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An affordable, reliable, competitive path to net zero

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At a glance

- **Though there has been meaningful momentum, the world is not on track to achieve the goal enshrined in the Paris Agreement of limiting warming to well below 2°C or ideally 1.5°C.** To meet that goal, countries and companies have committed to reaching net-zero emissions of CO_2 and reducing emissions of other greenhouse gases. But there has not been enough progress. The share of primary energy produced by renewable sources, for example, has risen slowly, from 8 percent in 2010 to 12 percent in 2021. If emissions stay on their current trajectory, estimates from various sources suggest, net zero would not arrive even by the end of the century.

- **A successful net-zero transition will require achieving not one objective but four interdependent ones: emissions reduction, affordability, reliability, and industrial competitiveness.** A poorly executed transition could make energy, materials, and other products less affordable, compromising economic empowerment. It could also make the supply of energy and materials less secure and resilient, and it could render some countries and companies less competitive. If that happened, progress toward net zero itself could stall.

- **Our research has found practical ways to address those objectives simultaneously.** Seven principles can help stakeholders successfully navigate the next phase of the transition. For example, deploying lower-cost solutions and driving down the cost of more expensive ones could bolster affordability. Managing existing and emerging energy systems in parallel could make access to energy more reliable. Seeking opportunities by using comparative advantage as a guide could help countries bolster their competitiveness.

- **Following those principles could substantially improve the world's current trajectory.** We examined the potential implications of applying two principles: deploying more lower-cost solutions and using R&D and other measures to double the expected rate of cost declines. Our illustrative analyses found that doing so could substantially improve the current trajectory of emissions and help limit warming to what the Paris Agreement envisions. Capital spending on low-emissions technologies would potentially be one and a half to two times as large as it is now—as opposed to about three times, as might be the case if the two principles were applied less extensively.

- **Embracing a change of mindset can help the world move closer to net zero.** In addition to global commitments to reach net zero in the future, stakeholders should commit to making more and more progress every year and doing so in a way that addresses all four objectives.

Introduction

Today, the world is undertaking the net-zero transition, an ambitious effort to reach net-zero emissions of CO_2 and reduce emissions of other greenhouse gases (GHGs). The goal of the transition is outlined in the Paris Agreement adopted at the United Nations in 2015: to limit global warming above preindustrial levels to well below 2.0°C, and ideally to 1.5°C. Doing so would reduce the odds of initiating the most catastrophic impacts of climate change.[1] According to the Intergovernmental Panel on Climate Change (IPCC), limiting warming to 1.5°C would require reducing GHG emissions by 43 percent between 2019 and 2030 and cutting net emissions of CO_2 to zero by around 2050.[2]

But the effort to meet the goals of the Paris Agreement is not currently on track, as a recent report from the United Nations shows.[3] Many public and private actors, aspiring to meet those goals, are working to usher in the transition's next phase, one in which more capital flows toward the transition and the deployment of necessary technologies expands substantially.

Often, the transition is envisioned as a single great challenge: reducing emissions from energy, materials, and land-use and other systems. In practice, it consists of four objectives: emissions reduction, affordability, reliability, and industrial competitiveness.[4] If achieving the first of those objectives risks compromising the other three, momentum toward net zero could be derailed. In this report, we outline principles that can guide stakeholders in addressing all four objectives simultaneously—and even help accelerate the progress of the transition.[5]

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[1] See *Global warming of 1.5°C*, Intergovernmental Panel on Climate Change (IPCC), 2018.

[2] *Climate change 2022: Mitigation of climate change*, IPCC, 2022.

[3] See *Technical dialogue of the first global stocktake: Synthesis report by the co-facilitators on the technical dialogue*, United Nations Framework Convention on Climate Change, September 2023.

[4] Affordability is a particularly important priority. Recent research from the McKinsey Global Institute (MGI) has found that 4.7 billion people are not yet economically empowered—that is, they cannot meet essential needs and begin to achieve financial security. For details, including more about that definition of economic empowerment, see *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023.

[5] This research focuses on the net-zero transition. Adaptation to climate change is another important part of the climate agenda. The subject is outside the scope of this report but will be explored in upcoming research by MGI.

There has been meaningful momentum toward net zero

The world has made headway in reducing emissions. Today, net-zero commitments have been made by more than 8,000 companies and by countries representing 90 percent of global GDP; also, 150 countries have pledged to reduce methane emissions.[6] Climate policy and legislation have become increasingly ambitious. And calls are growing to keep the transition from disproportionately affecting the developing world and vulnerable communities.[7]

The good news is not limited to commitments and laws; solid, measurable progress is being made as well. Innovation has made many new technologies more viable. For example, solar power and wind power account for more than 10 percent of electricity generation and 75 percent of new electricity-generating capacity.[8] Electric vehicles (EVs) make up about 15 percent of new vehicle sales, and the range of the average EV has increased nearly three times during the past decade.[9] Large-scale plants are being built for such newer technologies as low-emissions steel production and carbon capture, utilization, and storage (CCUS). Businesses are starting to reallocate resources from high-emissions to low-emissions products.[10] Climate-related venture capital investments reached $70 billion in 2022, almost double the 2021 amount.[11] The global financial sector is strengthening its response to climate change; annual global investment in transition technologies has doubled, from $660 billion in 2015 to more than $1 trillion today.[12] And new market instruments, such as advance market commitments, are emerging to spur innovation.[13]

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[6] "Race to zero campaign," United Nations Framework Convention on Climate Change, 2023; "Data explorer," Net Zero Tracker, 2023; "Global methane pledge: From moment to momentum," US Department of State, November 2022.

[7] For example, see "UNCTAD urges channelling net-zero finance to support the energy transition in developing economies," United Nations Conference on Trade and Development, October 17, 2023.

[8] "Growth in renewables achieved despite energy crisis," International Renewable Energy Agency, March 2023; and "Renewables," International Energy Agency, July 2023.

[9] "Electric vehicles," International Energy Agency, July 2023; and *Global EV outlook 2022*, International Energy Agency, May 2022.

[10] Rob Bland, Anna Granskog, and Tomas Nauclér, "Accelerating toward net zero: The green business building opportunity," McKinsey & Company, June 2022.

[11] "Defying gravity, 2022 climate tech VC funding totals $70.1B, up 89% on 2021," HolonIQ, January 3, 2023.

[12] *Global landscape of renewable energy finance 2023*, International Renewable Energy Agency and Climate Policy Initiative, 2023.

[13] For example, Frontier Climate has already helped put in place prepurchase agreements for CO_2 removals that will, once the technologies are developed, remove more than 200,000 tons of CO_2 emissions.

Nevertheless, the world is not on track to reach net zero by 2050

Despite all that good news, numerous estimates, including a recent one from the United Nations, show that emissions are not on track to reach net zero emissions of CO_2 by 2050—which, most estimates suggest, would be needed to limit warming to 1.5°C.[14] We examined 23 “current policy” scenarios from the IPCC, McKinsey’s *Global energy perspective 2023*, the Network for Greening the Financial System (NGFS), and the International Energy Agency (IEA).[15] In none of the scenarios do global emissions of CO_2 reach net zero, even by the end of the century (Exhibit 1). In the IPCC scenarios, the median level of warming by the end of the century is 2.9°C, and in the more recent McKinsey, NGFS, and IEA scenarios, it is 2.3°C, 2.8°C, and 2.4°C, respectively.[16]

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[14] *Technical dialogue of the first global stocktake: Synthesis report by the co-facilitators on the technical dialogue*, United Nations Framework Convention on Climate Change, September 2023. The IPCC has found that to limit global warming to 1.5°C with no or limited overshoot (with a greater than 50 percent probability), GHG emissions would have to be reduced by 43 percent by 2030 and carbon dioxide 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.

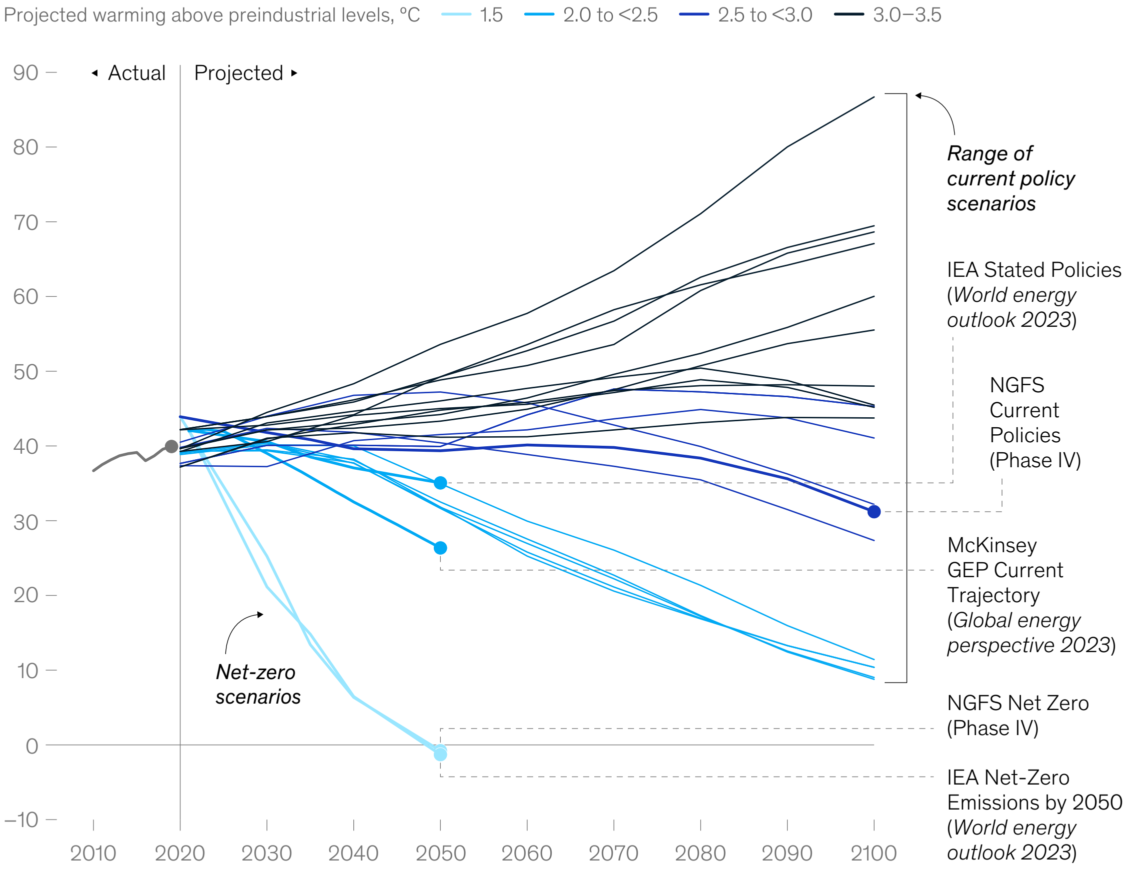
[15] See “AR6 Scenario Explorer and Database hosted by IIASA,” International Institute for Applied Systems Analysis, 2022; *Global energy perspective 2023*, McKinsey & Company, October 2023; *NGFS climate scenarios for central banks and supervisors—Phase IV*, Network for Greening the Financial System, November 2023; and *World energy outlook 2023*, International Energy Agency, October 2023.

