replace fossil fuels*, GTK, August 2021.

43 In some cases, the cost of individual low-emissions assets may also be lower than that of high-emissions ones. The most common example of this is the levelized cost of electricity (LCOE) generation from solar and wind onshore, which can be lower than fossil-fuel-based power generation's. However, LCOE comparisons are an incomplete means to compare technologies with very different generation profiles (such as solar in comparison to gas generation). For example, LCOE does not factor in additional system integration costs (such as the need for storage or impacts on the utilization rate of existing thermal assets) or the value of the contribution of different generation assets to the overall power system. These aspects and others would need to be evaluated to design affordable energy systems. For more detail, see chapter 5 of this report and "Batteries and secure energy transitions," in *World energy outlook special report*, IEA, April 2024; *Levelized costs of new generation resources in the Annual Energy Outlook 2023*, US Energy Information Administration, April 2023; *2023 Levelized Cost Of Energy+*, Lazard, 2023; and *Projected costs of generating electricity*, IEA and Nuclear Energy Agency, December 2020.

44 Gas-fired peaking plants are designed to balance fluctuating power in the electricity network, operating when demand is high and the electricity supply falls short.

45 The capacity factor of a generation asset indicates what share of the time it is generating power. It is calculated by dividing output over a period by the maximum possible output if the asset were running at full capacity continuously over the same period. See *Land-based wind market report: 2023 edition*, Office of Energy Efficiency & Renewable Energy, US Department of Energy, August 2023; and McKinsey Battery Insights. High-emissions technologies also improve over time, and the relative performance of the system as a whole depends on improvements across both low- and high-emissions technologies. See *Vehicle fuel economy in major markets 2005–2019*, IEA, August 2021. For example, the mileage of ICEs in the United States has roughly doubled in the past 50 years.

46 *Net-zero heat: Long-duration energy storage to accelerate energy system decarbonization*, McKinsey Sustainability, November 2022; and "Industrial heat pumps: Five considerations for future growth," McKinsey, March 2024.

47 Raw materials encompass a wide range of physical elements, including minerals, fossil fuels, and agricultural and forestry products. This research focuses on critical minerals for the energy transition, defined as those that are essential for the development and deployment of low-emissions energy and technologies, and that may be in high demand while limited in their availability during the energy transition.

48 *CO_2 emissions in 2023: A new record high, but is there light at the end of the tunnel?*, IEA, March 2024; and *Statistical review of world energy*, Energy Institute, 2023.

49 This research uses primary energy here because it is a widely available global metric that gives a rough indication of current contributions of different energy sources to the energy system and therefore helps gauge the scale of the future transformation that is needed. But there are limitations to comparisons of primary energy contributions from fossil fuels and other energy sources, given that most energy contained in fossil fuels is lost in conversions. Today, almost 70 percent of primary energy in the United States is lost in energy conversions, with only 30 percent being converted into useful energy. While the primary energy metric used by the Energy Institute cited here accounts for some of the conversion losses by using a substitution method, use losses are not factored in. During the energy transition, therefore, not all primary energy supply would need to be replaced one-for-one, given that many electrification technologies have higher end-use efficiencies with less conversion loss. See *Primary energy consumption as of 2022*, Energy Institute, accessed May 2024; and *Energy flow charts*, Lawrence Livermore National Laboratory, 2022.

50 *Electrification*, IEA, accessed May 2024.

51 Share of deployment is used to understand the current state of the transition and to understand the nature of what lies ahead. Of course, today's low-emissions stock of assets may not exist by 2050 (for example, some assets may have lifetimes of ten or 15 years and would need to be replaced before then), and some of today's high-emissions assets could also be naturally turned over between now and 2050 as they reach the end of their useful life. Moreover, the energy system is expected to grow, and some of the deployment required in 2050 is driven by growth and not solely by the substitution of existing low-emissions assets. Nonetheless, this measure of today's deployment of low-emissions assets relative to the deployment needed by 2050 is a helpful indication of the degree of transformation that has been accomplished to date, how far along the energy transition is, and the scale of future transformation needed.

52 *Global EV Data Explorer*, IEA, April 23, 2024; and *Renewable capacity statistics 2023*, International Renewable Energy Agency, 2023.

53 This report typically uses the 2023 McKinsey Achieved Commitments scenario to define progress made to date and the magnitude of the transformation needed. This scenario provides detail across different economies and types of assets about the deployment levels that would be required for those economies to meet the climate commitments they have made. This scenario assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments, and that warming reaches 1.6°C relative to preindustrial levels by 2100. See *Global energy perspective 2023*, McKinsey, October 2023. Other net-zero scenarios may contain slightly different combinations of technologies and rates of deployment, but the broad trends and themes described in this research would still apply.

54 This report is based on analysis as of September 2023. Subsequent developments in the energy system may lead to different outcomes, which will be covered in forthcoming McKinsey research.

55 For example, the IPPC has found that to limit global warming to 1.5°C with no, or limited, overshoot (with a

greater than 50 percent probability), greenhouse gas emissions would have to be reduced by 43 percent by 2030, and CO_2 emissions by about 100 percent by 2050, in relation to modeled 2019 emissions levels. (Each of those values is the median of the estimates in various scenarios). See *Climate change 2022: Mitigation of climate change*, IPCC, 2022.

56 *Global energy perspective 2023*, McKinsey, October 2023.

57 Variable renewable energy sources include sources whose output depends on weather conditions and is therefore not guaranteed at all times, for example solar and wind power. Clean firm power sources combine low emissions with the ability to have a controllable output that does not vary with weather conditions. They are nuclear, hydropower, geothermal, and power plants with carbon capture, among others. See Jesse D. Jenkins, Max Luke, and Samuel Thernstrom, "Getting to zero carbon emissions in the electric power sector," *Joule*, volume 2, issue 12, December 2018.

58 *Electricity 2024: Analysis and forecast to 2026*, IEA, revised January and May 2024.

59 Ibid.

60 Nelson Nsitem, "Global energy storage market records biggest jump yet," BloombergNEF, April 25, 2024.

61 EVs refers to battery EVs (BEVs) and fuel-cell EVs (FCEVs). BEVs are powered by electricity stored in a battery pack and use an electric motor instead of an ICE. FCEVs are also propelled by an electric motor but are powered by hydrogen fuel cells. See *How do all-electric cars work?* US Department of Energy, accessed May 2024; and *How do fuel cell electric vehicles work using hydrogen?* US Department of Energy, accessed May 2024. The figures cited include passenger vehicles, trucks, light commercial vehicles, and buses. They exclude two- and three-wheelers. Under McKinsey's Achieved Commitments scenario, ICEs still constitute about 20 percent of total four-wheeled vehicle stock in 2050. Electric two- and three-wheelers have experienced comparatively larger deployment, with a penetration rate currently of about 8 percent. See *Global EV outlook*, IEA, April 2024.

62 *Global EV outlook 2024*, IEA, April 2024.

63 Both battery electric and fuel-cell electric trucks are included; McKinsey Center for Future Mobility model.

64 See "Shipping and aviation," in *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023. Other forms of transportation such as rail contribute only about 1 percent of total emissions and are not discussed as part of this report. See *Global energy perspective 2023*, McKinsey, October 2023.

65 *Global energy perspective 2023*, McKinsey, October 2023; and *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

66 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

67 *Net zero by 2050: A roadmap for the global energy sector*, IEA, May 2021.

68 McKinsey MineSpans.

69 McKinsey MineSpans; and *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023.

70 Between 380 and 450 million tonnes of hydrogen would need to be produced by 2050, according to McKinsey's 2023 Achieved Commitments Scenario and the net-zero scenarios of the IEA and BloombergNEF. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; *Global energy perspective 2023*, McKinsey, October 2023; and *New energy outlook 2024*, BloombergNEF, May 2024.

71 "Summary for policymakers," in *Climate change 2022: Mitigation of climate change*, IPCC, 2022. In this analysis, energy efficiency includes, for example, the following mitigation options: avoid demand for energy services; efficient lighting, appliances, and equipment; fuel efficiency in light- and heavy-duty vehicles; efficiency and optimization in shipping; and energy efficiency in aviation and industry.

72 *Global energy perspective 2023*, McKinsey, October 2023.

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73 EV range is the distance that a vehicle can drive from a full to empty battery. The US Environmental Protection Agency tests vehicles in a laboratory setting, and real-world ranges will likely differ due to driving behaviors and use of ancillaries, such as air conditioning. See *Fuel economy and EV range testing*, US Environmental Protection Agency, November 2023; and *US: Median EPA range of 2022 BEVs amounted to 257 miles*, Inside EVs, May 2023. Fast charging depends on the vehicle and the charging infrastructure. Best-in-class BEVs can recharge sufficiently to give them a range of 100 kilometers in about five to ten minutes when using a fast charger. Average BEVs take about ten to 15 minutes for the same driving range. With slow-charging technology, it can take as much as six hours. See "Most fast charging electric vehicles," Electric Vehicle Database, accessed May 26, 2024; and *Charger types and speeds*, US Department of Transportation, June 2023.

74 The effective range of BEVs may be 20 percent lower than reported under normal driving conditions. In extreme cold weather, this figure may reach as much as 30 percent. The median range of a BEV—even considering a buffer of 30 percent—would enable 70 percent or more of US households to complete their long single-day journeys (more than 100 kilometers) without stopping to recharge on the vast majority of days in the year (more than 360). See McKinsey Center for Future Mobility; Matthias Steinsträter, Tobias Heinrich, and Markus Lienkamp, "Effect of low temperature on electric vehicle range," *World Electric Vehicle Journal*, volume 12, issue 3, August 2021. The analysis is based on adapted data from the US Federal Highway Administration on household trips measured as the number of days per household. See *Exploring national long distance passenger travel demand modeling and simulation*, Traveler Analysis Framework, Office of Highway Policy Information, Federal Highway Administration, accessed May 2024.

75 McKinsey Battery Insights; and "Evolution of average range of electric vehicles by powertrain, 2010–2021," IEA, May 2022. Beyond improvements in battery energy density, additional deployment of fast-charging infrastructure could also help more users meet their range needs while minimizing charging times. In this way, a moderate interdependency also exists with Challenge 10: Charging up EVs.

76 McKinsey Center for Future Mobility; McKinsey 2023 Achieved Commitments scenario.

77 Currently, there are just over 1,000 hydrogen fueling stations around the world, the majority of which are in China, Japan, and South Korea. See *Global hydrogen review 2023*, IEA, September 2023.

78 Under McKinsey's 2023 Achieved Commitments scenario; McKinsey Battery Insights.

79 See chapter 6, Challenge 9 for further detail on the calculation.

80 *Global EV outlook 2024; Moving towards increased affordability*, IEA, April 2024.

81 This research maps current CO_2 emissions to different energy-producing and energy-consuming sectors. Level 3 challenges associated with enablers, such as hydrogen or carbon capture, are accounted for within the domains that would rely on such enablers to abate current emissions.

82 About 30 to 60 percent of total power system emissions are classified as Level 3. This quantification of power system emissions tied to Level 3 challenges is based on the share of potential emissions that could be abated by deploying VRE at levels at which managing their variability becomes harder. For more detail, see the discussion later in this chapter.

83 About one-third to half of the emissions of the industrial domain are classified as Level 3. The quantification here of the industrial emissions tied to Level 3 challenges considers two additional aspects. The first is the share of the abatement of these four industrial materials that could still be achieved using existing mature technologies; for example, using clinker substitutes to reduce emissions associated with cement. The emissions reduction associated with such measures is not counted in this report's quantification of emissions associated with Level 3 challenges. The second is the emissions associated with "other industries" that nonetheless rely on Level 3 challenges (that is, related to the decarbonization of the power domain) being solved. For example, the electrification of heating technologies in these other industries would rely to some extent on solving the Level 3 challenge of variability in the power grid, and some portion of their emissions is therefore counted in the Level 3 quantification.

84 Abating some emissions associated with the decarbonization of passenger vehicle transportation relies on solving Level 3 challenges in the power domain, since reaching their full emission abatement potential would rely on running on a decarbonized grid.

85 Others have made similar assessments, primarily considering how much emissions reduction would rely on technologies at different stages of maturity. For example, analysis by the IEA and McKinsey finds that 35 to 45 percent of the emissions reduction required by 2050 in a net-zero scenario would come from technologies that are not yet available in the market; they are in the concept, prototype, or demonstration stage. In this report, many Level 3 challenges rely on technologies that typically are classified as being in these more nascent stages of maturity. The IEA figure corresponds to technologies in the concept, prototype, and demonstration phases, while the McKinsey Platform for Climate

Technologies refers to "in concept" and "early innovation" technologies. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; and *What would it take to scale critical climate technologies?* McKinsey Sustainability, December 2023.

86 The IEA classifies photovoltaic technologies and onshore wind as TRL 9-10, corresponding in an "early adoption" phase in which they are already operating commercially. See *EPT clean energy guide*, IEA, September 14, 2023.

87 This analysis assumes that deploying VREs beyond the point at which they make up more than 50 to 70 percent of all generation is a Level 3 challenge. At a global level, this equates to about 30 to 60 percent of the total emissions arising within the power domain being associated with tackling a Level 3 challenge. The quantification is based on analyses that examine the magnitude of VRE penetration at which required supply-side flexibility either significantly increases in amount or nature (through, for example, increases in longer-duration flexibility needs). Overall two quantification approaches were undertaken. The first approach is based on a literature review, which considers a wide range of sources that evaluate how flexibility needs evolve at higher penetrations of VRE as a share of total generation. They evaluate metrics such as total need for flexibility, total cost of flexibility, or the different types or duration of flexibility options required. For example, see *How much storage do we need?* Storage Lab, accessed June 2024; *Energy storage – Underpinning a decarbonized and secure EU energy system*, European Commission, March 14, 2023; *Net-zero power: Long duration energy storage for a renewable grid*, Long Duration Energy Storage Council and McKinsey, November 2021; T. Brown and L. Reichenberg, "Decreasing market value of variable renewables can be avoided by policy action," *Energy Economics*, volume 100, August 2021; and Conrad Nichols, *When and why is long duration energy storage technology needed?* IDTechEx, February 1, 2024. The second approach is based on McKinsey Power Model simulations of the total amount and type of supply-side flexibility needed for a sample of advanced and emerging economies. These simulations included evaluating the point of VRE deployment at which various forms of flexibility needed to start to grow more quickly; and at which novel forms of flexibility (such as novel long-duration energy storage [LDES] and hydrogen turbines) would start to account for a more material share of the total flexibility mix (considering as an example a threshold of 10 percent of the total flexibility mix). Given the inherent uncertainty associated with how required flexibility could evolve over time and across countries, these figures were calibrated for different economies according to their individual profiles and considered a range of potential results, rather than precise point estimates.

88 Electric vehicles and heat pumps rely on a low-emissions grid to fully reach their decarbonization potential and therefore rely on solving the Level 3 challenges in the power domain.

89 Demand-side flexibility is explored as part of Challenge 3.

90 Flexibility is defined in this context as total flexible capacity divided by average power demand. Flexible capacity includes dispatchable generation assets running at low utilization (benchmarked against 50 percent utilization), interconnections, and storage. For example, from 2022 to 2050, flexibility would need to grow twice as fast as overall power demand in Italy, and seven times faster in India. Simulations are based on the McKinsey Power Model, using the McKinsey 2023 Achieved Commitments scenario.

91 *Electricity information*, IEA, April 2024 ; Ember; Energy Institute; and Our World in Data.

92 *Global energy perspective 2023*, McKinsey, October 2023.

93 Flexibility is defined as hour-to-hour ramping-up needs. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

94 *Update on the rollout of smart meters, Seventy-second report of the sessions 2022–23*, House of Commons Committee of Public Accounts, October 2023; *Energy consumers' experiences and perceptions of smart 'time of use' tariffs*, Great Britain's Office of Gas and Electricity Markets, September 2020; and *Review of GB energy system operation*, Office of Gas and Electricity Markets, January 2021.

