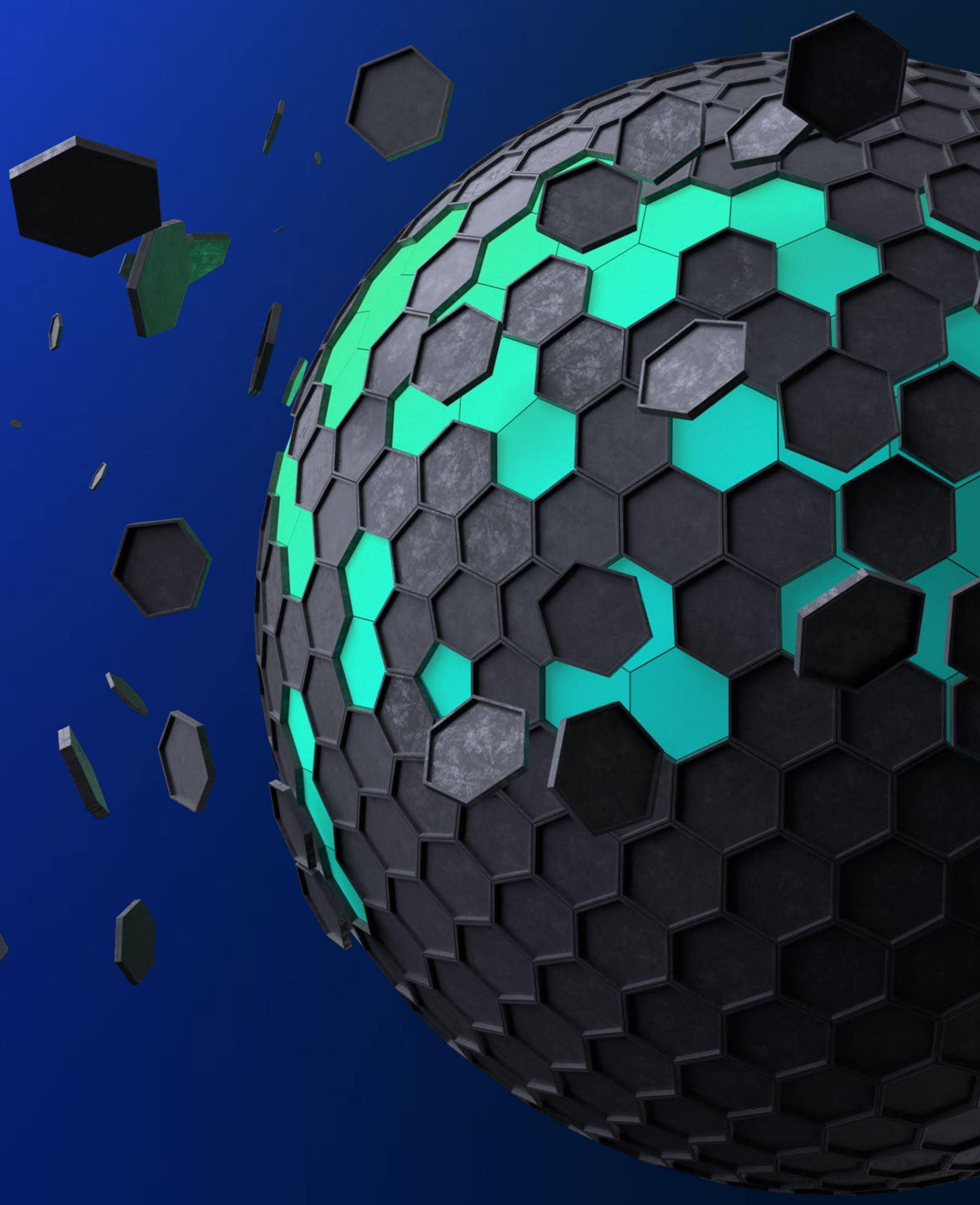
McKinsey Global Institute

Executive summary

The hard stuff

Navigating the physical realities of the energy transition



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Cover image: Green sphere inside a black one
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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.

This document contains only the executive summary. To read our full report click **here**, or go to **mck.co/physicaltransition**

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

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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.