[16] The IPCC scenarios represent policies as of 2020. The McKinsey, NGFS, and IEA scenarios represent more recent policies. Other research by the IPCC, reporting the median of warming outcomes in 29 scenarios, has found that warming by the end of the century could reach 3.2°C above preindustrial levels. See *Climate change 2023 synthesis report*, IPCC, 2023.

Exhibit 1

A wide range of scenarios shows that if the world stays on its current trajectory, net zero will not arrive during this century.

Global CO_2 emissions by scenario,[1] metric gigatons



Note: Each line in the chart, other than IEA Net-Zero Emissions by 2050 (*World energy outlook 2023*) and NGFS Net Zero (Phase IV), corresponds to a current policy scenario—that is, a scenario that tries to show what will happen under policies implemented as of 2020 or later and with expected improvements in low-emissions technologies. Unlabeled lines represent scenarios identified as "implemented policies" in the Intergovernmental Panel on Climate Change's *Sixth Assessment Report*. In the IEA scenarios, we added emissions from agriculture, forestry, and other land use, using the IEA's stated assumptions for each of those scenarios.

[1] Net emissions of CO_2 from energy, materials, land-use, and other systems.

Source: Publicly available data from International Energy Agency (IEA), Network for Greening the Financial System (NGFS) Phase IV, and "AR6 Scenario Explorer and Database hosted by IIASA," International Institute for Applied Systems Analysis, 2022; McKinsey's *Global energy perspective 2023* (GEP); McKinsey analysis

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One reason the net-zero transition has been slower than hoped is its unprecedented complexity. It calls for transforming not only energy systems but also materials, land-use, and other systems—in short, the global economy—and doing so in a coordinated and integrated way (Exhibit 2).[17] To successfully meet the global goals enshrined in the Paris Agreement will require a vast increase in total capital spent each year, from $5.7 trillion spent on low- and high-emissions technologies

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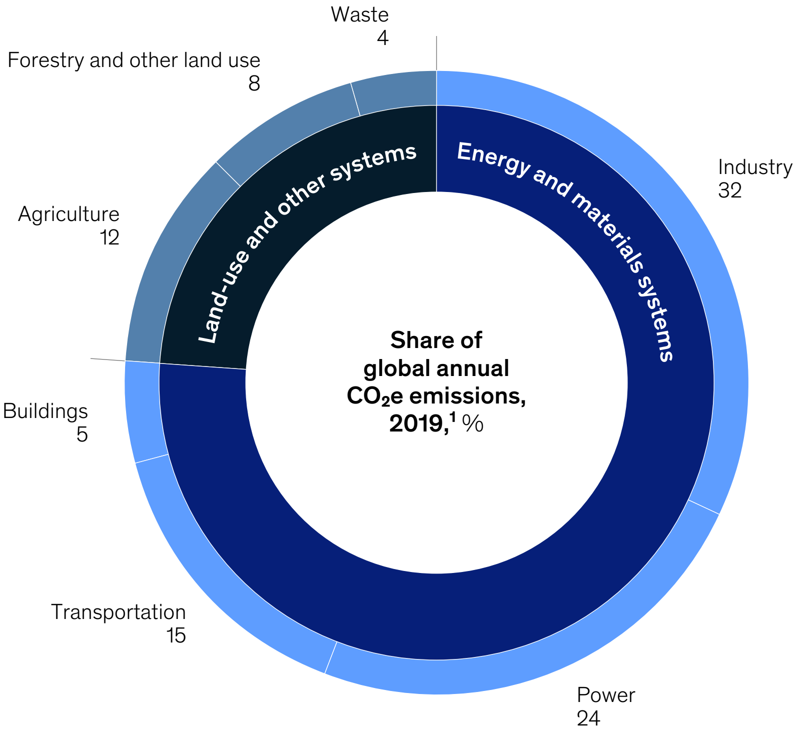
[17] See *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.

Exhibit 2

The transition calls for transforming the energy, materials, land-use, and other systems that emit greenhouse gases.



Note: **Industry** includes emissions from industrial processes for cement, chemicals, metals, and mining, as well as oil and gas processes such as upstream processes, refining, and pipeline transportation. **Power** includes emissions from electricity generation and heat generation. **Transportation** includes emissions from road vehicles, rail, aviation, and maritime transportation. **Buildings** includes emissions from cooking and heating in commercial and residential buildings. **Agriculture** includes crop residues, enteric fermentation, fishing, manure, on-farm energy use, rice, and synthetic fertilizers. **Forestry and other land use** includes emissions from drained organic soils, net forest conversion (the anthropogenic conversion of sitting forest land to other land uses or vice versa), fires in organic soils, and fires in humid tropical forests. It does not include emissions from other forest fires (in unmanaged lands), which represent roughly 0.2 metric gigaton of GHG emissions. It also does not include negative emissions from existing forestland, which represent a CO_2 sink of approximately 2.6 metric gigatons. **Waste** includes emissions from the biological treatment of solid waste, solid waste disposal, wastewater treatment and discharge, and the incineration or open burning of waste.

[1] CO_2e, or carbon dioxide equivalent, includes not only carbon dioxide but also other greenhouse gases. CO_2e is calculated with a measure called global warming potential, which indicates how much energy the emissions of one ton of a greenhouse gas will absorb in relation to the emissions of one ton of CO_2 over a given period—in this case, 100 years.

Source: Food and Agriculture Organization of the United Nations, “FAOStat”; McKinsey EMIT database (2021); McKinsey analysis

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today to as much as $9.2 trillion, on average, spent over the next three decades.[18] During that period, the low-emissions part of that spending would need to grow from approximately $1.5 trillion per year now to about $7.0 trillion, on average.[19]

The problem is not just the scale of spending on low-emissions technologies but also what it would fund. Our past research has found that partly because many low-emissions technologies will not be cost competitive by 2030 under current policy frameworks, only 50 percent of the capital spending on those technologies needed by then to eventually achieve net zero could occur without additional societal commitment.[20] Examples of such commitment include new public spending (which may be difficult) and additional policy measures, such as carbon prices.

Furthermore, the transition would rebuild in about three decades efficient systems that took centuries to build, carrying out a massive physical transformation. Consider that most proposed pathways to net zero envision making the power system three times larger than it is now and electrifying many end uses of energy, such as transportation and heating. Yet even though solar power, wind power, and other renewable sources of energy are becoming much more common, the share of primary energy that they produce has risen only slowly, from 8 percent in 2010 to 12 percent in 2021.[21]

Finally, the transition would require actions to be taken now in exchange for benefits—in particular, avoided physical damage from climate change—that would mostly appear in future decades.[22] And the costs of those actions, in terms of spending and transformation today, would not be borne evenly by all stakeholders.

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[18] Even after expected increases in spending resulting from current policies and income growth are accounted for, the necessary increase in total high- and low-emissions spending would be large at $1 trillion. The $9.2 trillion estimate is based on a net-zero scenario from the Network for Greening the Financial System (NGFS) that limits warming by 2100 to 1.5°C above preindustrial levels. In quantifying investment, we include what is typically considered investment in national accounts, such as investment in solar and wind power capacity, as well as some spending on what are typically considered consumer durables, such as electric vehicles. The investment numbers take into consideration energy, materials, and land-use systems that account for roughly 85 percent of overall CO_2 emissions today. These estimates are higher than others in the literature because we have included spending on high-emissions technologies, agriculture, and other land use and have also taken an expansive view of the spending required in end-use sectors. Our analysis distinguishes high-emissions assets and technologies from low-emissions ones. Low-emissions assets emit relatively low amounts of GHGs but are not necessarily carbon neutral. Examples of low-emissions assets are solar and wind farms and electric vehicles. In some cases, we also include enabling infrastructure, such as the transmission and distribution infrastructure needed for renewable power or the charging infrastructure needed for electric vehicles. Examples of high-emissions assets are fossil fuel–based power and vehicles with internal combustion engines. In the NGFS's scenario, some spending on high-emissions assets continues, particularly in the early years of the transition. For more details, see *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.

[19] Recent research from MGI estimated the spending needed on low-emissions technologies at $55 trillion cumulatively from 2021 to 2030, an increase of $41 trillion over the amount that would result if spending in 2020 took place in every year from 2021 through 2030. The $55 trillion estimate works out to $5.5 trillion annually, on average, and that $5.5 trillion estimate differs from the $7.0 trillion cited here because it covers a different period and applies in a scenario of high GDP growth. For further details, see *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023.

[20] *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023. That 50 percent includes both a continuation of today's spending levels and increased spending likely under current policy frameworks.

[21] "International," US Energy Information Administration, 2023. Primary energy refers to the total amount of energy that is available in natural resources before any conversion or transformation takes place. The percentage contributions that different energy sources make to total primary energy may be different from the percentage contributions that those sources make to energy consumed by end users because different uses lead to different amounts of conversion loss.

[22] Other potential benefits include improved air quality, water quality, and biodiversity. See "Costs and benefits of a net-zero target for the UK," in *Net zero: The UK's contribution to stopping global warming*, Committee on Climate Change, May 2019.