95 Suitable land excludes artificial surfaces (including urban and associated areas), tree-covered areas, woody crops, mangroves, aquatic or regularly flooded areas, and permanent snow and glaciers. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

96 Bloomberg New Energy Forum's net-zero scenario envisages a rough doubling in the length of the global grid. The IEA Net Zero Emissions scenario projects an almost threefold expansion. See *A power grid long enough to reach the sun is key to the climate fight*, BloombergNEF, March 2023; and *Energy technology perspectives 2023*, IEA, January 2023.

97 *Electricity grids and secure energy transitions*, IEA, October 2023.

98 Gracie Brown, Bernice Chan, Rory Clune, and Zak Cutler, "Upgrade the grid: Speed is of the essence in the energy transition," McKinsey, February 2022.

99 *At COP28, countries launch declaration to triple nuclear energy capacity by 2050, recognizing the key role of nuclear energy in reaching net zero*, US Department of Energy, December 1, 2023.

100 "What will it take for nuclear power to meet the climate challenge?" McKinsey, March 2023.

101 A range of nonphysical factors, notably cost and consumer preferences, could also be important in determining EV adoption, but these are not the focus of this research. For more detail on the decarbonization of mobility, see, for example, Martin Linder, Tomas Nauclér, Stefan Nekovar, Alexander Pfeiffer, and Nikola Vekić, "The race to decarbonize electric-vehicle batteries," McKinsey, February 23, 2023; Hussein Basma and Felipe Rodríguez, *Fuel cell electric tractor-trailers: Technology overview and fuel economy*, ICCT, July 2022; *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; "Global energy perspective 2023: Sustainable fuels outlook," McKinsey, January 10, 2024; and Axel Esqué, Adam Mitchell, Kritika Rastogi, and Robin Riedel, *Decarbonizing the aviation sector: Making net zero aviation possible*, McKinsey, July 15, 2022.

102 The R&D GREET model (Software v1.3.0.13991) developed by Argonne National Laboratory was used to determine the vehicle manufacturing CO_2-equivalent (CO_2-e) emissions and the well-to-pump CO_2-e emissions of ICEs. Data inputs for tailpipe CO_2-e emissions of vehicles were adjusted using European Environmental Agency and US Department of Energy data. BEVs have no direct tailpipe or well-to-pump emissions—their impact is measured by emissions from the electrical grid, known as grid intensity. The 2022 emissions intensity data come from *Climate Transparency report 2022*, Climate Transparency, October 2022. Future grid intensity projections come from *Global energy perspective 2023*, McKinsey, October 2023. The McKinsey Center for Future Mobility tracks manufacturing emissions associated with BEVs.

103 *See Climate Transparency report 2022*, Climate Transparency, October 2022.

104 *Global EV outlook*, IEA, April 2024.

105 EV range is the distance that a vehicle can drive from a full to empty battery. The US Environmental Protection Agency tests vehicles in a laboratory setting, and real-world ranges will likely differ due to driving behaviors and use of ancillaries, such as air conditioning. See *Fuel economy and EV range testing*, US Environmental Protection Agency, November 2023; and *US: Median EPA range of 2022 BEVs amounted to 257 miles*, Inside EVs, May 2023. Fast charging depends on the vehicle and the charging infrastructure. Best-in-class BEVs can recharge sufficiently to give them a range of 100 kilometers in about five to ten minutes when using a fast charger. Average BEVs take about ten to fifteen minutes for the same driving range. With slow-charging technology, it can take as long as six hours. See "Most fast charging electric vehicles," Electric Vehicle Database; and *Charger types and speeds*, US Department of Transportation, June 2023.

106 The effective range of BEVs may be 20 percent lower than reported under normal driving conditions. In extreme cold weather, this figure may reach as much as 30 percent. See McKinsey Center for Future Mobility; and Matthias Steinsträter, Tobias Heinrich, and Markus Lienkamp, "Effect of low temperature on electric vehicle range," *World Electric Vehicle Journal*, volume 12, issue 3, August 2021.

107 Analysis based on adapted data from the US Federal Highway Administration on household trips, measured as the number of days per household. See *Exploring national long distance passenger travel demand modeling and simulation*, Traveler Analysis Framework, Office of Highway Policy Information, Federal Highway Administration, accessed May 2024.

108 McKinsey Battery Insights; *Evolution of average range of electric vehicles by powertrain, 2010–2021*, IEA, May 2022.

109 See chapter 6, Challenge 9 for further detail on the calculation.

110 McKinsey Battery Insights.

111 McKinsey Center for Future Mobility; and China Electric Vehicle Charging Infrastructure Promotion Alliance, April 2024.

112 *Global hydrogen review 2023*, IEA, September 2023.

113 "Aviation and shipping analysis," in *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

114 *Clean skies for tomorrow: Sustainable aviation fuels as a pathway to net-zero aviation*, Insight Report, World Economic Forum in collaboration with McKinsey, November 2020.

115 Arjen Kersing and Matt Stone, "Charting fuel choices as the shipping industry sails toward net zero," McKinsey, April 2023; and *Decarbonization of shipping: An ambitious global test bed for green ships sets sail*, World Economic Forum, January 2024.

116 *The first hybrid electric vessel built in South America will use a Corvus battery system*, Corvus Energy press release, March 14, 2024.

117 Vaclav Smil, "The modern world can't exist without these four ingredients. They all require fossil fuels," *Time*, May 12, 2022.

118 The physical challenges currently associated with these industries also mean the production costs of many of the new processes being investigated are higher than for conventional processes. Decarbonizing the production of high-temperature heat is generally harder than decarbonizing low- and medium-temperature heat. Electrification, in particular, is often more difficult for two main reasons. First, a narrower set of low-emissions technologies can deliver high heat. For example, heat pumps and mechanical vapor recompression evaporators can only reach temperatures of about 250 to 300°C. Second, the delivery of higher-temperature heat can require larger asset reconfigurations, because the form of heat transfer often needs to change.

119 Natural gas is used in the direct iron reduction process in some cases, but it accounts for less than 5 percent of current global production of steel; McKinsey Basic Materials Institute.

120 For example, biodegradable polyhydroxyalkanoates. See *Pathways to commercial liftoff: Decarbonizing chemicals & refining*, US Department of Energy, September 2023.

121 *Hydrogen*, IEA.

122 Junwen Cao et al., "Recent advances and challenges of nitrogen/nitrate electro catalytic reduction to ammonia synthesis," *Frontiers in Energy*, November 2023; and Tingting Wu et al., "Electrochemical synthesis of ammonia: Progress and challenges," *Materials Today Physics*, volume 16, January 2021.

123 *Global energy perspective 2023*, McKinsey, 2023. Aluminum is the exception. Its production requires temperatures of more than 1,000°C. However, unlike the big four industrial materials, most of this high-temperature energy demand is already delivered through electricity. See "Aluminum decarbonization at a cost that makes sense," McKinsey, April 2023; and *Making net-zero aluminum possible*, Mission Possible Partnership, September 2022.

124 *Building value by decarbonizing the built environment*, McKinsey, June 2023.

125 Other operational challenges related to the scale-up of heat pumps are not discussed in this research. They include the need to scale up manufacturing capacity for heat pumps, whether sufficient skilled labor is available to install them, whether consumers adopt them given their associated costs, and the large turnover that their installation would entail.

126 Duncan Gibb et al., "Coming in from the cold: Heat pump efficiency at low temperatures," *Joule*, volume 7, issue 9, September 2023. The efficiency of a heat pump is measured by the coefficient of performance (COP), which typically ranges from two to five for heat pumps, meaning that for every unit of electrical energy consumed, the heat pump is able to deliver two to five units of heat. For further context, see *Understanding COP: Coefficient of performance of heat pumps*, Learn Metrics, accessed May 2024.

127 See Emily Waltz, *Heat pumps take on cold climates: Eight companies aim to prove that their heat pumps are viable in subzero temps*, IEEE Spectrum, February 2024; *DOE announces leading heat pump manufacturers successfully develop next-generation prototypes to withstand subfreezing temperature*, US Department of Energy, January 2024; *Heating and cooling with a heat pump*, Government of Canada, August 2022; and *Performance assessment of heat pump systems*, Sustainable Technologies Evaluation Program, October 2014.

128 Based on analysis by McKinsey Climate Analytics, October 2023.

129 This is based on a study that compares current electricity demand to a scenario with 100 percent electrification of current buildings' heat demand in the United States. It calculates peak demand over the course of a year in such a scenario, relative to today's peak demand, assuming that a top-performing heat pump (90th percentile) is used. The analysis does not consider other potential growth of energy demand across domains, for example due to population growth or electrification of mobility or industry. See Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020. Other McKinsey and external research found similar increases of two to three times for colder states. *The role of natural gas in the move to cleaner, more reliable power*, McKinsey, September 2023; and *2050 transition study*, ISO New England Inc. Transmission Planning, February 2024.

130 Raw materials encompass a wide range of physical elements, including minerals, fossil fuels, and agricultural and forestry products. This research focuses on critical minerals for the energy transition, defined as those that are essential for the development and deployment of low-emissions energy and technologies, and that may be in high demand while limited in their availability during the energy transition.

131 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023.

132 From 2030 to 2050, this imbalance could be less pronounced as demand could grow more slowly in that period and more supply would have time to come online; McKinsey MineSpans.

133 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023.

134 *Global critical minerals outlook 2024*, IEA, May 2024.

135 McKinsey MineSpans.

136 *Mineral commodity summaries 2024*, US Geological Survey, January 2024.

137 *Global hydrogen review 2023*, IEA, revised version September and December 2023; and *The European hydrogen market landscape*, European Hydrogen Observatory, Report 01, November 2023.

138 Hydrogen can also be produced from fossil-fuel feedstock. However, in McKinsey's 2023 Achieved Commitments scenario, the majority of hydrogen production is expected to come from electrolysis (using electricity to produce hydrogen from water). Therefore, this analysis focuses on efficiencies from electrolytic hydrogen.

139 This is based on analysis of end-to-end efficiencies starting from the point of final energy. The efficiency of different technologies is based on *Hydrogen insights*, McKinsey and the Hydrogen Council, 2023; *Net-zero heat: Long-duration energy storage to accelerate energy system decarbonization*, McKinsey and LDES Council, 2022; and *Net-zero power: Long-duration energy storage for a renewable grid*, McKinsey and LDES Council, 2022.

140 *Hydrogen insights 2023*, Hydrogen Council and McKinsey, December 2023.

141 *Hydrogen, Net zero emissions guide*, IEA, September 2023; and *Policies for green hydrogen*, International Renewable Energy Agency, accessed May 2024.

142 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

143 McKinsey Global Hydrogen Flows Model.

144 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; and "Tracking biofuels supply," in *Tracking clean energy progress 2023*, IEA, July 2023.

145 *Summary for policymakers, Climate change 2022: Mitigation of climate change*, IPCC, 2022. In this analysis, energy efficiency includes the following mitigation options: avoiding demand for energy services; efficient lighting, appliances, and equipment; fuel efficiency in light- and heavy-duty vehicles; efficiency and optimization in shipping; and energy efficiency in aviation and industry.

146 The rebound effect of energy efficiency happens when gains in energy efficiency prompt consumers to use more energy in some cases, and therefore energy demand falls less than it would have otherwise. Estimates of rebound effects vary significantly, but the literature agrees that they are probably well below 100 percent—improving energy efficiency still leads to overall savings in energy. See Kenneth Gillingham, David Rapson, and Gernot Wagner, "The rebound effect and energy efficiency policy," *Review of Environmental Economics and Policy*, volume 10, number 1, winter 2016; and Paul E. Brockway et al., "Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications," *Renewable and Sustainable Energy Reviews*, volume 141, May 2021. Moreover, empirical evidence suggests that realized cost savings may be substantially lower than modeled ones for specific energy-efficiency programs, particularly those related to retrofitting homes. Therefore, stakeholders seeking to improve energy efficiency should carefully assess which measures will actually result in savings. See Meredith Fowlie, Michael Greenstone, and Catherine D. Wolfram, *Do energy efficiency investments deliver? Evidence from the Weatherization Assistance Program*, Becker Friedman Institute for Economics, working paper number 2621817, January 2018.

147 "The world needs to capture, use, and store gigatons of CO_2: Where and how?" McKinsey, April 2023; and "Scaling the CCUS industry to achieve net-zero emissions," McKinsey, October 2022.

148 *Carbon removals: How to scale a new gigaton industry*, McKinsey Sustainability, December 2023.

149 *Direct air capture*, IEA, accessed June 2024.

150 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

151 *Direct air capture 2022: A key technology for net zero*, IEA, April 2022.

Chapter 3

152 McKinsey Climate Analytics.

153 "Building decarbonization: How electric heat pumps could help reduce emissions today and going forward," McKinsey, July 2022.

154 Power Reactor Information System, International Atomic Energy Agency, accessed May 2024; *Electricity 2024: Analysis and forecast to 2026*, IEA, January 2024.

155 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023; and *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023.

156 *The electrified commercial cement kiln*, Cemnet, January 6, 2023.

157 Daniel Muteti, "Carmakers race to develop solid-state batteries for EVs," Deutsche Welle, August 15, 2023.

158 Maddy Savage, "The race across Europe to build green steel plants," BBC News, February 17, 2023.

159 McKinsey MineSpans; and Simon Nicholas, "Iron ore miners try different multi-billion strategies to lower emissions for steel producers," Energy Post, February 20, 2024.

Chapter 4

160 *Climate change 2023: AR6 synthesis report*, IPCC, 2023.

161 Jamie Brick, Dumitru Dediu, and Jesse Noffsinger, "The role of natural gas in the move to cleaner, more reliable power," McKinsey, September 2023.

162 "Bold moves to boost European freight," McKinsey, January 2022.

163 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020.

164 "Playing offense to create value in the net-zero transition," *McKinsey Quarterly*, April 2022.

165 *An affordable, reliable, competitive path to net zero*, McKinsey Sustainability, November 2023.

Chapter 5

166 The IEA classifies households as those that have access to electricity by being connected to an electricity grid or through a renewable standalone system or minigrid connection with sufficient capacity to deliver a minimum bundle of energy services. This includes the powering of several light bulbs, phone charging, a radio, and potentially a fan or television. See *Electricity*, IEA, accessed July 2024; and *Access to electricity improves slightly in 2023, but still far from the pace needed to meet SDG7*, IEA, September 2023.

167 *Climate transparency report 2022*, G-20, 2022.

168 2022 figures. See *Global energy perspective 2023*, McKinsey, October 2023.

169 *Electricity 2024: Analysis and forecast to 2026*, IEA, revised January and May 2024.

170 Ibid.

171 The power domain has no Level 1 challenges, defined as challenges that require progress in deploying established technologies and face the least hurdles.

172 *As solar capacity grows, duck curves are getting deeper in California*, US Energy Information Administration, June 2023.

173 The McKinsey Power Model is a proprietary nodal capacity expansion power model designed to meet electricity demand on an hourly basis as well as exogenous and endogenous demand for other commodities, such as hydrogen. Hourly simulations are performed for defined yearly horizons on a set of optimally sampled days (based on the 2019 weather year), accounting for both intra- and interday flexibility. The model tracks the state of charge throughout the year for storage technologies, shifts flexible load intraday, and builds or overbuilds generation capacity and transmission to ensure that demand is reliably met.

174 *Use of natural gas-fired generation differs in the United States by technology and region*, US Energy Information Administration, February 2024; and *Southwestern states have better solar resources and higher solar PV capacity factors*, US Energy Information Administration, June 2019.

175 Capacity is the total output of electricity a generator can produce in an ideal scenario and is typically measured in megawatts. The utilization rate is the percentage of generation from a given capacity in a particular period.