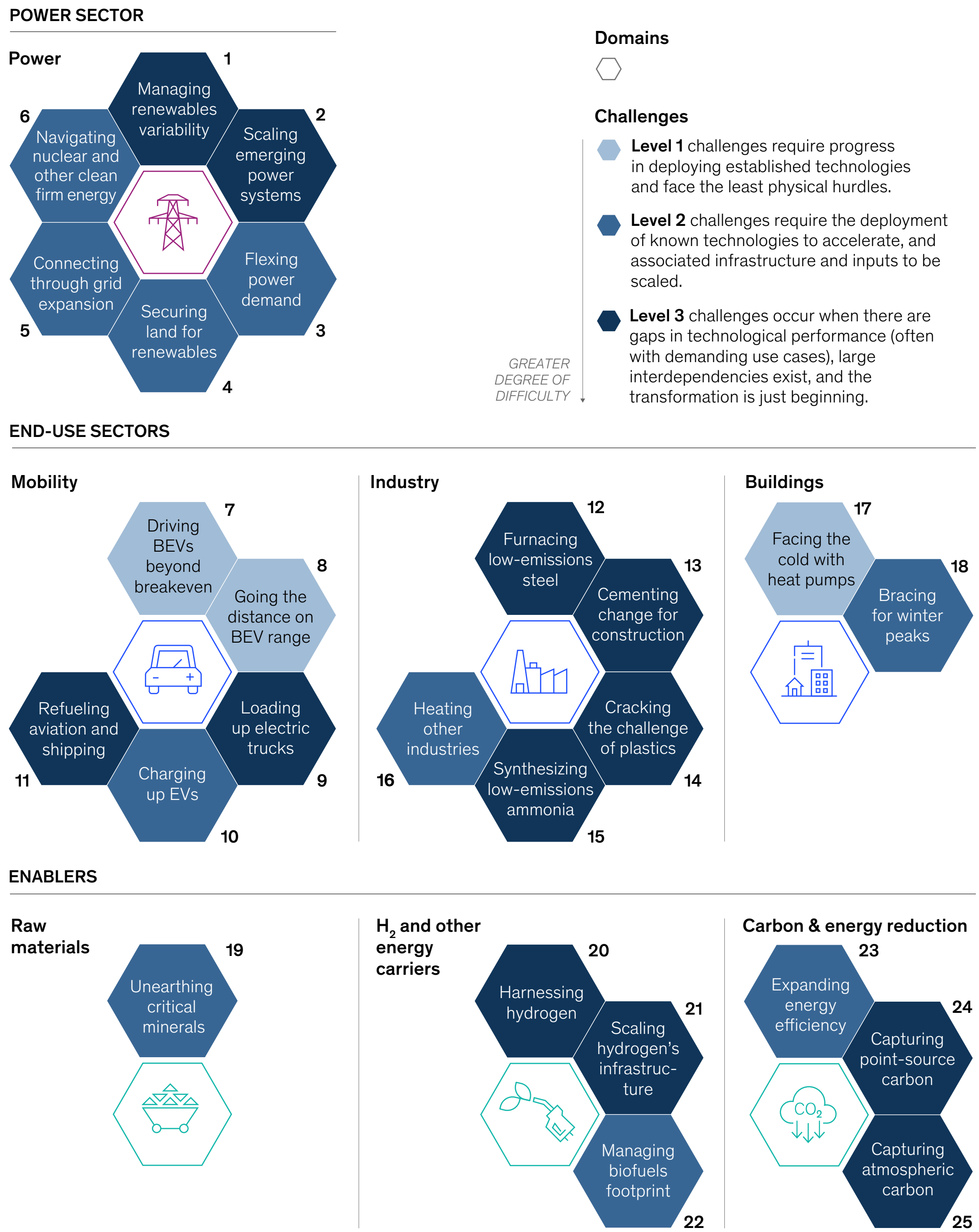
Recent years have seen momentum on many—but not all—fronts. For instance, about 90 percent of all battery EV sales and almost 60 percent of solar and wind power capacity added was in the past five years.[19] But overall, the transition is in its early stages. Deployment of low-emissions technologies 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.

This document contains only the executive summary. To read our full report click **here**, or go to **mck.co/physicaltransition**

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.

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