A poorly executed transition could compromise affordability, reliability, and competitiveness—and slow progress toward net zero

The net-zero transition is too often regarded as a singular problem. In fact, it is four connected challenges (Exhibit 3). Reducing emissions of GHGs is indeed at the heart of the transition.[23] But if the transition is poorly executed, it could compromise three other important objectives: affordability, reliability, and industrial competitiveness. Those objectives enhance economic well-being on their own; moreover, compromising them would make the emissions reductions themselves less likely to endure.[24]

That outcome is not inevitable. If the net-zero transition is managed well, there are many ways in which it could further affordability, reliability, and industrial competitiveness over time. The most obvious is that the world would have to spend less on adapting to climate change and withstanding the damage it causes.[25] Also, provided that cost declines continue at expected rates and that manufacturing capacity is scaled up effectively, more and more low-emissions technologies could soon become cost competitive with traditional technologies in various markets on a total-cost-

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[23] This report focuses on net zero, but other sustainability objectives exist, such as improving the quality of air and water and managing nature-related risks. Similarly, the report does not consider adaptation actions to manage rising physical risks posed by climate change, which is another important part of the climate agenda.

[24] Other researchers have also highlighted potential tensions between the transition and other objectives, such as addressing climate change, affordability, availability, security, equity, environmental justice, and employment. See, for instance, *World energy trilemma index 2022*, World Energy Council, 2022; Haiying Liu et al., “Roles of trilemma in the world energy sector and transition towards sustainable energy: A study of economic growth and the environment,” *Energy Policy*, volume 170, November 2022; and A. G. Olabi, “Energy quadrilemma and the future of renewable energy,” *Energy*, volume 108, August 2016.

[25] The Network for Greening the Financial System estimates that global GDP in 2100 could be up to 18 percent lower in a scenario in which current policies continue than in a baseline in which there were no physical risks from climate change or risks posed by the transition. It also estimates that in a scenario in which warming was 1.5°C above preindustrial levels, GDP in 2100 would be 3 percent lower than in that baseline. See *NGFS Climate Scenarios for central banks and supervisors*, Network for Greening the Financial System, September 2022. That analysis leads to two conclusions. First, over time, the transition will lead to higher GDP than in a scenario with high physical risks. Second, the transition will lead to slightly lower GDP than in the baseline scenario. See *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2022.

Exhibit 3

A successful net-zero transition will require achieving not one objective but four interdependent ones.

Emissions reduction

Reducing emissions of greenhouse gases[1]

Affordability

Ensuring that energy, materials, and other products remain affordable and cost competitive with traditional alternatives

Industrial competitiveness

Ensuring that individual countries, regions, and companies remain competitive and benefit from opportunities during the transition

Reliability

Ensuring that energy, materials, and other products are supplied securely during the transition and that energy systems are resilient

[1] This report focuses on the net-zero transition, but other sustainability objectives exist, such as improving the quality of air and water and managing nature-related risks. Similarly, the report does not consider adaptation actions to manage rising physical risks posed by climate change, which is another important part of the climate agenda.
Source: McKinsey analysis

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of-ownership basis.[26] Energy security could benefit as well in some ways, because the transition could lead to more domestic generation of electricity (for example, from solar and wind) and less dependence on imported energy. And there will be many opportunities to compete to provide materials, manufactured goods, and services—indeed, whole new industries—for the transition.

But it is nevertheless the case that a poorly executed transition could impair affordability, reliability, and industrial competitiveness. Start with affordability. As previous work by McKinsey has pointed out, both the net-zero transition and economic empowerment are urgent and simultaneous goals.[27] But there are several ways that the net-zero transition, if not executed well, could make energy, materials, and other products less affordable than traditional alternatives.[28] Even though wind and solar generate electricity more cheaply than fossil fuels do, they will require additional spending as their share in the overall generation mix rises—for storage; other "firming capacity," which is electricity that can be used at times when solar and wind are not providing enough energy; and grid infrastructure. If the costs of technologies, such as batteries, do not decline as expected, or if grids are not designed thoughtfully, the delivered cost of electricity could rise. For materials, decarbonizing the production of steel, aluminum, and cement could increase production costs by

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[26] See, for example, *The future of heat pumps*, International Energy Agency, December 2022. Technologies' relative cost-competitiveness also depends on other factors, such as how energy prices and interest rates evolve.

[27] *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023.

[28] This discussion does not account for any role that a carbon price might play.

15 percent or more by 2050.[29] If costs of energy and other products were to rise, economic growth could suffer, posing a particular problem for developing countries.[30] And as we mentioned above, the scale of spending needed for the transition could stretch public finances.[31]

A poorly executed transition could also compromise the reliable supply of energy and the resiliency of energy systems, and it could affect the inputs needed for the transition itself. For example, when solar and wind power are low—such as at night or on windless days—poorly designed energy systems might not provide regions with enough storage, firming capacity, or other ways to meet demand reliably. Also, the transition will require many physical inputs: materials and manufactured goods, water, land, infrastructure, and labor. If the transition is not well executed, especially in the near term, the supply of those inputs could be insufficient for what is needed, leading to shortages and slowing the growth of new energy systems. Past McKinsey research has found that shortages of many minerals used in making EV batteries, wind turbines, and other low-emissions technologies could begin before 2030, caused by rapidly growing demand from the transition and the long time it takes to bring new mines on line (five to 15 years, in some cases).[32] The shortages could also have price implications; research estimates that if they are not addressed, the price of nickel, cobalt, and lithium could increase by several hundred percent from 2020 levels in a net-zero scenario over the next decade.[33] Furthermore, the supply of raw materials is often concentrated, creating potential risk from supply chain disruptions. Three countries or fewer account for the extraction of 80 percent or more of several critical minerals. Refining is often even more concentrated.[34] And long approval times can slow deployment; in the United States, the typical electrical power project requesting connection to the grid took an average of five years in 2022.[35]

For individual countries and companies, the transition could also threaten competitiveness if it is not well conceived. Of course, affordability and competitiveness are tightly interlinked; for example, if one country's emissions-reduction initiatives pushed up production costs, its products could become less competitive in global markets.[36] Some countries or regions could be especially vulnerable to the effects of rising production costs. Asia, for example, is where much of the world's manufacturing takes place, so if production there became more expensive, it might be disproportionately affected.[37] But there are other ways that competitiveness could be harmed. During the transition, some legacy industries and natural endowments could lose relevance, affecting jobs and communities.[38] Without robust planning, workers may find it hard to move to new jobs and build new skills. And as many countries adopt assertive industrial policy for climate technologies, they run the risk, if they do not design that policy carefully, of affecting businesses' incentives to innovate and produce efficiently, hurting productivity.

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[29] *Making net-zero steel possible*, Mission Possible Partnership, September 2022; Making net-zero aluminum possible, Mission Possible Partnership, April 2023; *Mission Possible sectoral focus: Cement*, Energy Transitions Commission, January 2019.

[30] In this report, we use the term "developing countries" to mean those that the World Bank classifies as low- or middle-income.

[31] See also *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023.

[32] *The net-zero materials transition: Implications for global supply chains*, McKinsey & Company, July 2023.

[33] Nico Valckx, Andrea Pescatori, and Lukas Boer, "Metals may become the new oil in net-zero emissions scenario," VoxEU, November 5, 2021.

[34] *Mineral commodity summaries 2023*, US Geological Survey, January 2023.

[35] Joseph Rand et al., "Queued up: Characteristics of power plants seeking transmission interconnection as of the end of 2022," Lawrence Berkeley National Laboratory, April 2023.

[36] Researchers have examined the impact of environmental regulation on competitiveness as measured by such factors as trade, industry location, and productivity. They find that such measures have led to statistically significant adverse impacts, but small ones. They add, however, that more research is needed to understand why the impacts have been small, and they conjecture that one reason might be that environmental policy has been strategically set to limit the impact on competitiveness. See Antoine Dechezleprêtre and Misato Sato, "The impacts of environmental regulations on competitiveness," *Review of Environmental Economics and Policy*, volume 11, number 2, summer 2017.

[37] For more details, see *Asia on the cusp of a new era*, McKinsey Global Institute, September 2023.

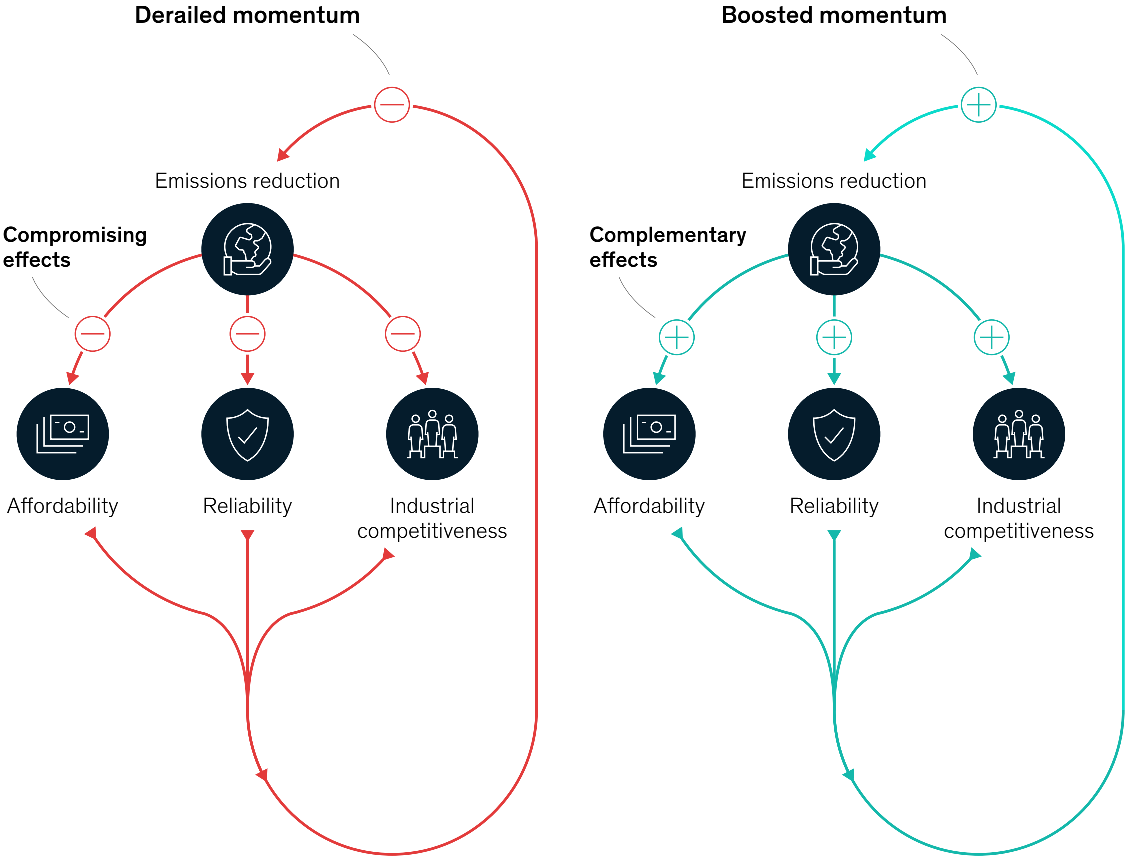
[38] Our past research has shown that job losses during the net-zero transition would be concentrated in certain sectors and regions. For instance, more than 10 percent of jobs in 44 US counties are in fossil fuel extraction and refining, fossil fuel–based power, and automotive manufacturing. For further details, see *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.