176 Nestor A. Sepulveda et al., "The role of firm low-carbon electricity resources in deep decarbonization of power generation," *Joule*, volume 2, issue 11, 2018; and Robert Idel, "Levelized full system costs of electricity," *Energy*, volume 259, November 2022; Simon Evans, *In-depth: The whole system costs of renewables*, Carbon Brief, February 2017; *Projected costs of generating electricity*, IEA and Nuclear Energy Agency, December 2020; and *The costs of decarbonisation: System costs with high shares of nuclear and renewables*, Nuclear Energy Agency, OECD, 2019.

177 Flexibility is defined as total flexible capacity divided by average power demand. Flexible capacity includes dispatchable generation assets running at low utilization (benchmarked against 50 percent utilization), interconnections, and storage. See *Use of natural gas-fired generation differs in the United States by technology and region*, US Energy Information Administration, February 2024.

178 *Managing the seasonal variability of electricity demand and supply*, IEA, 2024.

179 Other observers have found similar results. See, for instance, *Commission Recommendation on energy storage—underpinning a decarbonised and secure EU energy system*, Directorate-General for Energy, European Commission, 2023; and *The costs of decarbonisation: System costs with high shares of nuclear and renewables*, Nuclear Energy Agency, OECD, 2019; and *Monetizing energy storage: A toolkit to assess future cost and value*, Oxford University Press, 2023.

180 "'World's largest' compressed air energy storage project connects to the grid in China," Energy Storage News, April 10, 2024.

181 *Biden-Harris Administration announces $325 million for long-duration energy storage projects to increase grid resilience and protect America's communities*, US Department of Energy, September 22, 2023.

182 *Net-zero power: Long-duration energy storage for a renewable grid*, LDES Council and McKinsey, November 2021.

183 This excludes pumped storage hydropower.

184 Nelson Nsitem, "Global energy storage market records biggest jump yet," BloombergNEF, April 25, 2024.

185 US Energy Information Administration.

186 Comparison is between high-income countries, as defined by the World Bank, and African countries in 2020, using the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI) as electricity reliability metrics. SAIDI measures the minutes of nonmomentary electric interruptions per year experienced by the average customer. SAIFI measures the number of nonmomentary electric interruptions in a year experienced by the average customer.

187 *Electricity information*, IEA, April 2024 ; Ember; Energy Institute; and Our World in Data.

188 Flexible capacity includes dispatchable generation assets running at low utilization (benchmarked against 50 percent utilization), interconnections, and storage. Dispatchable generation assets include coal, gas, gas with carbon capture and storage, nuclear, oil, and other clean thermal assets. Interconnections refer to physical connections with other power systems, representing the maximum amount of electricity that can be imported at a given time. Storage includes pumped hydro, batteries, and novel LDES.

189 César Augier, Hauke Engel, François Jurd de Girancourt, and Oliver Onyekweli, "Green energy in Africa presents significant investment opportunities," McKinsey Sustainability, October 2023.

190 "China almost quadrupled its new energy storage capacity in 2023," Bloomberg News, January 24, 2024; and *Energy storage: Connecting India to clean power on demand*, Institute for Energy Economics and Financial Analysis, December 2023.

191 César Augier, Hauke Engel, François Jurd de Girancourt, and Oliver Onyekweli, "Green energy in Africa presents significant investment opportunities," McKinsey Sustainability, October 2023.

192 *Net zero by 2050: A roadmap for the global energy sector*, IEA, May 2021; and *Demand response*, IEA, accessed May 2024.

193 For reference, total global electrical storage currently stands at about 250 gigawatts. See *Demand response*, IEA, accessed May 2024.

194 *Report on distribution tariff methodologies in Europe*, EU Agency for the Cooperation of Energy Regulators, February 2021.

195 *Net zero by 2050: A roadmap for the global energy sector*, IEA, May 2021.

196 *Pathways to commercial liftoff: Virtual power plants*, US Department of Energy, September 2023.

197 Based on an analysis of different decarbonization scenarios. See *Digitalisation of energy flexibility*, Energy Transition Expertise Centre, European Commission, 2022.

198 *Digitalisation of energy flexibility*, Energy Transition Expertise Centre, European Commission, 2022.

199 US Environmental Protection Agency; *American Driving Survey, 2020–2021*, AAA Foundation for Traffic Safety, October 2022.

200 Based on an analysis of different decarbonization scenarios. See *Digitalisation of energy flexibility*, Energy Transition Expertise Centre, European Commission, 2022.

201 *California SB233: Battery electric vehicles and electric vehicle supply equipment: bidirectional capability*, TrackBill, accessed May 2024.

202 Peter Johnson, *The nation's largest electric school bus fleet providing grid demand response solutions*, Electrek, November 2022.

203 *National Development and Reform Commission and other departments on strengthening new energy vehicles: Implementation opinions in interaction with grid integration*, National Development and Reform Commission, China, 2023.

204 Including cryptocurrency mining. See *Data centres and data transmission networks*, IEA, accessed May 2024; and *Electricity 2024: Analysis and forecast to 2026*, IEA, revised January and May 2024.

205 Ibid.

206 Varun Mehra and Raiden Hasegawa, *Supporting power grids with demand response at Google data centers*, Google Cloud, October 2023; and Robert Walton, *Bitcoin mining as a grid resource? 'It's complicated.,'* Utility Dive, February 17, 2022.

207 Matt Hamblen, "Shearwater's data center move to Iceland lowers energy costs, ups sustainability," Fierce Electronics, October 26, 2023.

208 *Electricity demand side management measures*, Climate Change Laws of the World, 2023.

209 Based on an analysis of different decarbonization scenarios. See *Digitalisation of energy flexibility*, Energy Transition Expertise Centre, European Commission, 2022.

210 Martin Linder, Jesse Noffsinger, Robert Riesebieter, Ken Somers, Humayun Tai, and Godart van Gendt, "Net-zero heat: Long-duration energy storage to accelerate energy system decarbonization," McKinsey Sustainability, November 2022.

211 *Global energy perspective 2023*, McKinsey, October 2023.

212 *Update on the rollout of smart meters*, House of Commons Committee of Public Accounts, Seventy-second report of the session 2022–23, October 2023.

213 Evan Polymeneas, Adam Rubin, and Humayun Tai, "Modernizing the investment approach for electric grids," McKinsey, November 2020.

214 *Smart meters at a glance*, The Institute for Electric Innovation at The Edison Foundation, May 2023; *Energy retail and consumer protection: 2023 market monitoring report*, European Union Agency for the Cooperation of Energy Regulators and Council of European Energy Regulators, September 2023; and Adarsh Krishnan, *Smart electricity meter market 2024: Global adoption landscape*, IOT Analytics, February 2024.

215 *Smart grids*, IEA, accessed May 2024.

216 *Digitalisation of energy flexibility*, Energy Transition Expertise Centre, European Commission, 2022.

217 *Pathways to commercial liftoff: Virtual power plants*, US Department of Energy, September 2023.

218 *Demand Flexibility Service—consumers have their say*, ESO, July 6, 2023.

219 Hannah Ritchie, *How does the land use of different electricity sources compare?* Our World in Data, June 2022; and Gregory K. Ingram and Yu-Hung Hong, eds., *Climate change and land policies*, Proceedings of the 2010 Land Policy Conference, Lincoln Institute of Land Policy, 2010.

220 *Carbon neutrality in the UNECE region: Integrated life-cycle assessment of electricity sources*, United Nations Economic Commission for Europe, 2022.

221 Direct use of land by VRE would be about 0.1 percent. See Mark Z. Jacobson et al., "Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries," *Energy & Environmental Science*, volume 15, June 2022.

222 Suitable land excludes artificial surfaces (including urban and associated areas), tree-covered areas, woody crops, mangroves, aquatic or regularly flooded areas, and permanent snow and glaciers. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

223 Environmental constraints and protected land account for a further 16 percent of land being unavailable.

224 Sites are restricted to a distance of less than five kilometers to a substation.

225 "Land: A crucial resource for the energy transition," McKinsey, May 2023.

226 *Annual rooftop and utility scale installations in the EU*, SolarPower Europe, accessed May 2024.

227 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

228 Ibid.

229 *Electricity transmission and distribution*, IEA and Energy Technology Systems Analysis Programme, technology brief E12, April 2014.

230 In McKinsey's 2023 Achieved Commitments scenario, total installed capacity would need to grow by about five times to 41 terawatts by 2050.

231 *Preliminary monthly electric generator inventory (based on Form EIA-860M as a supplement to Form EIA-860)*, US Energy Information Agency, August 2023.

232 *Electricity grids and secure energy transitions*, IEA, October 2023.

233 *Energy technology perspectives 2023*, IEA, January 2023.

234 *Net zero by 2050 update*, IEA, October 2023.

235 Bloomberg New Energy Forum's net-zero scenario envisages a roughly twofold increase in the length of the global grid. The IEA projects an almost threefold expansion. See *A power grid long enough to reach the sun is key to the climate fight*, BloombergNEF, March 2023; and *Energy technology perspectives 2023*, IEA, January 2023.

236 *Energy technology perspectives 2023*, IEA, January 2023; and *Electricity grids and secure energy transitions*, IEA, October 2023.

237 *Energy technology perspectives 2023*, IEA, January 2023.

238 *DOE launches new initiative from President Biden's Bipartisan Infrastructure Law to modernize national grid*, US Department of Energy, January 12, 2022.

239 *Electricity grids and secure energy transitions*, IEA, October 2023.

240 *Electricity grids and secure energy transitions*, IEA, October 2023; and Gracie Brown, Bernice Chan, Rory Clune, and Zak Cutler, "Upgrade the grid: Speed is of the essence in the energy transition," McKinsey, February 2022.

241 Daniel Moore, "Grid transformer supply crunch threatens clean energy plans," Bloomberg Law, July 14, 2023.

242 *Infrastructure and Jobs act: "Building a Better Grid" initiative*, IEA, November 2022.

243 *System needs study: Opportunities for a more efficient European power system in 2030 and 2040*, European Network of Transmission System Operators for Electricity, May 2023.

244 *Building a unified national power market system in China: Pathways for spot power markets*, IEA, April 2023.

245 Nick Ferris, "Grid investment in China more than every other country combined," Energy Monitor, March 15, 2024.

246 *World electricity generation mix by fuel, 1971–2019*, IEA, August 2021.

247 Nestor A. Sepulveda et al., "The role of firm low-carbon electricity resources in deep decarbonization of power generation," *Joule*, November 2018.

248 Jane C.S Long et al., *Clean firm energy is the key to California's clean energy future*, Environmental Defense Fund, 2021.

249 Jessica Lovering et al., "Land-use intensity of electricity production and tomorrow's energy landscape," PLOS ONE, July 2022.

250 *The costs of decarbonisation: System costs with high shares of nuclear and renewables*, OECD and NEA, 2019.

251 *The role of critical minerals in clean energy transition*, IEA, March 2022.

252 *At COP28, countries launch declaration to triple nuclear energy capacity by 2050, recognizing the key role of nuclear energy in reaching net zero*, US Department of Energy, December 1, 2023.

253 *World electricity generation mix by fuel, 1971–2019*, IEA, August 2021.

254 *Nuclear power*, IEA, accessed May 2024.

255 Country profiles, World Nuclear Association; "What will it take for nuclear power to meet the climate challenge?" McKinsey, March 2023; *Nuclear power and secure energy transitions: From today's challenges to tomorrow's clean energy systems*, IEA, June 2022; *Pathways to commercial liftoff: Advanced nuclear*, US Department of Energy, March 2023.

256 *5 fast facts about spent nuclear fuel*, US Office of Nuclear Energy, October 2022.

257 "France sets out long-term nuclear recycling plans," World Nuclear News, March 8, 2024; and *Pathways to commercial liftoff: Advanced nuclear*, US Department of Energy, March 2023.

258 *Pathways to commercial liftoff: Advanced nuclear*, US Department of Energy, March 2023.

259 *Nuclear power and secure energy transitions: From today's challenges to tomorrow's clean energy systems*, IEA, June 2022; and "Finland to open the world's first final repository for spent nuclear fuel," Vattenfall, August 29, 2023.

260 "What will it take for nuclear power to meet the climate challenge?" McKinsey, March 2023.

261 *Nuclear power and secure energy transitions: From today's challenges to tomorrow's clean energy systems*, IEA, June 2022.

262 *Nuclear energy: Supply chain deep dive assessment*, US Department of Energy response to Executive Order 14017, February 24, 2022.

263 "What will it take for nuclear power to meet the climate challenge?" McKinsey, March 2023.

264 *Plans for new reactors worldwide*, World Nuclear Association, April 2024.

265 *Under construction reactors*, Power Reactor Information System, International Atomic Energy Agency, accessed May 2024.

266 Power Reactor Information System, International Atomic Energy Agency, accessed May 2024.

267 *Electricity 2024: Analysis and forecast to 2026*, IEA, January 2024.

268 IAEA ARIS nuclear reactor database; *GIF R&D outlook for generation IV nuclear energy systems 2018 update*, GEN IV International Forum, 2018; and *The NEA Small Modular Reactor Dashboard*, OECD, 2024.

269 *Processing of used nuclear fuel*, World Nuclear Association, December 2020.

Chapter 6

270 *Global energy perspective 2023*, McKinsey, October 2023.

271 Numbers on vehicle parc (the total stock of vehicles on the road) and sales include passenger vehicles, trucks, light commercial vehicles, and buses, which collectively account for 95 percent of road transportation emissions. The figures exclude two- and three-wheelers for data availability reasons. See *Global energy perspective 2023*, McKinsey, October 2023; and Simon Michaux, *It's time to wake up—there are bottlenecks in the raw materials supply chain*, Geological Survey of Finland, August 2021.

272 McKinsey Center for Future Mobility.

273 Light commercial vehicles include last-mile delivery vans, minibuses, and recreational vehicles (RVs). Heavy trucks include regional and long-haul trucks.

274 *Where the energy goes: Gasoline vehicles*, fueleconomy.gov, US Department of Energy and US Environmental Protection Agency, accessed May 2024; and *Electrofuels: Yes, we can … if we're efficient*, Transport & Environment (T&E), December 2020.

275 BEVs are powered by electricity stored in a battery pack and use an electric motor instead of an ICE. FCEVs are also propelled by an electric motor but are powered by hydrogen fuel cells. See *How do all-electric cars work?*, US Department of Energy, accessed June 2024; and *How do fuel cell electric vehicles work using hydrogen?* US Department of Energy, accessed June 2024.

276 *Global EV outlook 2024*, IEA, April 2024; and *EV sales growth slows: Market leader Tesla stalls*, Cox Automotive, April 11, 2024.

277 McKinsey's 2023 Achieved Commitments scenario assumes that net-zero commitments are achieved by 2050 by leading countries through purposeful policies and implies a 1.6°C rise in global temperatures by 2100. Vehicles included are passenger vehicles, trucks, light commercial vehicles, and buses. Under this scenario, the total stock of vehicles declines to about 1.3 billion by 2050, and ICEs still constitute about 20 percent of total stock in 2050.

278 Both battery electric trucks and fuel cell electric trucks are included; McKinsey Center for Future Mobility, Achieved Commitments scenario, 2023.

279 FCEV efficiency is discussed in chapter 10. See *Where the energy goes: Electric cars*, fueleconomy.gov, US Department of Energy and US Environmental Protection Agency, accessed May 2024; *Comparison of well-to-wheels energy use and emissions of a hydrogen fuel cell electric vehicle relative to a conventional gasoline-powered internal combustion engine vehicle*, Office of Scientific and Technical Information, US Department of Energy, November 2019; and *Electrofuels: Yes, we can … if we're efficient*, T&E, December 2020.