Affordability, reliability, and industrial competitiveness are independently important objectives. But if the transition risks compromising them, a separate problem could result: a derailing of momentum toward net zero (Exhibit 4). Affordability may be the most important objective in that respect. Citizens may be less willing to embrace the transition if energy becomes less affordable. Some consumers and companies may not want to switch to low-emissions products if they are unfamiliar or more expensive. Conversely, the more cost competitive the technologies needed for net zero become in relation to traditional, established alternatives, the easier it will be to fund and build them. But reliability and competitiveness matter too. If the transition were to challenge the secure supply of energy and materials, or the availability of jobs and economic opportunity, it could be harder to sustain momentum toward net zero.

If, however, emissions can be reduced while affordability, reliability, and industrial competitiveness are advanced, the transition's momentum could be boosted. For example, if more low-emissions technologies become cost competitive, capital will be likelier to flow to them. And if investing in the transition creates more opportunities for countries and companies to compete, they could be more likely to embrace the transition. A successful net-zero transition will therefore require achieving not one objective but four interdependent ones.

Exhibit 4

Emissions reduction could derail or boost its own momentum, depending on how it affects affordability, reliability, and industrial competitiveness.



Source: McKinsey analysis

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A well-managed transition would follow seven principles

How can the world reduce emissions in line with the Paris Agreement and do so while maintaining—and potentially improving—affordability, reliability, and industrial competitiveness? To start answering that question, we have identified seven principles that describe how decision-makers should approach this next phase of the net-zero transition (Exhibit 5).

The first three of those principles show how the world can undertake actions now to reduce the spending needed for a given amount of abatement and thus make the transition more affordable. The next two show how to redesign physical and financial systems in ways that can protect affordability and reliability over time. And the last two show how preparing for risks and opportunities can further all three objectives.

The principles do not provide one-size-fits-all answers to all the questions that stakeholders will confront. Rather, they provide a framework that can guide stakeholders as they navigate the next phase of the transition.

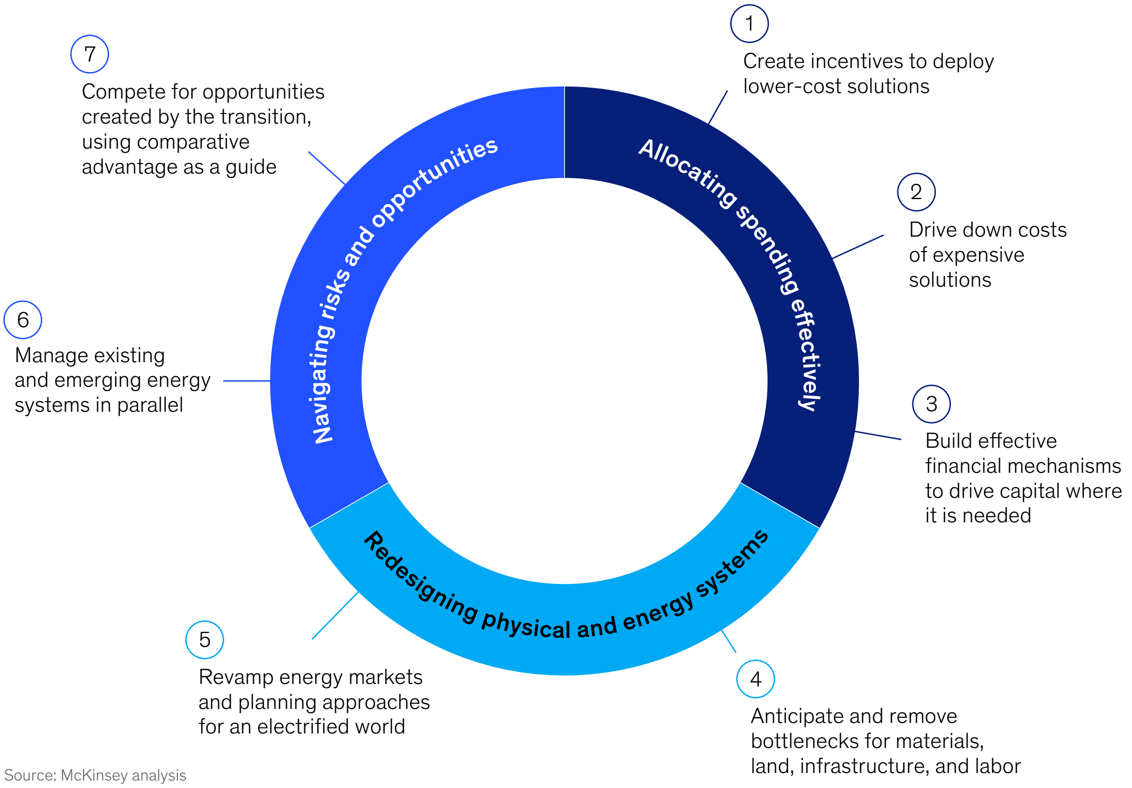
Allocating spending effectively

Our first three principles involve ways to allocate spending on the net-zero transition as effectively as possible. Deploying inexpensive solutions now would result in faster abatement of GHG emissions now. Driving down the cost of expensive solutions would make them ready to deploy when the time comes. And building effective financial mechanisms would help move capital where it is needed to fund the transition.

Later in this report, we describe an experiment that we performed to explore the possible results of applying the first two principles. Doing so, we find, might be able to improve the world's current emissions trajectory and help limit warming to what the Paris Agreement envisions. Capital spending on low-emissions technologies would potentially be one and a half to two times as large as it is

Exhibit 5

Seven principles could help the world reduce emissions while protecting affordability, reliability, and industrial competitiveness.



Source: McKinsey analysis

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now—as opposed to about three times, as might be the case if the two principles were applied less extensively. Such an approach may therefore warrant closer examination and more exploration.

Principle 1: Create incentives to deploy lower-cost solutions. The world currently emits about 55 metric gigatons of CO_2e per year, a quantity that will keep growing if action is not taken.[39] The IPCC estimates that by 2030, solutions that are relatively cheap—that is, costing less than $20 per metric ton of CO_2e abated—could potentially be abating as much as 19 metric gigatons per year (Exhibit 6).[40]

Investment in some of those solutions has begun to flow in recent years. One example is solar and wind power, whose initial deployment can often be carried out without further spending on

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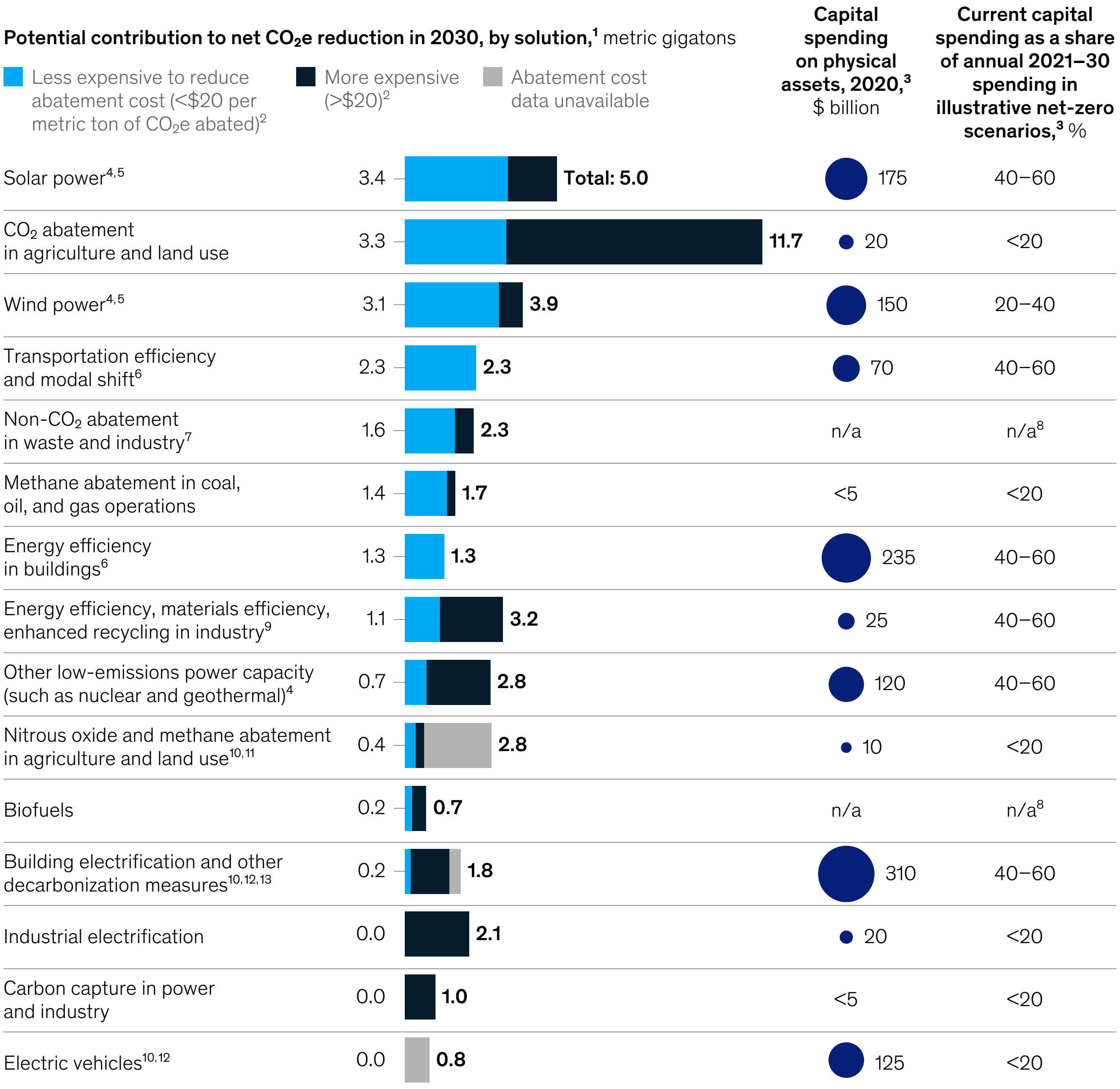
[39] See *Emissions gap report 2023: Broken record*, United Nations Environment Programme, November 2023, and *Emissions gap report 2022: The closing window—Climate crisis calls for rapid transformation of societies*, United Nations Environment Programme, October 2022. CO_2e, or carbon dioxide equivalent, includes not only carbon dioxide but also other GHGs. CO_2e is calculated with a measure called global warming potential, which indicates how much energy the emissions of one ton of a GHG will absorb in relation to the emissions of one ton of CO_2 over a given period—in this case, 100 years.

[40] The 19-metric-gigaton calculation is based on estimates from the IPCC. Cost is defined as the net lifetime discounted monetary cost of the solution (including both capital and operating costs) relative to the cost of the technology that is the traditional alternative to the solution. The IPCC acknowledges uncertainty associated with the magnitude of abatement potential; it also notes that abatement potentials are assessed independently for each solution, so they are not necessarily additive.

Exhibit 6

By 2030, solutions that are relatively low-cost have the potential to abate 19 gigatons of CO_2e per year.



Note: The solutions are ordered from the highest to lowest magnitude of low-cost abatement. Capital spending on physical assets in 2020 is rounded to the nearest $5 billion. Some solutions with little or no abatement potential have been excluded. In some instances, 2020 spending values may be estimates and not actuals. The IPCC acknowledges uncertainty associated with the magnitude of abatement potential; it also notes that abatement potentials are assessed independently for each solution, so they are not necessarily additive.

[1] CO_2e, or carbon dioxide equivalent, includes not only carbon dioxide but also other greenhouse gases. CO_2e is calculated with a measure called global warming potential, which indicates how much energy the emissions of one ton of a greenhouse gas will absorb in relation to the emissions of one ton of CO_2 over a given period—in this case, 100 years. For full details about the listed solutions, see *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change, figure SPM.7, 2022.

[2] Abatement costs shown are net lifetime costs, including capital and operating costs, of avoided greenhouse gas emissions. Costs are calculated in relation to a reference technology. [3] The 2021–30 spending required is based on various 1.5°C scenarios. It includes spending on physical assets, not operating spending. Capital spending includes both what are considered investments in national accounts and some spending on consumer durables. [4] Abatement costs for power are based on the levelized cost of electricity and do not include the cost of system integration (such as transmission and distribution capacity), so they may understate total costs. [5] Capital spending for solar and wind power includes spending for batteries and excludes spending for transmission and distribution.

[6] Abatement potential includes behavioral changes, such as lower thermostat settings in winter and higher occupancy in vehicles. [7] Abatement potential includes fluorinated gases, methane, and nitrogenated gases. [8] This spending is not shown for biofuels because sources assign it a wide range of values; it is not shown for non-CO_2 emissions from waste and industry because of a lack of robust data. [9] Abatement potential includes feedstock decarbonization and process change.

[10] The Intergovernmental Panel on Climate Change does not provide cost data for demand shifts in agriculture and land use, some categories of decarbonizing buildings, or the use of electric vehicles. [11] Abatement potential includes diet shift and reduced food waste. [12] Capital spending on electric vehicles also includes spending on infrastructure; capital spending on building electrification includes spending on residential and commercial heat pumps and district heating.

[13] Solutions include efficient heating, ventilation, and air conditioning, which could lead to additional efficiency improvements.

Source: Climate Policy Initiative; Intergovernmental Panel on Climate Change; International Energy Agency; Network for Greening the Financial System; McKinsey analysis

McKinsey & Company

expanding grids or building storage capacity.[41] But investment in lower-cost solutions remains lower than what is needed over the next decade to be consistent with a 1.5°C trajectory.

Stakeholders have a wide range of such solutions to consider. For example, implementing energy-efficiency measures and shifting behavior to reduce rates of energy consumption—by using energy-efficient appliances, making changes to industrial processes to minimize the use of energy and materials, improving efficiency in transportation, increasing the occupancy of passenger vehicles, and taking other measures—collectively have the potential to abate 4.8 metric gigatons of CO_2e.[42] Reducing GHGs other than CO_2, particularly methane, in such activities as coal mining, oil and natural gas operations, and solid waste operations could abate about 3.0 metric gigatons. Addressing emissions of CO_2, nitrous oxide, and methane from agriculture and land use—for example, by halting deforestation and improving forest management—could abate 3.7 metric gigatons.[43]

Some lower-cost solutions are "transition" solutions—that is, temporary ones that do not completely eliminate emissions but help reduce them at relatively low cost until alternatives become viable over time. Transition solutions being discussed by decision-makers include shifting from coal to gas to generate electricity, increasing the share of scrap steel used in existing steelmaking processes, and using hybrid heating systems that have both an electric heat pump and a gas furnace to heat homes.[44] Such solutions could offer a pragmatic way forward. They nonetheless will need to be carefully implemented: stakeholders have to make lifetime assessments of their emissions and costs (including the risk of stranded assets) and of the emissions and costs of low-emissions alternatives, to make sure that the transition solutions would truly help reduce emissions, maintain affordability, and not increase long-term costs.[45]

Deploying lower-cost solutions would have four key benefits. First, it would allow any given amount of capital spent on low-emissions technologies to have a large impact on abatement. Second, it would make progress in reducing emissions while other solutions were scaled up and came down

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[41] The marginal abatement costs shown in Exhibit 6 for wind and solar power are based on levelized costs only and do not include system integration costs, such as battery costs and costs associated with transmission and distribution.

[42] These assessments of abatement potential may not consider the "rebound effect" of energy efficiency, in which consumers use more energy, not less, as technology becomes more efficient. Estimates of rebound effects vary significantly, but the literature agrees that they are probably well below 100 percent, so that 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. Also, 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. So 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.

[43] A partial list of more detailed lower-cost solutions includes replacing low-efficiency lighting with high-efficiency lighting, improving the efficiency of kilns in cement production, installing smart energy and gas monitoring systems, flooding abandoned mines to trap methane, capturing landfill gas to use for power, optimizing fertilizer application, and improving rice cultivation practices.

[44] See Deborah Gordon et al., "Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates," *Environmental Research Letters*, volume 18, number 8, July 2023; Jamie Brick, Dumitru Dediu, and Jesse Noffsinger, "The role of natural gas in the move to cleaner, more reliable power," McKinsey & Company, September 2023; Ajitesh Anand, Toralf Hagenbruch, Anoop Muppalla, and Benedikt Zeumer, "Tackling the challenge of decarbonizing steelmaking," McKinsey & Company, May 2021; and Gustav Bolin, Ann Hewitt, Blake Houghton, Charlie Jersey, and Evan Polymeneas, "Building decarbonization: How electric heat pumps could help reduce emissions today and going forward," McKinsey & Company, July 2022. A "coal-to-gas" shift for generating electricity could involve either replacing existing coal-fired plants with gas-fired ones or prioritizing gas when building new fossil fuel–powered plants. Most transition scenarios anticipate a larger role for gas power in the future because it could provide future firming capacity; it has the potential to cut CO_2 emissions in half (provided that emissions associated with the production of gas are also reduced); and it could eventually be retrofitted with carbon capture and storage or hydrogen to further reduce emissions (provided that innovation brings those technologies to maturity).

[45] For example, some researchers suggest that the benefits of a coal-to-gas shift may be overstated because methane emissions from gas operations may be understated. Others suggest that a shift would lock large shares of fossil fuel capacity into the future energy grid. See Stefan Schwietzke et al., "Upward revision of global fossil fuel methane emissions based on isotope database," *Nature*, volume 538, October 2016; and Robert W. Howarth, "A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas," *Energy Science and Engineering*, volume 2, number 2, June 2014.

in cost.[46] Third, many of these measures, such as those improving energy efficiency, are cheaper than traditional alternatives over their lifetimes; implementing them could thus improve overall affordability. Fourth, some of the solutions would reduce methane emissions—which are highly potent in the near term—and could make a major contribution to reducing warming over the next ten to 20 years.[47]

Therefore, as stakeholders consider scaling up future spending for the next phase of the transition, they should ask themselves what opportunities exist to accelerate the deployment of lower-cost solutions. Various obstacles stand in the way, however. Some of the solutions would need to be executed at an enormous scale to have a meaningful impact on emissions; improving energy efficiency in millions of homes is a good example. Others call for changes to daily routines or lifestyles, such as altering modes of travel. Still others, particularly the transition solutions, may be perceived as temporary fixes and therefore ineffective.

But providing incentives can help. Changing building standards for new construction can lead to gains in energy efficiency, as can setting fuel-efficiency standards for vehicles.[48] Offering rebates or tax incentives to people or sectors can reduce the amount of energy they use. Preserving forests by providing financial incentives to protect them or by designating and enforcing protected areas can help prevent deforestation. And in addition to incentives, many solutions would need financing, as we discuss in principle 3.