280 Jakob Fleischmann, Mikael Hanicke, Evan Horetsky, Dina Ibrahim, Sören Jautelat, Martin Linder, Patrick Schaufuss, Lukas Torscht, and Alexandre van de Rijt, "Battery 2030: Resilient, sustainable, and circular," McKinsey, January 2023. This includes both AC and DC fast charging; McKinsey Center for Future Mobility.

281 This is based solely on tailpipe emissions; if upstream emissions from fuel production (drilling, refining, and transportation) were included, the figure could be closer to three kilograms of CO_2. See *Comparison: Your car vs. an electric vehicle*, US Environmental Protection Agency, accessed May 2024.

282 The focus of this challenge is BEVs rather than FCEVs because, in the case of passenger vehicles, BEV adoption is more than 100 times that of FCEVs. This is not to say that FCEVs will not play a role in decarbonizing passenger road mobility, but most scenarios, including McKinsey's 2023 Achieved Commitments scenario, expect BEVs rather than FCEVs to drive the decarbonization of passenger vehicles. Also see, for example, *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

283 See *Lifecycle analysis of greenhouse gas emissions under the Renewable Fuel Standard*, Renewal Fuel Standard Program, US Environmental Protection Agency, accessed May 2024.

284 The lower-emissions grid is based on the US power generation mix and the higher-emissions grid on the Indian power generation mix.

285 The actual number depends on the weight of the battery and how clean the energy used to manufacture it was. See McKinsey Center for Future Mobility.

286 Martin Linder, Tomas Nauclér, Stefan Nekovar, Alexander Pfeiffer, and Nikola Vekić, "The race to decarbonize electric-vehicle batteries," McKinsey, February 23, 2023.

287 Running emissions are those emitted when a vehicle is in use and do not include emissions associated with a car's manufacture. For top-performing ICEs, this figure assumes the 95th percentile of passenger vehicle tailpipe emissions and a fuel efficiency of approximately 35 miles per gallon, as well as upstream emissions associated with fuel production. It also assumes an average BEV fuel efficiency of 95 miles per gallon-equivalent. The calculation is based on the current intensity of the US grid, including upstream emissions. See fueleconomy.gov, US Department of Energy and US Environmental Protection Agency, accessed May 2024; *Climate Transparency Report 2022*, Climate Transparency, October 2022; and *Life cycle upstream emission factors (pilot edition)*, IEA, accessed June 2024.

288 This depends on the emissions intensity of the power grid mix used to charge the BEV.

289 The emissions intensities of the power grids, including upstream emissions, are 429 grams of CO_2-equivalent per kilowatt-hour in the left panel (United States) and 841 grams of CO_2-equivalent per kilowatt-hour in the right panel (India). See *Climate Transparency Report 2022*; and *Life cycle upstream emission factors (pilot edition)*, IEA, accessed June 2024.

290 Based on 150 grams of CO_2-equivalent well-to-wheel per kilometer on a top-quartile ICE (reported in Europe), compared with 250 grams of CO_2-equivalent per kilometer for the average ICE (reported in the United States). The distribution of ICE and EV emissions performance varies among regions, reflecting the specific cars driven and different emissions-reporting standards in each of them. See fueleconomy.gov, US Department of Energy and US Environmental Protection Agency, accessed May 2024.

291 *Emissions intensity and change in electricity generation emissions*, 2015–2022, IEA, updated July 15, 2021.

292 This is based on odometer readings of cars 12 years old (average lifespan of vehicles) or older in the United States in 2017. See National Household Travel Survey, US Federal Highway Administration, July 2018.

293 "How long does an electric car battery last?," EV Connect, November 2023.

294 "The race to decarbonize electric-vehicle batteries," McKinsey, February 2023.

295 *Climate Transparency Report 2022, Climate Transparency*, October 2022; and *Life cycle upstream emission factors (pilot edition)*, IEA, accessed June 2024.

296 Tom Voelk, "Europe and the US share a lot, except when it comes to cars," *New York Times*, March 4, 2020.

297 These calculations assume the average emissions mix at a given point.

298 Based on 150 grams of CO_2-equivalent per kilometer on a top-quartile ICE (Europe-based reporting), compared with 250 grams of CO_2 per kilometer for an average ICE (US-based reporting). See fueleconomy.gov, US Department of Energy and

US Environmental Protection Agency, accessed May 2024.

299 For example, see *Five things you know about electric vehicles that aren't exactly true*, The International Council on Clean Transportation, July 2021; *Comparative life-cycle greenhouse gas emissions of a mid-size BEV and ICE vehicle*, IEA, May 2021; *Joined in climate action: The pathway report*, Polestar and Rivian, August 2023; *The role of critical minerals in clean energy transitions*, IEA, March 2022; and *EV lifecycle analysis*, Transport Environment, accessed June 2024. Transport Environment estimates carbon savings of about 65 percent for a medium-sized BEV purchased in 2022 against a comparable ICE in Europe, assuming a lifetime distance driven of 200,000 kilometers and accounting for grid decarbonization over time. Polestar and Rivian estimate carbon savings of about 30 percent for a medium-sized BEV against a comparable ICE, assuming a lifetime of 16 years and 240,000 kilometers driven, a global average power grid and fuel/electricity production and tailpipe emissions decreasing by about 3 to 4 percent annually, and end-of-life emissions, including recycling credits. The IEA estimates carbon savings of about 50 percent for a medium-sized BEV against a comparable ICE, assuming a dynamic global average grid in line with the IEA Sustainable Development scenario, lifetime distance driven of 200,000 kilometers, ICE fuel economy of 6.8 liters of gasoline-equivalent per 100 kilometers, and BEV fuel economy of 0.19 kilowatt-hours per kilometer.

300 *Global energy perspective 2023*, McKinsey, October 2023.

301 Ibid.

302 Total emissions from manufacturing a BEV could fall by about 20 percent by 2035. McKinsey Center for Future Mobility.

303 *The 2023 EPA automotive trends report: Greenhouse gas emissions, fuel economy, and technology since 1975*, US Environmental Protection Agency, 2023.

304 "The race to decarbonize electric-vehicle batteries," McKinsey, February 2023; and Eric Hannon, Thomas Nauclér, Anders Suneson, and Fehmi Yüksel, "The zero-carbon car: Abating material emissions is next on the agenda," McKinsey Sustainability, September 2020.

305 *Global EV outlook*, IEA, April 2024.

306 *Climate Transparency Report 2022*, Climate Transparency, October 2022.

307 Corey Cantor, "No doubt about it: EVs really are cleaner than gas cars," BloombergNEF, March 21, 2024.

308 This is based on actual car-charging sessions across 44 US states and on carbon intensity data derived from generation fuel mix data from grid operators. See Wenbo Shi and Mohammad Karimzadeh, *Automating load shaping for EVs: Optimizing for cost, grid constraints, and … carbon?* Sense Labs and Singularity Energy, June 2021.

309 Lucas W. Davis, "How much are electric vehicles driven?," *Applied Economics Letters*, volume 26, number 18, 2019.

310 Viet Nguyen-Tien et al., *Estimating the longevity of electric vehicles: What do 300 million MOT tests tell us?* Centre for Economic Performance discussion paper number 1972, January 2024; and Viet Nguyen-Tien and Robert Elliott, *A novel way to estimate car longevity shows that electric vehicles' life mileage is increasing fast*, London School of Economics, February 2024.

311 Fast charging depends on the vehicle and the charging infrastructure. Average BEVs take ten to 15 minutes to give them a range of 100 kilometers. With slow-charging technology, it can take as much as six hours. See "Most fast charging electric vehicles," Electric Vehicle Database, accessed June 2024; and "Charger types and speeds," US Department of Transportation, June 2023. FCEVs take about one minute. As in the prior challenge, because BEV adoption is much higher than that of FCEVs, and BEVs are expected to be the primary solution for passenger vehicles, this research focuses on them rather than on FCEVs.

312 EV range is the distance that a vehicle can drive from a full to an empty battery. The US Environmental Protection Agency tests vehicles in a laboratory setting. See *Fuel economy and EV range testing*, US Environmental Protection Agency, November 2023; and "US: Median EPA range of 2022 BEVs amounted to 257 miles," Inside EVs, May 2023.

313 Under normal driving conditions, the effective range of BEVs may be 20 percent lower than reported. In extremely cold weather, this figure may reach as high as 30 percent. See McKinsey Center for Future Mobility; Matthias Steinsträter, Tobias Heinrich, and Markus Lienkamp, "Effect of low temperature on electric vehicle range," *World Electric Vehicle Journal*, volume 12, issue 3, August 2021; Surav Chowdhury et al., *Total thermal management of battery electric vehicles (BEVs)*, SAE technical paper number 2018-37-0026, 2018; Kang Li et al., "Investigation on the performance and characteristics of a heat pump system for electric vehicles under extreme temperature conditions," *Case Studies in Thermal Engineering*, volume 27, 2021; Jeff S. Bartlett and Gabe Shenhar, "CR tests show electric car range can fall far short of claims," Consumer Reports, January 2024; and Brandon August, *Heat pumps: Cold weather myth or worth it?*, Recurrent, November 2023.

314 The simulation is based on reported BEV ranges adjusted downward by 30 percent to account for the loss of range. For reference, about 90 percent of households would have to stop to recharge less than ten times per year, and 20 percent of households would never have to stop to recharge.

315 This analysis is based on adapted data from the US Federal Highway Administration on household trips measured as the number of days per household. Other researchers have reached similar conclusions, for instance suggesting that the latest BEV models could cover more than 95 percent of typical daily trips in Germany and the United States. See *Exploring national long distance passenger travel demand modeling and simulation*, Federal Highway Administration, US Department of Transportation, October 2018; and *Five things you know about electric vehicles that aren't exactly true*, The International Council on Clean Transportation, July 2021.

316 The average US driver drives 21,688 kilometers a year, according to the Federal Highway Administration. In other countries, this average hovers around 12,000 kilometers a year. See *Vehicles in use Europe 2022*, European Automobile Manufacturers' Association, January 2022; S*urvey of motor vehicle use, Australia*, Australian Bureau of Statistics, December 2020; *Average annual miles per driver by age group*, Federal Highway Administration, US Department of Transportation, May 2022; and *What is the average annual car mileage in the UK?*, Britannia Car Leasing, November 2023.

317 *Evolution of average range of electric vehicles by powertrain, 2010–2021*, IEA, May 2022.

318 McKinsey Battery Insights.

319 Battery chemistry is made up of the anode and the cathode, which store and transfer electrical energy.

320 Harry Dempsey et al., "How solid state batteries could transform transport," *Financial Times*, October 27, 2023.

321 *Heat pumps: Cold weather myth or worth it?*, Recurrent, November 2023; Kang Li et al., "Investigation on the performance and characteristics of a heat pump system for electric vehicles under extreme temperature conditions," *Case Studies in Thermal Engineering*, volume 27, 2021; and Emily Pandise and Lora Kolodny, "EV drivers wrestle with cold weather sapping their battery range," NBC News, January 18, 2024.

322 Julian Conzade, Hauke Engel, Adam Kendall, and Gillian Pais, "Power to move: Accelerating the electric transport transition in sub-Saharan Africa," McKinsey, February 2022; and *SANY's first intelligent battery swapping station debuts*, SANY press release, January 13, 2022.

323 The baseline of today's current parc is from the IEA's Global EV Data Explorer. Forward-looking estimates are from McKinsey.

324 Includes battery electric and fuel cell trucks. See EVvolume.com.

325 Freightliner's eCascadia electric semitruck, for instance, weighs about two tonnes more than the diesel equivalent. See Bianca Giacobone, "Electrifying trucking will mean sacrificing critical weight for heavy batteries, eating into already-slim margins," *Business Insider*, February 2, 2023; and Zeti Data Explorer.

326 *Guidance report: Electric trucks where they make sense*, North American Council for Freight Efficiency, 2018.

327 The payload-distance relationship is based on a 2022 International Council on Clean Transportation simulation that used EU trucking regulations from 2019 as a regulatory baseline. These regulations allow zero-emission powertrains to weigh two tonnes more (than diesel trucks) to compensate for batteries and fuel cell systems. Proposals are currently in place over increasing the allowance to four tonnes. The battery pack density in the simulation was updated to 180 watt-hours per kilogram to reflect improvements in the technology as of 2023. See Hussein Basma and Felipe Rodríguez, *Fuel cell electric tractor-trailers: Technology overview and fuel economy*, ICCT, July 2022; *Questions and answers on weights and dimensions: new proposal to accelerate the uptake of zero-emission heavy-duty vehicles and promote intermodal transport*, European Commission, July 11, 2023; and McKinsey Center for Future Mobility.

328 *Electric trucks where they make sense*, North American Council for Freight Efficiency, 2018.

329 *Road freight transport by journey characteristics*, Eurostat, September 2023. Europe has set targets over the past decade to shift long-haul freight to low-emissions transportation. By 2030, the region

aims to transport as much as 30 percent of road freight carried farther than 300 kilometers using other modes, such as rail and boat. See Raphaëlle Chapuis, Theo Delporte, Steffen Köpke, Carsten Lotz, and Anselm Ott, "Bold moves to boost European rail freight," McKinsey, January 2022.

330 The proportion of long-haul heavy-duty trucking use cases that could be unmet by BEVs on a single charge is estimated by combining the EU payload-distance relationship with the US distributions of gross vehicle weight and distance-driven (this combination is due to data availability reasons). These distributions show, for example, that more than half of this US trucking segment carries up to 18,000 kilograms in payload on a typical daily journey, and that a similar proportion travels up to around 700 kilometers daily. Today, US federal trucking weight regulations are generally stricter than those in the EU, and the US profile tends involve heavier payloads and longer distances. Therefore, if certain US journeys are unmet under EU regulations, they are also unmet under US federal regulations. Fleet payloads and distances are based on 2018 survey results from North America. See Hussein Basma and Felipe Rodríguez, *Fuel cell electric tractor-trailers: Technology overview and fuel economy*, International Council on Clean Transportation, July 2022; *Electric trucks where they make sense*, North American Council for Freight Efficiency, 2018; and McKinsey Center for Future Mobility.

331 Hussein Basma and Felipe Rodríguez, *Fuel cell electric tractor-trailers: Technology overview and fuel economy*, ICCT, July 2022; and Bernd Heid, Martin Linder, Anna Orthofer, and Markus Wilthaner, "Hydrogen: The next wave for electric vehicles?," McKinsey, November 2017.

332 Andreas Breiter, Peter Fröde, Vineet Jain, and Shannon Peloquin, "Powering the transition to zero-emission trucks through infrastructure," McKinsey, April 2023.

333 Hussein Basma and Felipe Rodríguez, *Fuel cell electric tractor-trailers: Technology overview and fuel economy*, ICCT, July 2022.

334 Zeti Data Explorer; and *Semi: The future of trucking is electric*, Tesla, accessed June 2024.

335 Jessica DiNapoli, "Tesla Semi trucks in short supply for PepsiCo as its rivals use competing EV big rigs," Reuters, April 19 2024.

336 *Commercial vehicles–weights and dimensions (evaluation)*, European Commission, December 2023; and *Questions and answers on weights and dimensions: new proposal to accelerate the uptake of zero-emission heavy-duty vehicles and promote intermodal transport*, European Commission, July 11, 2023.

337 "Size differences," Federal Motor Carrier Safety Administration; and John Harvey et al., *Effects of increased weights of alternative fuel trucks on pavement and bridges*, UC Davis Institute of Transportation Studies Report No. UC-ITS-2020-19, November 2020.

338 Growth of e-commerce sales in recent years has shifted demand for trucking and contributed to the shortening of the average freight-shipping distance. See Patricia Hu et al., *Transportation statistics annual report 2022*, Bureau of Transportation Statistics, US Department of Transportation, December 2022.

339 This assumes that a truck is traveling at 90 kilometers an hour for those 4.5 hours. See *EU rules for working in road transport*, Your Europe, accessed June 2024.