Principle 2: Drive down costs of expensive solutions. At the same time, many of the technologies that the world needs to reach net zero are not yet cost competitive. The IPCC estimates that by 2030, more than 20 metric gigatons of GHGs could cost more than $20 per metric ton to abate, and 14 metric gigatons could cost more than $50 per metric ton.[49]

Another way to think about the cost of technologies is to consider their maturity, because immature technologies are by definition not yet fully viable and therefore not cost competitive. Various analyses suggest that 10 to 20 percent of the emissions reductions needed by 2050 could come from technologies that are already commercially mature (Exhibit 7).[50] But at the other end of the

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[46] For example, it will take time to fully scale up low-emissions sources of electricity. In the meantime, lower-cost solutions like improving energy efficiency can reduce demand for energy and therefore reduce emissions.

[47] In some instances, however, it may be appropriate to also focus on higher-cost solutions in the near term. One example, as we discuss in principle 2, is when deploying them would reduce costs via the learning that happens as companies start to build and deploy a product or via economies of scale. A second example is when they have particularly large adjustment costs, including costs and time associated with developing supply chains or building the necessary skills in the workforce; in those cases, deploying the solutions early and incrementally over time can help minimize the adjustment costs and remove bottlenecks. These ideas are similar to those we describe in principle 4. See Adrien Vogt-Schilb, Guy Meunier, and Stéphane Hallegatte, “When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment,” *Journal of Environmental Economics and Management*, volume 88, March 2018. As we stated above, deploying lower-cost solutions can in fact go hand in hand with these other measures and allow for simultaneous, targeted efforts to drive down costs of expensive solutions and remove bottlenecks.

[48] M. Tyler et al., *Impacts of model building energy codes—Interim update*, Pacific Northwest National Laboratory, July 2021; and Antonio M. Bento et al., “Estimating the costs and benefits of fuel-economy standards,” *Environmental and Energy Policy and the Economy*, volume 1, 2020.

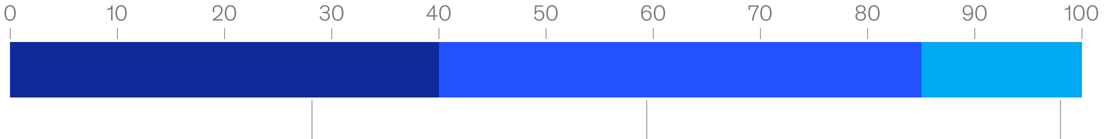
[49] *Climate change 2023 synthesis report*, IPCC, 2023.

[50] The stages mentioned in this discussion (the concept, prototype, and demonstration stages, the early market stage, and commercial maturity) are groupings based on technology readiness levels (TRLs) from the International Energy Agency. The ranges mentioned (for example, the 10 to 20 percent of emissions reductions that could come from commercially mature technologies) are based on several analyses, including the International Energy Agency’s Net Zero Emissions by 2050 Scenario and forthcoming McKinsey research. See *Net zero roadmap: A global pathway to keep the 1.5°C goal in reach*, International Energy Agency, September 2023. The shares of technologies at various stages of maturity could differ in different parts of the world because of technologies’ different cost profiles, local adoption rates, and other factors. We excluded behavioral change (which has a small contribution to emissions reduction) from the IEA’s analysis and rounded the resulting shares to the nearest 5 percent. Though TRLs can be an effective framework for understanding the maturity of individual technologies, they do not consider other factors relevant to commercialization. Such factors include, for example, the technology’s potential to perform as well as traditional alternatives in a range of uses, the maturity of the supply chain and other inputs needed for the technology, and the maturity of supporting systems that the technology would depend on (such as batteries for full-scale intermittent renewable energy generation). Most of the lower-cost solutions described in principle 1 are either in the commercially mature category or are not technological (for example, altering modes of travel). A few exceptions are in the early market stage but close to commercial maturity.

Exhibit 7

Many technologies needed to reduce emissions to net zero are not yet commercially mature.

Share of CO_2 emissions reductions from technologies needed to reach net zero by 2050,[1] %



■ **Concept, prototype, or demonstration stage,[2]**
35–45

Representative technologies:
- Concept (0–5%): Nuclear fusion; lithium-air batteries
- Prototype (15–20%): Hydrogen aviation; concrete recycling
- Demonstration (~20%): Small modular nuclear reactors (SMRs); natural gas power with carbon capture, utilization, and storage

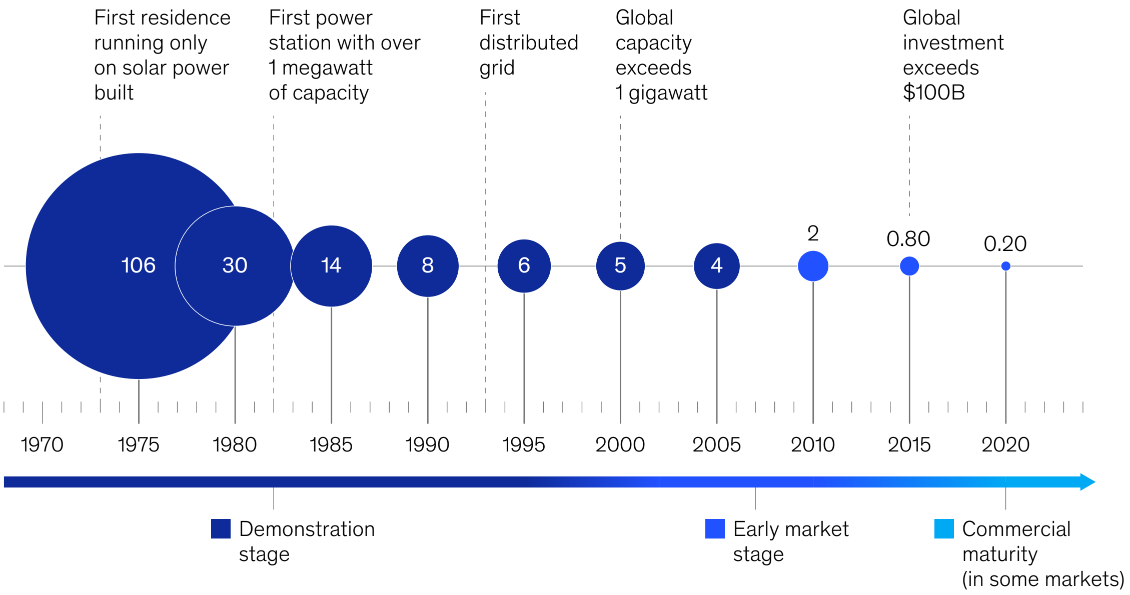
■ **Early market stage,[2]**
~45

Representative technologies:
- Air-source heat pumps
- Onshore wind power
- Passenger battery-electric vehicles
- Lithium-ion battery storage
- Hydrogen fuel cell electric vehicles
- Alkaline water electrolyzers

■ **Commercially mature,[2]**
10–20

Representative technologies:
- Geothermal power
- Hydropower
- Conventional LED lighting
- Induction cooking
- Large nuclear plants

One representative technology's evolution through each stage: solar photovoltaic modules, price per watt,[3] $



[1] Reductions relative to 2022 emissions; technology readiness levels (TRLs) as of 2022.
[2] These categories are based on TRLs from the International Energy Agency. What we call the concept, prototype, and demonstration stages correspond to TRLs 1 through 8; the early market stage corresponds to TRLs 9 and 10; and commercial maturity corresponds to TRL 11. We excluded behavioral change (which has a small contribution to emissions reduction) from the IEA's analysis and rounded the resulting shares to the nearest 5%. Although TRLs can be an effective framework, they do not consider every factor that is relevant to commercialization.
[3] Prices and maturity refer to those of the solar photovoltaic modules and do not include system costs.
Source: International Energy Agency; ETP Clean Energy Technology Guide, "Evolution of solar PV module cost by data source, 1970–2020," and *World energy outlook 2023*; US Department of Energy; McKinsey Platform for Climate Technologies; McKinsey analysis

McKinsey & Company

maturity spectrum, 35 to 45 percent could come from technologies that are still in the concept, prototype, or demonstration stage. Examples of technologies in those stages include lithium-air batteries, hydrogen aviation, and small modular nuclear reactors, respectively. In some cases, technologies need to overcome fundamental scientific or engineering challenges. In others, they would need to grow much cheaper to become cost competitive with traditional technologies.

The remaining 40 to 50 percent of the emissions reductions needed by 2050 are expected to come from technologies that are currently in the early market stage (for example, lithium-ion energy storage, onshore wind power, and passenger battery EVs).[51] These technologies have been proven to work and are commercially available, but they may not yet be fully scaled up or cost competitive with traditional technologies. They may also face integration challenges or unresolved technological difficulties in specific uses.

Improving the maturity of technologies and bringing their costs down will need three mutually reinforcing mechanisms: first, R&D; second, "learning-by-doing" (the learning that happens as companies that are starting to build and deploy a product enhance its technological performance, improve manufacturing processes, build supply chains, and develop appropriate business models); and third, the economies of scale that emerge when deployment becomes widespread.[52]

Those three mechanisms often work together to drive down costs. In the early stages, R&D is a major factor. As technologies start to grow, learning-by-doing can play a larger role and also provide real-world feedback to guide additional R&D efforts. In later stages, economies of scale begin playing a greater role as increasing the size of production plants spreads fixed costs over more produced units (though in later stages, too, R&D and learning-by-doing can still improve technologies and drive down costs). From 1980 to 2001, R&D and learning-by-doing accounted for as much as 65 percent of the cost decline of solar panels, economies of scale for 20 percent, and other factors for the remainder. From 2001 to 2012, R&D and learning-by-doing represented 50 percent of the cost decline, and economies of scale accounted for about 45 percent.[53]

Various measures can help improve the viability of technologies and reduce their cost. The public sector can play a key role by convening stakeholders in various sectors, collaborating with them to establish cross-sector decarbonization road maps, directly funding R&D, or providing incentives or subsidies for companies to engage in it. In the energy sector, investing more in R&D is surely warranted; as a share of GDP, it has remained flat since the early 1990s and is 60 percent lower than it was at its historical peak.[54]

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[51] What we call the early market stage corresponds to the IEA's TRLs 9 and 10. TRL 9, "commercial operation in relevant environment," refers to technologies that are commercially available but need improvement to stay competitive, such as hydrogen fuel cell electric vehicles and alkaline water electrolyzers. TRL 10, "integration needed at scale," refers to technologies that are commercial and competitive but need further integration efforts, such as air-source heat pumps and lithium-ion batteries for energy storage. Some technologies that have reached commercial maturity in some locations are still in the early market stage in others. See *ETP clean energy technology guide*, International Energy Agency, September 2023.