340 In the future, the charging capacity of a single fast charger for trucking could exceed one megawatt, compared with 50 to 350 kilowatts currently. See *High-power medium- and heavy-duty electric vehicle charging*, National Renewable Energy Lab, accessed June 2024; and *Charger types and speeds*, US Department of Transportation, June 2023.

341 *Road Freight Zero: Pathways to faster adoption of zero-emission trucks*, Insight Report, Road Freight Zero, Mission Possible Partnership, and World Economic Forum, October 2021.

342 Ethan S. Hecht and Joseph Pratt, *Comparison of conventional vs. modular hydrogen refueling stations, and on-site production vs. delivery*, Sandia National Laboratories, March 2017.

343 McKinsey Battery Insights.

344 In the IEA's Net Zero by 2050 scenario. See *Global hydrogen review 2023*, IEA, September 2023.

345 Thirty-two percent per year between 2022 and 2030 under McKinsey's 2023 Achieved Commitments scenario, compared with 44 percent per year between 2018 and 2022. McKinsey Battery Insights, third quarter, 2023.

346 See *Energy technology perspectives 2023*, IEA, 2023.

347 "Federal incentives help drive $52B of investments in 17 EV battery production facilities: BofA," Utility Dive, February 2023; Victoria Waldersee, "Politics aside, China's CATL ramps up cell production in Germany," Reuters, January 26, 2023.

348 Jakob Fleischmann, Mikael Hanicke, Evan Horetsky, Dina Ibrahim, Sören Jautelat, Martin Linder, Patrick Schaufuss, Lukas Torscht, and Alexandre van de Rijt, "Battery 2030: Resilient, sustainable, and circular," McKinsey, January 2023.

349 *Global hydrogen review 2023*, IEA, September 2023.

350 In the IEA Net Zero 2050 scenario. See *Global hydrogen review 2023*, IEA, September 2023.

351 Jakob Fleischmann, Mikael Hanicke, Evan Horetsky, Dina Ibrahim, Sören Jautelat, Martin Linder, Patrick Schaufuss, Lukas Torscht, and Alexandre van de Rijt, "Battery 2030: Resilient, sustainable, and circular," McKinsey, January 2023.

352 Olivia White, Lola Woetzel, Sven Smit, Jeongmin Seong, and Tiago Devesa, "The complication of concentration in global trade," McKinsey Global Institute, January 2023.

353 McKinsey Center for Future Mobility, Achieved Commitments scenario, 2023.

354 Ibid.

355 McKinsey Center for Future Mobility; *Fuel up on facts*, American Petroleum Institute, accessed June 2024.

356 *Global hydrogen review 2023*, IEA, September 2023.

357 In the IEA Net Zero 2050 scenario, the number of hydrogen-refueling stations climbs to 46,000 by 2050. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

358 This includes both AC and DC fast charging; McKinsey Center for Future Mobility; and China Electric Vehicle Charging Infrastructure Promotion Alliance, April 2024.

359 Scooter Doll, *7 auto giants unite to build universal network of 30k+ clean-energy powered fast chargers to North America*, Electrek, July 26, 2023.

360 *Alternative fuels infrastructure: Council adopts new law for more recharging and refuelling stations across Europe*, Council of the EU press release, July 25, 2023.

361 Madeleine Ngo, "Slow rollout of national charging system could hinder E.V. adoption," *New York Times*, December 13, 2023.

362 Julia Payne, "EV charging growth plans hindered by EU's power grid problems," Reuters, December 4, 2023.

363 An example of electricity demand on a February day in California's grid today is provided by *Current and forecasted demand*, California ISO, accessed March 2024.

364 Pierre-Louis Ragon et al., *Near-term infrastructure deployment to support zero-emission medium- and heavy-duty vehicles in the United States*, The International Council on Clean Transportation, May 2023.

365 *Global energy perspective 2023*, McKinsey, October 2023.

Chapter 7

366 Vaclav Smil, "The modern world can't exist without these four ingredients. They all require fossil fuels," *Time*, May 12, 2022; *Global energy perspective 2023*, McKinsey, October 2023.

367 McKinsey Basic Materials Institute; "Golden Gate Bridge fast facts," CNN, July 19, 2023.

368 *Steel use by sector*, World Steel Association, accessed May 2024.

369 All figures (2022) are for direct emissions only and exclude indirect emissions, such as from power generation. See *Global energy perspective 2023*, McKinsey, October 2023.

370 Christian Hoffmann, Michel van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey, June 2020.

371 Robbie M. Andrew, *Global CO_2 emissions from cement production*, Earth System Science Data, 2018.

372 McKinsey Basic Materials Institute; this assumes cement makes up 10 to 15 percent of concrete. See "Statue of Liberty fast facts," CNN, August 5, 2022.

373 *The new plastics economy: Rethinking the future of plastics*, World Economic Forum, Ellen MacArthur Foundation, and McKinsey, 2016.

374 *Plastic pollution facts, data and statistics*, Plastic Collective, blog, December 11, 2023.

375 All figures are for direct emissions only and exclude indirect emissions from power generation. See *Global energy perspective 2023*, McKinsey, October 2023; and *Global plastics outlook*, OECD, accessed May 2024.

376 Synthesizing low-emissions ammonia is Challenge 15. It is discussed briefly in chapter 2 but not explored further in this chapter. This research examines 25 significant physical

challenges associated with the transition. Twenty of these are explored in detail in the deep dives. These 20 were chosen to illustrate and understand the broad dynamics associated with the physical transformation of the energy system and draw overarching conclusions.

377 *Ammonia technology roadmap: Towards more sustainable nitrogen fertiliser production*, IEA, October 2021; Vaclav Smil, "The modern world can't exist without these four ingredients. They all require fossil fuels," *Time*, May 12, 2022.

378 *Ammonia technology roadmap: Towards more sustainable nitrogen fertiliser production*, IEA, October 2021.

379 Ibid.

380 *Hydrogen*, IEA, accessed May 2024.

381 *Global energy perspective 2023*, McKinsey, October 2023; *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

382 For example, in the case of lower/medium temperature heat, heat is often delivered in the form of steam. Reconfiguration is then more limited to the mechanism to create the steam itself.

383 See Arnout de Pee, Dickon Pinner, Occo Roelofsen, Ken Somers, Eveline Speelman, and Maaike Witteveen, "Decarbonization of industrial sectors: The next frontier," McKinsey, June 2018. Industrial emissions from burning fossil fuels for these four industries account for 55 percent of total industrial emissions and come from the generation of high-temperature heat (35 percent), the generation of medium- or low-temperature heat and other fossil fuel uses on the industrial site (13 percent), and machine drive—using fossil fuels to fuel machines that, for instance, grind feedstocks in the production of cement or run compressors (7 percent).

384 Aluminum is the exception. Its production requires temperatures exceeding 1,000°C. However, unlike the big four industrial materials, most of this high-temperature energy demand is already delivered through electricity. See "Aluminum decarbonization at a cost that makes sense," McKinsey, April 2023.

385 The industry domain has no Level 1 challenges, defined as those requiring progress in deploying established technologies and facing the least hurdles.

386 "Decarbonize and create value: How incumbents can tackle the steep challenge," McKinsey Sustainability, October 2023. Energy efficiency is not discussed in this chapter but is covered in Challenge 23: Expanding energy efficiency, in chapter 2.

387 "Reduction" refers to the process that removes the oxygen present in iron ore to produce iron, as discussed further as part of Challenge 12.

388 That is, electrifying the process of breaking down hydrocarbon molecules into smaller monomers, as discussed as part of Challenge 14: Cracking the challenge of plastics.

389 *Pathways to commercial liftoff: Industrial decarbonization*, US Department of Energy, September 2023.

390 McKinsey MineSpans; Christian Hoffmann, Michel van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey, June 2020. In primary steel production, about 95 percent is currently produced using a blast furnace and basic oxygen furnace. The rest is produced using natural-gas-based direct iron reduction and an electric arc furnace (EAF).

391 steelFacts, World Steel Association, 2022.

392 McKinsey MineSpans; M. Shahabuddin, Geoffrey Brooks, and Muhammad Akbar Rhamdhani, "Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis," *Journal of Cleaner Production*, volume 395, April 2023.

393 *Global blast furnace tracker*, Global Energy Monitor, accessed May 2024.

394 Integrated steel production facilities are large industrial complexes that carry out all the processes involved in steelmaking, from the initial processing of raw materials to the final finishing of steel products.

395 *POSCO Gwangyang steel plant*, Global Energy Monitor, accessed May 2024.

396 Casey Crownhart, "How green steel made with electricity could clean up a dirty industry," *MIT Technology Review*, June 2022; and *Biomass in steelmaking, World Steel Association*, September 2021.

397 McKinsey Basic Materials Institute. Also see M. Shahabuddin, Geoffrey Brooks, and Muhammad Akbar Rhamdhani, "Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis," *Journal of Cleaner Production*, volume 395, April 2023.

398 McKinsey Basic Materials Institute.

399 The fact that scrap steel may contain contaminants that are not fully purified in an EAF means that some grades of steel, such as high-strength galvanized/peritectic steel that is used in the automotive and defense industries, cannot currently be produced from scrap steel. See *Pathways to commercial liftoff: Industrial decarbonization*, US Department of Energy, September 2023.

400 Hot briquetted iron is a compacted form of DRI, which is easier and safer to transport. For simplicity, DRI is used to cover all forms of DRI including hot briquetted iron. Some other reducing agents are also being explored, including biomass. Coal is already used as a reductant agent in DRI, but its use results in higher emissions.

401 McKinsey Basic Materials Institute; M. Shahabuddin, Geoffrey Brooks, and Muhammad Akbar Rhamdhani, "Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis," *Journal of Cleaner Production*, volume 395, April 2023. When using hydrogen, the only byproduct is water, and therefore almost all emissions are abated. Residual emissions are indirect ones from the electricity used. In the case of natural gas, the reduction reaction leads to CO_2 being released, albeit less than in the case of coke used in the blast-furnace process.

402 Soroush Basirat, *Green steel opportunity in the Middle East and North Africa: Region can lead green hydrogen use in steel sector*, Institute for Energy Economics and Financial Analysis, September 2022.

403 *Hamburg H2: Working towards the production of zero-carbon emissions steel with hydrogen*, ArcelorMittal, accessed May 2024; "Sweden's H2 Green Steel plans to raise $1.65 bln for Boden plant," Reuters, April 24, 2023; and *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

404 This process can also use higher-emissions power sources, but then the carbon savings in comparison with BF-BOF would be lower.

405 BF-BOF plants typically have a power plant where off-gases from the blast furnaces are used to generate power, and therefore these plants purchase little to no power from the grid. See "The resilience of steel: Navigating the crossroads," McKinsey, April 2023.

406 Maddy Savage, "The race across Europe to build green steel plants," BBC News, February 17, 2023.

407 McKinsey MineSpans; M. Shahabuddin, Geoffrey Brooks, and Muhammad Akbar Rhamdhani, "Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis," *Journal of Cleaner Production*, volume 395, April 2023; and Thomas Echterhof, "Review on the use of alternative carbon sources in EAF steelmaking," *Metals*, volume 11, number 2, January 2021.

408 Where feasible, natural gas–based DRI can be complemented by carbon capture facilities to further lower emissions. One such plant is currently operating in Abu Dhabi. See *Carbon capture and storage (CCS)*, World Steel Association, accessed May 2024.

409 "Global energy perspective 2023: Hydrogen outlook," McKinsey, January 10, 2024; and *Global hydrogen demand in the net zero scenario 2022-2050*, IEA, September 26, 2023.

410 *15 insights on the global steel transformation*, Agora Industry and Wuppertal Institute, June 2023.

411 High-quality iron ore with more than 65 percent iron content and lower impurity improves efficiency (increases throughput). See Simon Nicholas and Soroush Basirat, *Solving iron ore quality issues for low-carbon steel*, Institute for Energy Economics and Financial Analysis, August 2022.

412 McKinsey MineSpans.

413 Simon Nicholas, "Big iron ore's long-term strategies diverging in the face of steel decarbonisation," Institute for Energy Economics and Financial Analysis, February 2024.

414 McKinsey MineSpans. Ore with more than 65 percent iron content and aluminum oxide content below 1 percent. Technically below-grade ores could still be beneficiated, but the relative cost of such beneficiation becomes incrementally more expensive.

415 McKinsey MineSpans.

416 Andrew Gadd et al., *Pathways to decarbonization episode seven: The electric smelting furnace*, BHP, June 2023. The reason a BOF is used instead of an EAF as in the previous pathway is that the BOF manages to further remove impurities more effectively than an EAF.

417 The BOF is used in this process to enable further purification of the resulting steel. Both the premelter and BOF emissions in this process would be limited. The BOF step accounts for a comparatively low share of emissions (less than 10 percent of the total). As for the premelter, using low-emissions power would lead to low emissions from this step.

418 Marion Rae, "Iron ore giants join forces on electric smelter for green steel," Renew Economy, February 2024.

419 Relining refers to the process of replacing or refurbishing the lining of the furnace's interior, which over time can degrade due to the intense heat, chemical reactions, and mechanical stresses.

420 *15 insights on the global steel transformation*, Agora Industry and Wuppertal Institute, June 2023; Molly Lempriere, *Steel industry makes 'pivotal' shift towards lower-carbon production*, Carbon Brief, July 2023; *Cleveland-Cliffs submits application for front-end engineering design for large-scale carbon capture*, Cleveland-Cliffs press release, December 7, 2022; *NETL collaborates with U.S. Steel to capture greenhouse gas at Edgar Thomson Plant*, United States Steel press release, September 20, 2023.

421 Capture rates are defined as the share of emissions from the BF-BOF process that would be captured and not released into the atmosphere. McKinsey Basic Materials Institute. Also see M. Shahabuddin, Geoffrey Brooks, and Muhammad Akbar Rhamdhani, "Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis," *Journal of Cleaner Production*, volume 395, April 2023; and *15 insights on the global steel transformation*, Agora Industry and Wuppertal Institute, June 2023.

422 Ibid.

423 *Steel*, IEA, accessed May 2024; and *Decarbonizing steelmaking for a net-zero future*, Boston Metal, accessed May 2024.

424 *Rio Tinto's BioIron™ proves successful for low-carbon iron-making*, Rio Tinto press release, November 23, 2022.

425 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020.

426 Examples include alternative binders such as geopolymers, Hoffmann cement binders, and Celitement; novel production processes, such as making cement from calcium silicate and using electrolysis; and mineralization—"carbonating" materials by binding CO_2 with them to create carbonate minerals, such as calcium carbonate. Those technologies are more nascent than the technologies discussed in this chapter, being mostly in their pilot or demonstration stage. See Fabian Apel, Johanna Hoyt, Francisco Marques, Sebastian Reiter, and Patrick Schulze, "Cementing your lead: The cement industry in the net-zero transition," McKinsey, October 2023.

427 CO_2 emissions—both process and heat emissions—are roughly directly proportional to the amount of clinker produced when fossil fuels are used. See Danyang Cheng et al., "Projecting future carbon emissions from cement production in developing countries," *Nature Communications*, volume 14, article 8213, December 2023.

428 SCMs comprise a wide range of both naturally occurring and industrial byproduct materials, such as fly ash, blast furnace slag, and limestone. See *Pathways to commercial liftoff: Low-carbon cement*, US Department of Energy, September 2023.

429 *SIP 1—Limits on quantity of supplementary cementitious materials*, National Ready Mixed Concrete Association, 2015.

430 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020; *Pathways to commercial liftoff: Low-carbon cement*, US Department of Energy, September 2023.

431 *Pathways to commercial liftoff: Low-carbon cement*, US Department of Energy, September 2023.

432 *Calcined clays*, Global Cement and Concrete Association, accessed May 2024.