[52] Other factors can also drive changes in technology costs over time. For example, the cost of silicon, an important driver of the cost of solar photovoltaic modules, declined between 1980 and 2001 because of developments in the semiconductor industry. See Goksin Kavlak et al., "Evaluating the causes of cost reduction in photovoltaic modules," *Energy Policy*, volume 123, December 2018.

[53] Between 1980 and 2001, economies of scale accounted for 20 percent of cost declines for solar photovoltaic modules, while other factors accounted for 15 percent. Between 2001 and 2012, R&D, learning-by-doing, and other factors represented 43, 7, and 5 percent of cost declines for solar photovoltaic modules, respectively. The impact of learning-by-doing on its own was relatively small. Market-stimulating policies played a significant role in driving costs down by unlocking private R&D, economies of scale, and learning-by-doing; these together contributed an estimated 60 percent of the cost decline for solar photovoltaic modules between 1980 and 2012. See Goksin Kavlak et al., "Evaluating the causes of cost reduction in photovoltaic modules," *Energy Policy*, volume 123, December 2018.

[54] *World energy investment 2022*, International Energy Agency, 2022. That calculation is of investment in 31 IEA member countries, and it includes R&D in energy efficiency, fossil fuels, CCUS, renewable energy, nuclear fission and fusion, hydrogen and fuel cells, other power and storage technologies, and other technologies.

For technologies that show promise, a broader approach may be called for, one in which market-stimulating mechanisms, as well as actions by venture capital firms and other organizations, provide incentives for private R&D and for early deployment. Those measures can push the private sector to build new businesses and scale up technologies.[55] One way to do so is to guarantee future demand in order to encourage companies to develop and scale up new technologies. Another approach would establish innovation clusters or hubs where academic researchers, venture capital firms, and companies could work together to develop and scale up technologies.

Even commercially mature technologies may need help if they are still seen as risky or if moving to them from older technologies causes consumers to incur switching costs. One way to accelerate their deployment is to drive financial flows to them; see our next principle for more.

In implementing all these measures, it will be important to encourage collaboration among sectors in different countries. Such collaboration brings a broader pool of talent and ideas to bear on problems and promotes the wide applicability of technologies. One example is the Renewable Energy Technology Action Platform, a collaboration between India and the United States that aims to enable knowledge sharing about green hydrogen, wind energy, long-duration energy storage, and other emerging technologies.[56]

For companies looking to systematically drive down costs, a crucial step is setting ambitious goals that can help focus their attention and efforts. Consider Tesla's master plan, which has set an ambitious agenda to reduce battery costs by 56 percent between 2020 and 2025.[57] And society and industry need to be focused on reducing the cost not just of individual technologies but of entire systems.

Principle 3: Build effective financial mechanisms to drive capital where it is needed. Financial markets and institutions are key actors in effectively allocating capital. They do so by channeling money efficiently from providers of capital to investments. But those markets and institutions face two challenges in facilitating a capital reallocation as large and complex as the net-zero transition.

First, low-emissions technologies are still nascent in some sectors and not yet cost competitive in others, and their risk-return profiles differ from those of traditional alternatives. Providers of capital may therefore have a hard time evaluating their viability and risk and may be hesitant to lend to them or invest in them. Second, consumers and companies may have a limited appetite to move to these new technologies, which can affect demand for climate finance.

Innovation, as we noted earlier, can play an important role by ensuring that low-emissions alternatives continue to become cost competitive. But a number of additional solutions could help accelerate the necessary reallocation of capital. Those solutions would reduce the risk of

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[55] There is some debate about whether governments, in trying to lower the cost of low-emissions technologies, should focus on R&D or on driving deployment. As we discussed above, the importance of the two in lowering costs varies depending on the stage of the technology. For technologies in earlier stages, direct incentives for R&D may matter more; for those in later stages, R&D, learning-by-doing, and economies of scale can all play a role and reinforce one another. There is a related debate about how much to focus on improving technologies and how much to focus on deploying existing technologies (for example, through adoption subsidies or through enacting a carbon tax on high-emitting assets). Research suggests that the two agendas need to work in parallel. For example, adoption subsidies can help increase the use of low-emissions technologies, but over time they will be expensive unless the cost and performance of those technologies improve. And carbon taxes tend to be most effective when viable and cost-competitive low-emissions technologies already exist; in such cases, the taxes discourage the use of high-emissions technologies and encourage a switch to the low-emissions ones. See Daron Acemoglu et al., "The environment and directed technical change," *American Economic Review*, volume 102, number 1, February 2012.

[56] "Renewable energy technology action platform under US–India strategic clean energy partnership," Ministry of New and Renewable Energy, Government of India, August 2023.

[57] "Battery day presentation," Tesla, September 2020.

investments, better match capital providers with the investment needs that are most suitable for them, or unlock demand for climate finance.

One of the solutions is developing and scaling up voluntary carbon markets in the near term. They would need to be large, transparent, verifiable, and environmentally robust.[58] If designed well, they could particularly encourage the flow of capital to developing countries and to measures that could otherwise be hard to finance, such as avoiding deforestation. Another possible solution is mandatory markets and carbon prices. This approach would require companies to pay for their emissions and give them an incentive to invest in projects that reduce emissions.[59]

Another opportunity is expanding and revamping existing sources of capital, such as project finance. In developed markets, environmental, social, and governance indexes, climate indexes, green bonds, and sustainability-linked loans have also gained popularity. However, concerns are growing that these instruments are not working well. Improving the functioning of such instruments—for example, by crafting better standards or formulating better ways of verifying that the standards are actually met—can help increase their effectiveness.

Entirely new asset classes and funds could be built as well. Industrial venture capital funds, which tend to play an active role in a technology's early stages, and growth infrastructure funds, which can be instrumental in bringing a mature technology to scale, could be developed to drive capital to climate solutions. Special-purpose vehicles, which manage financial resources for a clearly defined purpose and period, could help companies continue funding high-emitting assets that remain necessary in the near term—but for a specified period and with a clear plan for winding them down. Sustainable land and forestry funds could help preserve forests, and "brown-to-green" funds could help carbon-intensive companies decarbonize.

Scaling up blended finance could also help increase capital flows. Blended finance combines public and private capital, reducing the risk faced by private capital providers. Philanthropic capital can play a part as well. Because public capital is often limited, it is important that it be carefully channeled into areas where the need is most acute, such as supporting the transition in lower-income or lower-middle-income countries. For example, those countries may be investing in raising energy access, but doing so with low-emissions technologies could incur high capital costs. Various reforms are also being considered to ensure that blended finance, grant funding, and loans on concessional terms are used to their full potential, such as increasing the funding available via multilateral institutions and adjusting the terms on which it can be provided.[60] Also, implementing blended-finance projects can be slow; to address that problem, financial institutions and multilateral institutions could develop "off-the-shelf" guidance on general financing structures and frameworks that could then be tailored to different needs.

Companies can use the various sources of capital discussed above, such as project finance or brown-to-green funds. But they could also reallocate their own capital resources from high- to

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[58] Voluntary carbon markets would include markets for avoidance credits (for example, to prevent forests from being cut down) and for removal credits (for example, for planting forests or direct air capture). For further details, see *Final report*, Taskforce on Scaling Voluntary Carbon Markets, January 2021.

[59] One way carbon prices can be implemented is in the form of a carbon tax on emitting parts of the economy. Estimates suggest that the application of such a tax could result in increased prices of energy and other products for end consumers, creating affordability concerns. However, the extent of the affordability impact for consumers depends on the magnitude of the carbon tax applied and on how the revenue generated from the tax, if any, is recycled back into the economy. See *Fiscal monitor: How to mitigate climate change*, International Monetary Fund, October 2019. Moreover, as we discussed earlier, using R&D and other measures to develop and drive down the costs of low-emissions technologies can work hand in hand with carbon taxes and reduce challenges to affordability.

[60] By multilateral institutions, we mean those that are funded by the governments of more than one country. See *Scaling up blended finance in developing countries*, OECD, 2022; and *Strengthening multilateral development banks: The triple agenda*, Independent Expert Group commissioned by Indian G-20 Presidency, 2023.

low-emissions businesses. That often involves making large capital investments or transforming large physical assets. The step is not a straightforward one, and it will require creating incentives for companies to make the investments. Long-term purchase agreements, for example, provide companies with a guaranteed source of revenue over an extended period, giving them an incentive to invest in new technologies.

All these solutions would need to be supported by more transparency and a better understanding of the potential demand, costs, and risks of specific new technologies and projects. Climate-related disclosures could help, and so could efforts by companies and financial institutions to build capabilities to better assess new risk-return profiles and identify new opportunities.

Redesigning physical and energy systems

The net-zero transition calls for far-ranging changes to many existing systems. Some of those systems provide the physical inputs necessary to build low-emissions assets; others provide energy. If not performed well, the changes could compromise affordability, reliability, and the pace of emissions reduction. The next three principles show how to make the changes effectively.

Principle 4: Anticipate and remove bottlenecks for materials, land, infrastructure, and labor.
The transition will call for increases in the supply of certain minerals, such as lithium and nickel, and of manufactured goods, such as wind turbines and electrolyzers. It will require substantial amounts of water for mining, hydrogen production, and other uses. It will also require a great deal of land for solar panels, wind farms, transmission infrastructure, forests, and crops that could be turned into biofuels. Infrastructure, such as EV charging networks, electrical grids, and hydrogen pipelines, will need to be scaled up. And a great deal of labor will be needed to build and operate new physical assets.

The potential supply of those inputs will generally not be a limitation. For example, enough mineral reserves exist to meet the demand expected under the net-zero transition. But various bottlenecks could limit access, especially in the near term. This is not an unprecedented problem; bottlenecks have threatened high-emissions supply chains in the past, and they have been managed effectively. But if the bottlenecks threatening the transition are not also managed effectively, material shortages and price spikes could result, impairing affordability, reliability, and the pace of the transition.