433 *Holcim launches Europe's first calcined clay operation*, ZKG Cement press release, February 2023; and Emily Thomas, *Cementir Group launches FUTURECEM in France and Benelux*, World Cement, March 2, 2022.

434 Ellis Gartner, "Industrially interesting approaches to 'low-CO_2' cements," *Cement and Concrete Research*, volume 34, issue 9, 2004; *LEILAC*, European Climate, Infrastructure and Environment Executive Agency, accessed May 2024.

435 The increased viscosity necessitates the use of a rotating kiln to help mix and move the material through the kiln. This rotation makes it difficult to add heating elements, which would furthermore need to withstand the harsh environment inside the kiln.

436 *The electrified commercial cement kiln*, Cemnet, January 6, 2023.

437 For example, no other combustion gases are produced and there are fewer impurities.

438 "Experiences with alternative fuels," Cemnet, June 12, 2020.

439 *Pathways to commercial liftoff: Low-carbon cement*, US Department of Energy, September 2023.

440 *Renewables 2023: Analysis and forecast to 2028*, IEA, January 2024.

441 *Pathways to commercial liftoff: Low-carbon cement*, US Department of Energy, September 2023.

442 Ibid.

443 *Heidelberg Materials to install 70,000t/y carbon capture system at Lengfurt cement plant*, Global Cement, April 2023; *ECCO$_2$ develops carbon capture cement plant in Spain*, Aggregates Business, January 2022; Stephanie Cram, "Why this company is adopting carbon capture and storage technology in its cement production," CBC News, January 15, 2024; *Air Liquide and Holcim to collaborate on a project to decarbonize cement production in Belgium*, Air Liquide, May 2, 2023.

444 *LEILAC*, European Climate, Infrastructure and Environment Executive Agency, accessed May 2024.

445 *LEILAC technology roadmap to 2050, A cost-effective path to carbon neutral industrial production*, Leilac, 2021.

446 *Wienerberger launches first CO_2-neutral brick production line*, Wienerberger press release, February 11, 2022.

447 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020; and Chris Bataille, *Low and zero emissions in the steel and cement industries: Barriers, technologies, and policies*, OECD Green Growth Papers, number 2020/02, January 2020.

448 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey, May 2020; Andrew Moore, "5 benefits of building with cross-laminated timber," *College of Natural Resources News, August 2022*; and *How does the climate impact of cross-laminated timber compare to steel or concrete?* MIT Climate Portal, June 2023.

449 *Building value by decarbonizing the built environment*, McKinsey, June 2023; and Adel Younis and Ambrose Dodoo, "Cross-laminated timber for building construction: A life-cycle-assessment overview," *Journal of Building Engineering*, volume 52, July 2022.

450 Victor De Araujo and André Christoforo, "The global cross-laminated timber (CLT) industry: A systematic review and a sectoral survey of its main developers," *Sustainability*, volume 15, issue 10, 2023.

451 *Wienerberger launches first CO_2-neutral brick production line*, Wienerberger press release, February 11, 2022.

452 Two important aspects of plastics are beyond the scope of this report. The first is modification of consumer behavior that could reduce overall demand for plastics. The second is the additional impact that plastics have on the environment beyond emissions.

453 See *Pathways to commercial liftoff: Decarbonizing chemicals and refining*, US Department of Energy, September 2023. Electrification could also be implemented in other steps in the plastics production process, such as polymerization.

454 Kerry Hebden, "Dow and Shell's 'e-cracker' technology now operational," *The Chemical Engineer*, June 2022.

455 *Optimization of electric ethylene production: Exploring the role of cracker flexibility, batteries, and renewable energy integration*, Industrial & Engineering Chemistry Research, September 2023.

456 See, for example, *Dow and X-energy advance efforts to deploy first advanced small modular nuclear reactor at industrial site under DOE's Advanced Reactor Demonstration Program*, Dow press release, March 1, 2023.

457 M.E.H. Tijani, Herbert Zondag, and Yvonne van Delft, "Review of electric cracking of hydrocarbons," *ACS Sustainable Chemistry and Engineering*, volume 10, number 49, December 2022.

458 See, for example, *Fort Saskatchewan Path2Zero*, Dow, accessed May 2024.

459 *Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry*, Material Economics, 2019; *Fort Saskatchewan Path2Zero*, Dow, accessed May 2024.

460 The specific emissions profile would also depend on direct and indirect land-use effects and how end-of-life emissions, as well as negative emissions associated with carbon uptake by the biomass used, are accounted for (if it leads to long-term removal of carbon from its natural cycle). See *Pathways to commercial liftoff: Decarbonizing chemicals and refining*, US Department of Energy, September 2023.

461 "Sustainable feedstocks: Accelerating recarbonization of chemicals," McKinsey, October 2023.

462 McKinsey Basic Materials Institute; and A. Negri and T. Ligthart, *Decarbonisation options for the Dutch polyolefins industry*, Manufacturing Industry Decarbonisation Data Exchange Network, February 2, 2021.

463 *Pathways to commercial liftoff: Decarbonizing chemicals and refining*, US Department of Energy, September 2023.

464 "Sustainable feedstocks: Accelerating recarbonization in chemicals," McKinsey, October 26, 2023.

465 Ibid.

466 "No time to waste: What plastics recycling could offer," McKinsey, September 21, 2018.

467 Nikolaos Voulvoulis et al., *Examining material evidence: The carbon fingerprint*, Imperial College London, October 8, 2020.

468 Vasileios Rizos et al., *Chemical recycling of plastics: Technologies, trends and policy implications*, CEPS, 2023.

469 *Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry*, Material Economics, 2019.

470 Ibid.

471 Each cycle can degrade the polymer's quality, leading to weaker, less-versatile plastics. This limit is due to the physical and chemical changes the polymers undergo during the recycling process. Chemical recycling can potentially overcome these limitations. It breaks down polymers into their monomers or other basic chemicals, effectively resetting the material's properties. This process allows for the potential to recycle plastics indefinitely, as the fundamental building blocks can be reconstituted into new polymers without degradation of quality.

472 *Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry*, Material Economics, 2019.

473 *Chemical recycling: State of play*, Eunomia, December 2020.

474 Zhou Peng, Theo Jan Simons, Jeremy Wallach, and Adam Youngman, "Advanced recycling: Opportunities for growth," McKinsey, May 2022.

475 Neste, Uponor, *Wastewise Group and Borealis enable chemical recycling of hard-to-recycle plastic waste into new high-quality plastic pipes*, Neste press release, February 14, 2023; and *ETP clean energy technology guide*, IEA, September 2023.

476 McKinsey Materials Practice.

477 *Industrial transformation 2050—pathways to net-zero emissions from EU heavy industry*, Material Economics, 2019

478 This approach is different from the previously discussed use of biobased feedstocks to produce plastics. While in the former approach, the plastics are chemically identical to their fossil-fuel-based counterparts and therefore exhibit the same properties, in this case the material being produced is different and would display different properties.

479 Stefan Helmcke, Thomas Hundertmark, Chris Musso, Wen Jie Ong, Jonas Oxgaard, and Jeremy Wallach, "Climate impact of plastics," McKinsey, July 2022.

480 Ibid.

481 *Electrifying industrial heat: A trillion euro opportunity hiding in plain sight*, Ambienta Environmental Investments, February 2023.

482 *Businesses in the manufacturing sector*, Eurostat, January 2024.

483 *Global energy perspective 2023*, McKinsey, October 2023.

484 Aluminum is the exception. Its production requires temperatures of over 1,000°C. However, unlike the big four industrial materials, most of this high-temperature energy demand is already delivered through electricity. See "Aluminum decarbonization at a cost that makes sense," McKinsey, April 2023; and *Making net-zero aluminum possible*, Mission Possible Partnership, September 2022.

485 *Direct CO_2 emissions from industry in the net zero scenario*, 2000–2030, IEA, September 2022.

486 *Global energy perspective 2023*, McKinsey, October 2023.

487 *Waste heat recovery: Technology and opportunities in U.S. industry*, US Department of Energy, March 2008.

488 *Chinese long-distance nuclear heating project begins operation*, China National Nuclear Corporation, November 30, 2023.

489 Lubos Palata, "Nuclear heating: A low-cost, greener option?" *Deutsche Welle*, April 2021.

490 Carlos Cariaga, *Graben-Neudorf project, Germany produces 200C thermal water*, ThinkGeoEnergy, August 2023.

491 *The world's first Eavor-loop™ for heat and power is under construction in Germany*, Eavor, accessed May 2024.

492 For example, a paper and pulp plant in Sweden is being built that will produce syngas on site to provide heating for temperatures up to 600°C. See *Innovation fund: Driving clean innovative technologies towards the market*, European Commission, 2021.

493 This considers charging and discharging efficiency, because the energy is stored as heat and the conversion losses when going from one type of heat to another are minimal. See *Net-zero heat: Long duration energy storage to accelerate energy system decarbonization*, Long Duration Energy Storage Council and McKinsey, November 2022.

Chapter 8

494 Total CO_2 emissions for buildings are allocated as follows: 54 percent for space heating, 22 percent for water heating, 9 percent for appliances, 8 percent for space cooling, 5 percent for lighting, and 2 percent for cooking. See Brodie Boland, Shailesh Lekhwani, Sebastian Reiter, and Erik Sjödin, "Building value by decarbonizing the built environment," McKinsey, June 2023.

495 Coal, oil, and natural gas account for about 60 percent of total final consumption for residential and commercial buildings. See McKinsey Energy Insights, 2022; and *Global energy perspective 2023*, McKinsey, October 2023.

496 This report does not cover cooking, but it is important to note that cleaner cooking has the potential not only to reduce emissions but also to improve health, particularly in emerging markets. Approaches include electrifying heat sources and using cleaner fuels such as natural gas, liquefied petroleum gas, bioethanol, and biogas. See *A vision for clean cooking access for all*, World Energy Outlook special report, IEA, July 2023; and Brodie Boland, Shailesh Lekhwani, Sebastian Reiter, and Erik Sjödin, "Building value by decarbonizing the built environment," McKinsey, June 2023.

497 Excluding air-conditioning-only systems. Reversible heat pumps can be used for space cooling.

498 *Net zero by 2050: A roadmap for the global energy sector*, IEA, May 2021.

499 This share of heat provided by electricity is in terms of pre-efficiency useful heat in terajoules, as per McKinsey's 2023 Achieved Commitments scenario.

500 District heating includes more centralized solutions to generate and distribute heat to buildings, such as geothermal solutions and using waste heat from power plants or industrial sites. Solar thermal technology consists of harnessing solar energy and can be used to heat water or air in buildings. It is important to note that these solutions cannot be rolled out in all situations. For instance, district heating requires a central heating source, such as surplus heat from industry, and solar thermal may not be appropriate for geographies with low solar irradiance. See *Building decarbonization: How electric heat pumps could help reduce emissions today and going forward*, McKinsey, July 2022; *Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*, Energy Transitions Commission, November 2018; and *Space heating*, IEA, September 2023.

501 On the supply side, estimates suggest that global heat pump manufacturing capacity would need to quadruple in 2030 to meet projected demand in a net-zero scenario. The expansion of capacity indicated by publicly announced projects falls short of this goal, but short lead times of one to three years for manufacturing expansion or construction of new factories could minimize the gap. See *Energy technology perspectives 2023*, IEA, January 2023. In terms of other operational constraints, a key limit on installing heat pumps in new and existing buildings as well as carrying out the retrofits required to ensure heat pumps perform effectively (such as changing ductwork, pipes, or radiators) in existing homes is the availability of skilled labor. Another constraint relates to consumer adoption of heat pumps, which can be influenced by high up-front costs and, in the case of the existing stock of buildings, by the friction associated with transforming legacy heating and cooling systems. Such operational challenges would also need to be addressed.

502 The level of emissions saved by adopting heat pumps depends on a number of factors, such as the emissions intensity of the power grid and the refrigerant used. One common refrigerant, R-410a, is being phased out because of its high global warming potential. This research does not discuss refrigerants in detail because lower-emissions options are available and under development.

503 *Heat pump systems*, US Department of Energy, accessed May 2024.

504 *Global heat pump sales continue double-digit growth*, IEA, March 2023.

505 *The future of heat pumps in China*, IEA, March 2024.

506 Ibid.

507 COP and efficiency are similar concepts. COP is typically used to describe systems that transfer heat, such as heat pumps, and energy efficiency is

typically used to describe systems that generate heat, like gas furnaces. For further context, see *Understanding COP: Coefficient of performance of heat pumps*, Learn Metrics, accessed May 2024.

508 *Furnaces and boilers*, US Department of Energy, accessed May 2024; and *ENERGY STAR proposes updated furnace specification*, Office of State and Community Energy Programs, April 24, 2024.

509 *National climate report*, National Centers for Environmental Information, February 2023; and Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020.

510 Rachana Vidhi, "A review of underground soil and night sky as passive heat sink: Design configurations and models," *Energies*, volume 11, number 11, October 2018.

511 Emily Waltz, *Heat pumps take on cold climates: Eight companies aim to prove that their heat pumps are viable in subzero temps*, IEEE Spectrum, February 2024.

512 At a certain temperature, the heat capacity a heat pump can deliver may fall below the heating load, which means that either a larger (potentially oversize) or a better-performing heat pump or a backup source of heat would be required. See *Cold climate air source heat pump*, Minnesota Commerce Department, November 2017. The exact temperature threshold at which heating capacity falls below the heating load varies, but as a rule, heat pumps are sized to operate at a COP of at least two.

513 Duncan Gibb et al., "Coming in from the cold: Heat pump efficiency at low temperatures," *Joule*, volume 7, issue 9, September 2023.

514 See Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020; Duncan Gibb et al., "Coming in from the cold: Heat pump efficiency at low temperatures," *Joule*, volume 7, issue 9, September 2023; and Figure 3 in Austin Selvig, *Cost-effective net-zero energy houses optimization*, September 2015.

515 For example, if a local utility generates electricity with a combined-cycle natural gas power plant and 50 percent energy efficiency, the efficiency of the heat provided by a heat pump with a COP of two would be 100 percent. In comparison, the average efficiency of a gas furnace is 80 to 97 percent (accounting only for losses occurring in heat generation for both cases, excluding natural gas production and transportation). See *The future of heat pumps*, IEA, November 2022; *Transformative power systems*, Office of Fossil Energy and Carbon Management, US Department of Energy, accessed May 2024; and *Natural gas plants*, Annual Technology Baseline, National Renewable Energy Laboratory, accessed May 2024.

516 See Emily Waltz, *Heat pumps take on cold climates: Eight companies aim to prove that their heat pumps are viable in subzero temps*, IEEE Spectrum, February 2024; and *DOE announces leading heat pump manufacturers successfully develop next-generation prototypes to withstand subfreezing weather*, US Department of Energy, January 2024; *Heating and cooling with a heat pump*, Government of Canada, August 2022; *Performance assessment of heat pump systems*, Sustainable Technologies Evaluation Program, October 2014.

517 This analysis calculates the share of people who experience minimum daily temperature at a certain threshold at least once a year; based on analysis by McKinsey Climate Analytics.

518 Beatriz Santos, "US manufacturer releases cold climate heat pump," *PV Magazine*, April 18, 2023; and *Why use a cold climate air source heat pump?* Government of Canada, accessed April 2024.

519 *Residential cold climate heat pump challenge*, Office of Energy Efficiency & Renewable Energy, US Department of Energy, accessed May 2024.

520 *CCHP technology challenge specifications*, US Department of Energy, accessed May 2024.

521 The COPs of GSHPs can vary and do not always reach four. See Robbin Garber-Slaght, *Performance considerations for ground source heat pumps in cold climates*, National Renewable Energy Laboratory, June 2021.

522 *The difference between air source heat pumps and ground source heat pumps*, UK Alternative Energy, accessed May 2024.

523 A dual-fuel/hybrid heat pump has a fossil-fuel furnace as a backup for very cold days and times of peak electricity demand.

524 "Building decarbonization: How electric heat pumps could help reduce emissions today and going forward," McKinsey, July 2022.

525 *The future of heat pumps*, IEA, December 2022.

526 *Seasons in Finland*, Finnish Meteorological Institute; and Jan Rosenow et al., "Heating up the global heat pump market," *Nature Energy*, September 2022.

527 *Almost 200,000 heat pumps were sold last year. An increase of 50%*, Finnish Heat Pump Association, January 16, 2023.

528 In response to the increase in demand for electricity (partly due but not limited to increasing air-conditioning penetration), new power plants fueled by hydro, steam, coal, and natural gas came online, as did the world's first nuclear power plants. See *Hydroelectric power in the 20th century and beyond*, National Park Service, 2017.

529 Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020. This analysis assumes that the top-performing heat pump (90th percentile) is used. The analysis does not consider other potential growth of energy demand across domains, for example due to population growth or electrification of mobility or industry.

530 Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020.

531 This is based on a study that compares current electricity demand to a scenario with 100 percent electrification of current buildings heat demand in the United States. It calculates peak demand over the course of a year in such a scenario, relative to today's peak demand, and assumes that the top-performing heat pump (90th percentile) is used. The analysis does not consider other potential growth of energy demand across domains, for example due to population growth or electrification of mobility or industry. See Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020.

532 Peak loads refer to noncoincidental loads unless otherwise noted. See Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020. Recent research from the same authors, which considered more recent and higher-resolution data, estimated potential heating responses to different temperatures more precisely. Their findings imply that the precise extent of the increase in peak demand may be slightly lower than previously estimated and would require further research. See Yinbo Hu et al., "A data-driven approach for the disaggregation of building-sector heating and cooling loads from hourly utility load data," *Energy Strategy Reviews*, volume 49, September 2023.

533 See, for example, *The role of natural gas in the move to cleaner, more reliable power*, McKinsey, September 2023; and *2050 transmission study*, ISO New England Transmission Planning, February 2024.

534 Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020.

535 *DOE announces leading heat pump manufacturers successfully develop next-generation prototypes to withstand subfreezing weather*, US Department of Energy, January 2024.

536 Demand-side measures include, for instance, improvements in thermal envelope, intelligent thermal control, space-conditioning load shedding, and connected hot-water heaters. See Mike Specian, Charlotte Cohn, and Dan York, *Demand-side solutions to winter peaks and constraints*, American Council for an Energy-Efficient Economy, April 2021.

537 Examples include storing excess thermal energy in tanks, vessels, or rooms with materials such as wax or sand, and thermochemical storage, which utilizes reversible chemical reactions to store heat.

538 *Trane Technologies advances building decarbonization with industry-first ice-heating solution*, Trane Technologies press release, September 2023.

539 District heating solutions, such as geothermal and waste heat from power plants or industrial sites, produce heat from a central source, which is then delivered to individual buildings. Solar thermal systems use solar energy to heat water or air in buildings.

540 *Dual energy for sustainable decarbonization*, Hydro Québec; and *Hydro-Québec and Énergir: An unprecedented partnership to reduce greenhouse gas emissions*, press release, Hydro Québec, July 2021.

541 Michael Waite and Vijay Modi, "Electricity load implications of space heating decarbonization pathways," *Joule*, volume 4, issue 2, 2020.

Chapter 9

542 Raw materials encompass a wide range of physical elements, including minerals, fossil fuels, and agricultural and forestry products. This research focuses on critical minerals for the energy transition, defined as those that are essential for the development and deployment of low-emissions energy and technologies, and that may be in high demand while limited in their availability during the energy transition.

543 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023; and Ed

Conway, *Material world: A substantial story of our past and future*, Penguin, June 15, 2023.

544 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023. McKinsey's Achieved Commitments scenario assumes that net-zero commitments are achieved by 2050 by leading economies through purposeful policies and implies a 1.6°C rise in global temperatures by 2100.

545 Rare earth minerals are abundant in the Earth's crust but typically are dispersed. This often means that they lack the concentration necessary for viable mining.

546 Under McKinsey's 2023 Achieved Commitments scenario, the pace of growth of all eight critical minerals is slower after 2030 than it is anticipated to be from now to 2030. In the case of lithium, for instance, the pace would drop from about 25 percent per year through 2030 to about 10 percent per year from 2030 to 2050.

547 The research is anchored on the McKinsey MineSpans database, which contains more than 10,000 operating mines and mining projects in more than 130 economies. McKinsey MineSpans' base case of supply includes all operating mines (corrected for depletion and expected closure where relevant), and a selection of projects currently under construction or at the feasibility stage—in most cases with financing confirmed.

548 McKinsey MineSpans' high case of supply includes, for example, some projects in the feasibility stage with no financing confirmed, and with adjustments for potential delays. Potential imbalances between required demand and projected supply are classified into three categories. "High imbalance" corresponds to cases in which demand is more than 50 percent higher than projected supply. "Medium imbalance" corresponds to cases where demand is more than 10 percent higher than supply but less than 50 percent. "No or low imbalance" corresponds to cases where demand is lower than supply or higher by less than 10 percent.

549 *Global critical minerals outlook 2024*, IEA, May 2024; *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023; *The role of critical minerals in clean energy transitions*, IEA, March 2022; and *Geopolitics of the energy transition: Critical minerals*, International Renewable Energy Agency, July 2023.

550 *Mineral commodity summaries 2024*, US Geological Survey, January 2024.

551 Madeline Ruid, *Lithium and EV market update: Slower-than-expected sales growth just a bump in the road*, Nasdaq, May 7, 2024.

552 Thomas Biesheuval, "Battery metal price plunge is closing mines and killing deals," *Bloomberg Law*, January 9, 2024; and Aya Dufour, "Some minerals are 'critical' to the digital economy, but current prices don't reflect that," CBC News, March 4, 2024.

553 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 5, 2023.

554 Resources include the known material in or on the Earth's crust. Reserves are a subset of resources, which has been fully evaluated and is deemed commercially viable to extract. See *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 5, 2023.

555 The global average is based on the top 35 mining projects that came online between 2010 and 2019. See *The role of critical minerals in clean energy transitions*, IEA, March 2022.

556 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.

557 Timur Abenov, Margot Franklin-Hensler, Tino Grabbert, and Thibaut Larrat, "Has mining lost its luster? Why talent is moving elsewhere and how to bring them back," McKinsey, February 2023.

558 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.

559 See "The complexity of transforming rare earths from mine to magnet," Reuters, August 2, 2023; and Karl Tsuji, *Global value chains: Graphite in lithium-ion batteries for electric vehicles*, Office of Industries working paper ID-090, US International Trade Commission, May 2022.

560 *Global flows: The ties that bind in an interconnected world*, McKinsey Global Institute, November 2022.

561 Karl Tsuji, *Global value chains: Graphite in lithium-ion batteries for electric vehicles*, Office of Industries working paper ID-090, US International Trade Commission, May 2022.

562 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.

563 *Tenke Fungurume Copper-Cobalt Mine*, NS Energy, August 2021; *Kalongwe Copper-Cobalt Project*, NS Energy, February 2019; and *Chengtun Mining: Kalongwe Copper-Cobalt Project in Congo is ramping up production capacity*, SMM, May 2023.

564 Marcelo Azevedo, Magdalena Baczyńska, Ken Hoffman, and Aleksandra Krauze, "Lithium mining: How new production technologies could fuel the global EV revolution," McKinsey, April 2022; and *Eramet prepares to open Centenario-Ratones lithium project in Argentina*, BNamericas, April 23, 2024.

565 David Whitehouse, *Gates and Bezos-backed KoBold Metals sees AI as key to revolution in mining exploration*, FDI Intelligence, October 18, 2023.

566 "Bridging the copper supply gap," McKinsey, February 2023.

567 *Global critical minerals outlook 2024*, IEA, May 2024.

568 "Has mining lost its luster? Why talent is moving elsewhere and how to bring them back," McKinsey, February 2023.

569 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.

570 Edoardo Righetti and Vasileios Rizos, "The EU's quest for strategic raw materials: What role for mining and recycling?" *Intereconomics*, volume 58, number 2, 2023.

571 *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.

572 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

573 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 5, 2023.

574 *PEM vs alkaline electrolyzers*, Hydrogen Newsletter, accessed May 2024.

575 *Master Plan Part 3: Sustainable energy for all of Earth*, Tesla, April 5, 2023; and "The automakers and suppliers pushing to cut rare earths from EVs," Reuters, November 14, 2023.

576 James D. Widmer, Richard Martin, and Mohammed Kimiabeigi, *Electric vehicle traction motors without rare earth magnets*, Sustainable Materials and Technologies, April 2015.

577 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 5, 2023.

578 "Building better batteries: Insights on chemistry and design from China," McKinsey, April 22, 2021; and *Global EV outlook*, IEA, April 2024.

579 Stationary storage covers systems that are not mobile and typically used to store energy for grid applications, including systems like grid-scale battery installations, home energy storage systems, and other applications where the stored energy can be used to balance supply and demand, provide backup power, and improve grid stability.

580 Cameron Murray, "'World-first' grid-scale sodium-ion battery project in China launched," *Energy Storage News*, August 3, 2023; Carlos Ruiz et al., *Sodium-ion batteries ready for commercialisation: for grids, homes, even compact EVs*, Energy Post, September 11, 2023; and Richard Milne, "Northvolt in new sodium-ion battery breakthrough," *Financial Times*, November 2023.

581 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 5, 2023.

Chapter 10

582 Bill Gates, *To cut emissions, use this Swiss Army Knife*, GatesNotes, June 21, 2022.

583 "Global energy perspective 2023: Hydrogen outlook," McKinsey, January 2024; *Hydrogen for refineries is increasingly provided by industrial suppliers*, US Department of Energy, January 2016.

584 This research uses the 2023 McKinsey Achieved Commitments scenario because it provides detail across different economies and types of assets about the deployment levels that would be required for those economies to meet the climate commitments they have made. This scenario assumes that countries that have committed to net zero (some by 2050, some later) meet those commitments and that warming reaches 1.6°C relative to preindustrial levels by 2100. See *Global energy perspective 2023*, McKinsey, October 2023. Other scenarios may contain slightly different combinations of technologies and rates of deployment, but the broad trends and themes described in this research would still apply.

585 "Global energy perspective 2023: Hydrogen outlook," McKinsey, January 2024.

586 Simon Michaux, *Assessment of the extra capacity required of alternative energy electrical power systems to completely replace fossil fuels*, Geological Survey of Finland, August 2021.

587 Lucian Mihăescu et al., *Comparative analysis between methane and hydrogen regarding ignition*

and combustion in diffusive mode, E3S Web of Conferences 327, 2021.

588 McKinsey Hydrogen Insights; Simon Michaux, *Assessment of the extra capacity required of alternative energy electrical power systems to completely replace fossil fuels*, Geological Survey of Finland, August 2021.

589 Gaseous and liquefied hydrogen have, respectively, one-third and one-half of the volumetric energy density of gaseous and liquefied natural gas. See Simon Michaux, *Assessment of the extra capacity required of alternative energy electrical power systems to completely replace fossil fuels*, Geological Survey of Finland, August 2021.

590 *Safe use of hydrogen*, Office of Energy Efficiency & Renewable Energy, US Department of Energy, accessed June 2024.

591 For example, in multiple scenarios analyzed by the World Energy Council, 200 million to 600 million tonnes of hydrogen were estimated to be required by 2050, an increase of two to six times from today's total production. This is based on a range of decarbonization scenarios entailing less than 1.8°C of projected warming above preindustrial levels. See *Hydrogen demand and cost dynamics*, World Energy Council working paper, 2021.

592 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; and *Global energy perspective 2023*, McKinsey, October 2023; and *New energy outlook 2024*, BloombergNEF, May 2024.

593 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; and *Global energy perspective 2023*, McKinsey, October 2023.

594 *McKinsey Hydrogen insights 2023*, Hydrogen Council and McKinsey, December 2023.

595 This research examines 25 significant physical challenges associated with the transition. Twenty of these are explored in detail in the deep dives. These 20 were chosen to illustrate and understand the broad dynamics associated with the physical transformation of the energy system and draw overarching conclusions.

596 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023; "Tracking biofuels supply," in *Tracking clean energy progress 2023*, IEA, July 2023.

597 "Global energy perspective 2023: Hydrogen outlook," McKinsey, January 2024.

598 In the case of steel, carbon capture and direct electrification (for example, molten ore electrolysis) could also be possible, but they are expected to account for a smaller share of production than hydrogen-based steelmaking (see chapter 7 on the industry domain). In the case of shipping and aviation, biofuels are also expected to play a role, but could face limitations due to availability of feedstock. See "Global energy perspective 2023: Sustainable fuels outlook," McKinsey, January 2024.

599 When electrolyzers are used intermittently, that share is about 25 to 45 percent, and up to 70 percent if they are used more continuously. See *Global hydrogen review 2023*, IEA, revised September and December 2023; *The European hydrogen market landscape*, European Hydrogen Observatory, report 01, November 2023.

600 "Global energy perspective 2023: Hydrogen outlook," McKinsey, January 2024; *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

601 In this section, by convention, we display efficiencies based on the HHV of hydrogen. This value corresponds to the energy released when burning hydrogen with oxygen, considering the latent heat of the resulting water vapor that could be recovered. Note that some sources refer to the lower heating value (LHV) of hydrogen when presenting efficiency calculations. Hydrogen's LHV is about 85 percent of its HHV. Depending on whether HHV or LHV is used, efficiency values differ at various points in the chain (for example, electrolysis). The end-to-end efficiency of hydrogen is independent of the choice of metric. See Philipp Lettenmeier, *Efficiency—electrolysis*, Siemens Energy white paper, 2020; and *Making the hydrogen economy possible: Accelerating clean hydrogen in an electrified economy*, Energy Transitions Commission, March 2023.

602 All efficiency figures in this section are based on McKinsey Hydrogen Insights unless otherwise stated.

603 Current SOECs require steam at a temperature of about 500°C to operate. If the heat used to generate this steam is waste heat from other processes, and its value is therefore excluded from the energy input, SOECs can deliver an efficiency of about 100 percent. McKinsey Hydrogen Insights and Tony Leo et al., *Reducing the cost of hydrogen production*, Fuel Cell Energy white paper, 2024.

604 *Hydrogen*, IEA, accessed June 2024; *The future of hydrogen: Seizing today's opportunities*, IEA, June 2019.

605 McKinsey Hydrogen Insights; and Leigh Collins, "'Hydrogen leakage makes H_2 potentially more dangerous to climate than burning natural gas': Rio Tinto," Hydrogen Insight, December 2, 2022.

606 *The future of hydrogen: Seizing today's opportunities*, IEA, June 2019.

607 In LHV terms, natural gas and hydrogen boilers are often described as having efficiency of more than 90 percent, which corresponds to around 75 to 80 percent HHV efficiency. See McKinsey Hydrogen Insights; H2 Science Coalition; and Oddgeir Gudmundsson and Jan Eric Thorsen, "Source-to-sink efficiency of blue and green district heating and hydrogen-based heat supply systems," *Smart Energy*, volume 6, May 2022.

608 Additional losses of around 5 to 15 percent also occur in a hydrogen-powered fuel-cell vehicle; this relates to the inversion of alternate to direct current and the electric engine efficiency. See S. Vengatesan, Arunkumar Jayakumar, and Kishor Kumar Sadasivuni, "FCEV vs. BEV – a short overview on identifying the key contributors to affordable & clean energy (SDG-7)," *Energy Strategy Reviews*, volume 53, May 2024.

609 Energy efficiency is higher for fuel cells or combined-cycle turbines, and lower for open-cycle turbines. See McKinsey Hydrogen Insights, 2023; *Making the hydrogen economy possible: Accelerating clean hydrogen in an electrified economy*, Energy Transitions Commission, March 2023; and Dmitry Pashchenko, "Green hydrogen as a power plant fuel: What is energy efficiency from production to utilization? *Renewable Energy*, volume 223, March 2024.

610 McKinsey Hydrogen Insights; and Kamil Niesporek, Oliwia Baszczeńska, and Mateusz Brzęczek, "Hydrogen vs methane: A comparative study of modern combined cycle power plants," *Energy*, volume 291, March 14, 2024.

611 Sen Yu et al., "Hydrogen-based combined heat and power systems: A review of technologies and challenges," *International Journal of Hydrogen Energy*, volume 48, issue 89, November 2023.

612 The end-to-end efficiency is the result of the multiplication of each step: 90 times 80 times 50 percent equals 36 percent.

613 Efficiency figures are based on heat output at the point of its production (for instance, a boiler). Additional efficiencies in the delivery of that heat, such as in radiators in a home, are not considered.

614 LDES alternatives include liquid air, compressed air, gravity-based systems, power-to-gas-to-power, and metal anode batteries, among others. The 40 to 70 percent range is based on compressed air energy storage, which is one of the most mature novel LDES approaches. See *Net-zero power: Long duration energy storage for a renewable grid*, Long Duration Storage Council and McKinsey, November 2021; and *Managing seasonal and interannual variability of renewables*, IEA, April 2023.

615 *Utility-scale batteries and pumped storage return about 80% of the electricity they store*, US Energy Information Administration, February 2021; *Managing seasonal and interannual variability of renewables*, IEA, April 2023.

616 *Where the energy goes—gasoline vehicles*, fueleconomy.gov, US Department of Energy and US Environmental Protection Agency, accessed June 2024; *Net-zero America: Potential pathways, infrastructure, and impacts*, Princeton University, October 2021.

617 *McKinsey Hydrogen insights 2023*, Hydrogen Council and McKinsey, December 2023.

618 Joshua S. Hill, *Can aluminium be used as ultra long term storage for renewable energy and heat?* Renew Economy, August 22, 2022; *Managing seasonal and interannual variability of renewables*, IEA, April 2023.

619 This considers hydrogen's HHV. See *How the world really works: The science behind how we got here and where we are going*, Vaclav Smith, May 2022; and Reimund Neugebauer, *Hydrogen technologies*, Springer Nature, 2022.

620 "Global energy perspective 2023: Sustainable fuels outlook," McKinsey, January 2024.

621 Maddy Savage, "The race across Europe to build green steel plants," BBC News, February 17, 2023.

622 *Global hydrogen review 2023*, IEA, revised September and December 2023; *Hysata opens new electrolyser manufacturing facility in Port Kembla with 23m vote of confidence from Australian and Queensland governments*, Hysata, August 14, 2023.

623 "World's largest SOEC electrolyzer achieves record efficiency," Hydrogen Tech World, April 2022; Lingting Ye and Kui Xie, "High-temperature electrocatalysis and key materials in solid oxide electrolysis cells," *Journal of Energy Chemistry*, volume 53, March 2021.

624 *Global hydrogen review 2023*, IEA, revised September and December 2023.

625 *Global hydrogen review 2023*, IEA, revised September and December 2023; *Hysata opens new*

electrolyser manufacturing facility in Port Kembla with 23m vote of confidence from Australian and Queensland governments, Hysata, August 14, 2023.

626 "World's largest SOEC electrolyzer achieves record efficiency," *Hydrogen Tech World*, April 2022; Lingting Ye and Kui Xie, "High-temperature electrocatalysis and key materials in solid oxide electrolysis cells," *Journal of Energy Chemistry*, volume 53, March 2021.

627 Philipp C. Verpoort et al., "Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains," *Nature Energy*, volume 9, 2024.

628 Dirk Durinck, Wieland Gurlit, Fabian Müller, and Bruno van Albada, "Closing Europe's green-metallics gap," McKinsey, December 2022; and *Global hydrogen flows 2023 update*, McKinsey and Hydrogen Council, 2023.

629 *McKinsey Hydrogen insights 2023*, Hydrogen Council and McKinsey, December 2023. Final investment decision (FID) is the stage at which the decision to move forward with the sanctioning and construction of the infrastructure project is made.

630 *Global energy perspective 2023*, McKinsey, October 2023.

631 *Global hydrogen review 2023*, IEA, revised September and December 2023; *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023.

632 *Global hydrogen review 2023*, IEA, revised September and December 2023.

633 *NEOM Green Hydrogen Project*, Acwa Power, accessed June 2024.

634 *H_2U Technologies announces hydrogen industry's first commercial-scale non-iridium PEM electrolyzer*, H_2U Technologies, June 22, 2023.

635 *The net-zero materials transition: Implications for global supply chains*, McKinsey, July 2023.

636 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

637 Global Gas Infrastructure Tracker, Global Energy Monitor, accessed June 2024.

638 Daniel Onyango, "Germany delays 9,700-km hydrogen pipeline network to 2037 to workout financing structure," *Pipeline Technology Journal*, April 11, 2024.

639 *Global hydrogen review 2023*, IEA, 2023.

640 *Global hydrogen review 2023*, IEA, 2023. Large-scale projects include, for instance, 50,000 tonnes of ammonia a year from Saudi Arabia to the EU, and 25,000 tonnes a year from Saudi Arabia to China.

641 *Global hydrogen review 2023*, IEA, 2023.

642 *Global hydrogen flows 2023 update*, McKinsey and Hydrogen Council, November 2023; McKinsey Global Hydrogen Flow Model.

643 *Global hydrogen review 2023*, IEA, 2023; Polly Martin, *Final investment decision taken on Germany's first onshore liquid gases terminal, with eye on future hydrogen imports*, Hydrogen Insight, March 2024.

644 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

645 *Global hydrogen review 2023*, IEA, revised September and December 2023.

646 *Promising materials for hydrogen storage*, CORDIS, accessed June 2024; Rupert Wickens, *Hydrogen—an overview of the issues associated with its production, storage and transportation*, LFF Group, April 2022; *Innovative hydrogen energy storage project secures over £7 million in funding*, University of Bristol press release, November 29, 2022; *£7.7m award for hydrogen-uranium energy storage pilot*, Urenco, November 28, 2022; HyDus.

647 *Spotlight on: Turbines and renewable gases!* EUTurbines, March 2019; *Global hydrogen review*, IEA, 2023.

648 *Enabling or requiring hydrogen-ready industrial boiler equipment*, UK Department for Business, Energy and Industrial Strategy, 2022.

Chapter 11

649 *Summary for policymakers, Climate change 2022: Mitigation of climate change*, Intergovernmental Panel on Climate Change (IPCC), 2022.

650 Ibid. In this analysis, energy efficiency includes, for example, the following mitigation options: avoiding demand for energy services; efficient lighting, appliances, and equipment; fuel efficiency in light- and heavy-duty vehicles; efficiency and optimization in shipping; and energy efficiency in aviation and industry.

651 Out of this increase, about 0.5 percentage point could come from improvements in efficiency from electrification and the use of renewables, which is broader than the scope of this challenge. However, the remaining 1.5 percentage points would come largely from technical-efficiency improvements, such as improved insulation in buildings, or avoided demand (for example, through behavioral changes such as higher use of public transportation or limited heating of buildings). See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

652 This research examines 25 significant physical challenges associated with the transition. Twenty of these are explored in detail in the deep dives. These 20 were chosen to enable us to illustrate and understand the broad dynamics associated with the physical transformation of the energy system and draw overarching conclusions. Two of the three challenges described in this chapter are not explored in depth in this research: Challenge 23: Expanding energy efficiency, and Challenge 25: Capturing atmospheric carbon.

653 CDR can be achieved using technology-based solutions, such as DAC, by combining bioenergy with CCUS to create net-negative emissions or using nature-based solutions, including mangrove restoration, afforestation and reforestation, and regenerative soil projects. Scaling nature-based solutions would require addressing barriers including, but not limited to, lowering the cost of projects, improved transparency of standards, practices, and services, and creating regulatory clarity. See Peter Mannion, Emma Parry, Mark Patel, Erik Ringvold, and Jonathan Scott, *Carbon removals: How to scale a new gigaton industry*, McKinsey Sustainability, December 4, 2023; and Daniel Aminetzah, Emily Birch, Julien Claes, Sebastien Marlier, Antoine Stevens, Joshua Katz, Peter Mannion and Dickon Pinner, "Why investing in nature is key to climate mitigation," McKinsey, January 2021.

654 *Direct air capture*, IEA, accessed June 2024.

655 *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, IEA, September 2023.

656 James Hack, Nobutaka Maeda, and Daniel M. Meier, "Review on CO_2 capture using amine-functionalized materials," *ACS Omega*, volume 7, issue 44, November 2022.

657 Krysta Biniek, Kimberly Henderson, Matt Rogers, and Gregory Santoni, "Driving CO_2 emissions to zero (and beyond) with carbon capture, use, and storage," *McKinsey Quarterly*, June 2020; and *A new era for CCUS*, IEA, September 2020.

658 Gary T. Rochelle, "Amine scrubbing for CO_2 capture," *Science*, September 2009; and Krysta Biniek, Phil De Luna, Luciano Di Fiori, Alastair Hamilton, and Brandon Stackhouse, "Scaling the CCUS industry to achieve net-zero emissions," McKinsey, October 2022.

659 *Global status of CCS 2022*, Global CCS Institute, 2022; and *Special report on carbon capture utilisation and storage: CCUS in clean energy transitions*, IEA, September 2020.

660 Total CO_2 emissions in 2022 (million tonnes). See *Global energy perspective 2023*, McKinsey, October 2023.

661 *Global status of CCS 2022*, Global CCS Institute, 2022.

662 *Global energy perspective 2023*, McKinsey, October 2023.

663 The Global CCS Institute looked at a range of scenarios. In those consistent with limiting global temperature rises to 1.5°C, total CO_2 sequestered using CCUS is estimated to range from five gigatonnes of CO_2 per year to 28 gigatonnes in 2020. The average across scenarios is 11 gigatonnes. Under a 2°C pathway, the range is 0.4 gigatonnes of CO_2 a year to 30 gigatonnes; the average is 6.0 gigatonnes a year. See *Scaling up the CCS market to deliver net-zero emissions*, 2020 Thought Leadership, Global CCS Institute, 2020.

664 Emissions that arise from mobility and buildings are spread among a large number of individually small assets and can be described as diffuse emissions. Carbon capture usually isn't thought to play a large role in abating these emissions.

665 "CO_2 capture," in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use and storage*, National Petroleum Council, March 2021.

666 *How efficient is carbon capture and storage?*, MIT Climate Portal, February 2021; and T*echnology readiness and costs of CCS*, Global CCS Institute, March 2021.

667 Daniel Krekel et al., "The separation of CO_2 from ambient air: A techno-economic assessment," *Applied Energy*, volume 218, May 2018.

668 Jo Husebye et al., "Techno economic evaluation of amine based CO_2 capture: Impact of CO_2 concentration and steam supply," *Energy Procedia*, volume 23, 2012.

669 David Kearns, Harry Liu, and Chris Consoli, *Technology readiness and costs of CCS*, Global CCS Institute, March 2021.

670 Where the CO_2 is dilute, more equipment is required because the separation technology may rely on chemical rather than physical processes. See "Carbon capture" in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use, and storage*, National Petroleum Council, December 2019 (updated March 2021).

671 The reason is that lower concentrations also reduce the kinetics of capture processes.

672 David Kearns, Harry Liu, and Chris Consoli, *Technology readiness and costs of CCS*, Global CCS Institute, March 2021; Phil De Luna, Luciano Di Fiori, Yinsheng Li, Alastair Nojek, and Brandon Stackhouse, "The world needs to capture, use and store gigatons of CO_2: Where and how?," McKinsey, April 2023; and Adam Baylin-Stern and Niels Berghout, *Is carbon capture too expensive?* IEA, February 2021.

673 "The world needs to capture, use and store gigatons of CO_2: Where and how?" McKinsey, April 2023.

674 *Global energy perspective 2023*, McKinsey, October 2023.

675 *State of the art: CCS technologies 2023*, Global CCS Institute, July 2023; Chris Bataille et al., "A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement," *Journal of Cleaner Production*, volume 187, June 2018; *World energy outlook*, IEA, 2022; *15 insights on the global steel transition*, Agora Industry and Wuppertal Institute, 2023; and *Decarbonisation in the global steel sector: Tracking the progress*, New Climate Institute, December 2022.

676 Conway Nelson, *Carbon capture on BD3—successful by design*, International CCS Knowledge Centre, May 2023.

677 *Scaling up through 2030*, Global CCS Institute, 2023.

678 *Global status of CCUS 2022*, Global CCS Institute, 2022; *A new era for CCUS*, IEA, September 2020; and "Timely advances in carbon capture, utilisation and storage," in *The role of CCUS in low-carbon power systems*, IEA, July 2020.

679 Rui-Tang Guo et al., "Recent progress on CO_2 capture based on sterically hindered amines: A review," *Energy Fuels*, 2023.

680 "CO_2 capture," in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use and storage*, National Petroleum Council, March 2021.

681 In the conventional cement production process, lower-purity emissions from burning fossil fuels are mixed with high-purity process emissions, making the resulting stream harder to treat with CCUS approaches. See *LEILAC*, European Climate, Infrastructure and Environment Executive Agency, accessed May 2024.

682 *Carbon capture, usage and storage: A vision to establish a competitive market*, UK Department for Energy Security & Net Zero, December 2023.

683 Energy Act of 2020 (CCUS provisions), IEA, March 2022; and *Scaling up through 2030: Global status of CCS 2023*, Global CCS Institute, 2023.

684 David Kearns, Harry Liu, and Chris Consoli, *Technology readiness and costs of CCS*, Global CCS Institute, March 2021.

685 See *Net zero roadmap;: A global pathway to keep the 1.5°C goal in reach, 2023 update*, IEA, 2023; and CO_2 transport and storage, IEA, accessed June 2024.

686 David Kearns, Harry Liu, and Chris Consoli, *Technology readiness and costs of CCS*, Global CCS Institute, March 2021.

687 Ibid.

688 Krysta Biniek, Ryan Davies, and Kimberly Henderson, "Why commercial use could be the future of carbon capture," McKinsey Sustainability, January 2018; and *Maersk secures green e-methanol for the world's first container vessel operating on carbon neutral fuel*, Maersk, August 19, 2021.

689 Jordan Kearns et al., "Developing a consistent database for regional geologic CO_2 storage capacity worldwide," *Energy Procedia*, volume 114, July 2017; *The world has vast capacity to store CO_2: Net zero means we'll need it*, IEA, April 2021.

690 For comparison, 8,000 to 55,000 gigatonnes of storage corresponds to thousands of years of annual captured emissions (for instance, 4,200 million tonnes a year in 2050 in McKinsey's 2023 Achieved Commitments scenario). See *Global energy perspective 2023*, McKinsey, October 2023.

691 *CCUS policies and business models: Building a commercial market*, IEA, November 2023.

692 Examples of projects under development include CO_2 networks and terminals between Poland and France linking to storage in the North and Baltic seas in the European Union and a 3,200-kilometer CO_2 pipeline to link 30 small-scale bioethanol plants across five states in the United States. See Mathilde Fajardy, Carl Greenfield, and Rachael Moore, *How new business models are boosting momentum on CCUS*, IEA, March 2023; and *Scaling up through 2020, Global status of CCS 2023*, Global CCS Institute, 2023.

693 *CO_2 reduction through storage under the North Sea*, Porthos, April 2024; and The CCUS Hub, Porthos, accessed June 2024.

694 *CCUS around the world in 2021 – Northern Lights*, IEA, accessed June 2024.

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