Long lead times are often a problem. For example, the time that elapses between initial exploration and starting to operate a new mine is typically five to 15 years.[61] Partly for that reason, shortages of copper, lithium, nickel, rare earth metals, and cobalt—materials used heavily in EV batteries, wind turbines, and other low-emissions technologies—could begin before 2030.[62] Similarly, it can take three to 12 years for a new electricity transmission or distribution project to be planned, receive the necessary permits, be built, and become active.[63] In the United States, getting a new nuclear reactor approved can take up to five years of complex safety reviews, environmental assessments, and public hearings, and building it can take five years or more.[64]

Another potential bottleneck is concentration. For example, China produces more than 70 percent of the world's silica-based solar photovoltaic modules and two-thirds of battery cells.[65] While

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[61] *The net-zero materials transition: Implications for global supply chains*, McKinsey & Company, July 2023; and *Material and resource requirements for the energy transition*, Energy Transitions Commission, July 2023.

[62] Patricia Bingoto, Michel Foucart, Maria Gusakova, Thomas Hundertmark, and Michel Van Hoey, "The net-zero materials transition: Implications for global supply chains," McKinsey & Company, July 2023.

[63] *Average lead times to build new electricity grid assets in Europe and the United States, 2010–2021*, International Energy Agency, January 2023.

[64] "Nuclear explained: US nuclear industry," US Energy Information Administration, August 24, 2023.

[65] *Energy technology perspectives*, International Energy Agency, March 2023.

concentration can bring efficiency gains, it can create supply-chain bottlenecks if supply from the few sources is affected—say, by natural disasters or trade restrictions.

A multitude of constraints can affect the supply of land. Those constraints do not include the amount of land available in the world, but they do include the natural endowments of a given region (such as sunniness, windiness, and forests), competing priorities for land (for example, agriculture), local regulations, and public sentiment. As for labor, the availability of necessary skills is a potential challenge. Nuclear power could face shortages of workers with the required expertise because many are now reaching retirement age.[66] Similar challenges could exist for other jobs related to the manufacture and installation of low-emissions technologies.[67]

Stakeholders should therefore conduct analyses of where bottlenecks could emerge and take measures to remove them. Some ways of doing so would increase the supply of inputs. Long-term supply contracts, such as those that are forming between auto manufacturers and minerals producers to provide lithium used for battery technologies, help individual manufacturers secure supply of key inputs over long periods while supporting the scale-up of capacity for new materials.[68] And workforce retraining programs could increase the supply of workers with the necessary skills quickly. For example, teaching technicians who already install heating, ventilation, and air-conditioning systems how to install heat pumps could be a fast way of building a capable workforce.

Other measures would reduce the demand for inputs. Examples include recycling materials, developing new battery chemistries that rely less on raw materials that are in short supply, and replacing dated wind turbines in existing windmills with newer, more efficient ones, thus reducing the amount of land needed for a given supply of electricity.

Principle 5: Revamp energy markets and planning approaches for an electrified world. Electricity will play a larger and larger role as the transition takes hold. In a net-zero world, electricity systems could provide about three times as much energy as they do today, and the share of all electricity that was generated by wind and solar power could grow.[69] Almost twice as many transmission and distribution lines would need to be constructed as exist today.[70]

In a number of ways, current markets and planning approaches for the generation of electricity may no longer be suited for that expansion and may no longer function well once it happens.[71] Four challenges stand out.

The first is that companies may not have incentives to build and operate all the necessary generation capacity. Many markets currently use marginal costs (which are typically driven by the cost of using a fuel, such as gas or coal) to set electricity prices, and those prices serve as incentives to build capacity. But that arrangement will not work in a system in which generation assets have no marginal costs or low ones—examples are wind and solar power—because the resulting electricity prices would be very low and volatile, and generators would receive almost no payments for the power they supplied, on average (Exhibit 8).

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[66] "Nuclear industry census reveals positive signs of growth alongside workforce challenges," Nuclear Industry Association, January 25, 2022.

[67] *World energy employment 2023*, International Energy Agency, November 2023.

[68] "LG Energy Solution and Toyota sign long-term battery supply agreement to power electric vehicles in the U.S.," Toyota, October 4, 2023.

[69] *World energy transitions outlook 2023: 1.5°C pathway*, International Renewable Energy Agency, June 2023.

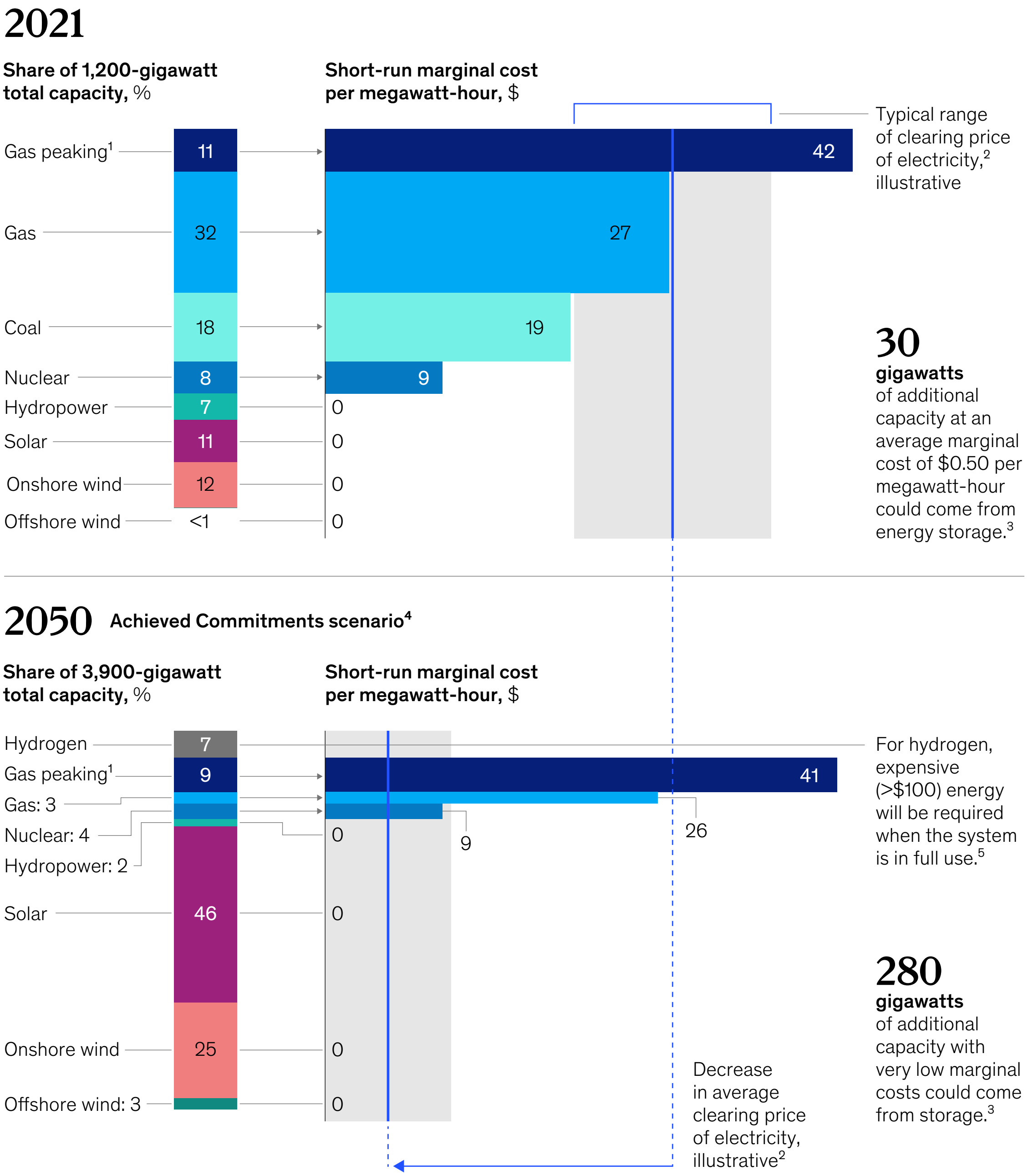
[70] *Energy technology perspectives*, International Energy Agency, March 2023.

[71] Though this discussion focuses on electricity, other energy markets will also need to shift or develop, including those for natural gas and hydrogen. We focus on electricity because it will undergo an especially dramatic transformation and will require especially innovative solutions.

Exhibit 8

Wind and solar power generation, which have very low marginal costs to operate, could become major parts of the energy mix in the future.

Projected change in distribution and cost of US energy sources



Typical range of clearing price of electricity,[2] illustrative

30 gigawatts of additional capacity at an average marginal cost of $0.50 per megawatt-hour could come from energy storage.[3]

For hydrogen, expensive (>$100) energy will be required when the system is in full use.[5]

280 gigawatts of additional capacity with very low marginal costs could come from storage.[3]

Decrease in average clearing price of electricity, illustrative[2]

[1] Gas peaking refers to gas-fired plants that run only when demand is high. [2] The range shows clearing prices during most hours. [3] Storage includes pumped-hydro and lithium-ion long-duration energy storage. Storage could increase the utilization potential of wind and solar power and displace some fossil fuel production. [4] Based on the US Achieved Commitments scenario published in *Global energy perspective 2023*, McKinsey & Company, October 2023. [5] This chart excludes hydrogen's short-run marginal cost of $150–$200 per megawatt-hour in 2050.

Source: Publicly available data from US Energy Information Administration and US National Renewable Energy Laboratory; McKinsey analysis

McKinsey & Company

The second challenge is that wind and solar power are intermittent. That is, they provide electricity only when the wind is blowing or the sun is shining. Therefore, planners and market designers need to ensure that the right plans and market signals exist to drive investment in assets, such as energy storage and gas plants, that can support wind and solar power.

Third, in an electrified world, it may be harder to time supply to match demand.[72] Demand for electricity may be especially high in the winter in places where people replace fossil fuel–based heating systems with electric ones. It may also be especially high at night if people continue to adopt EVs and to charge them overnight. So systems will need to be designed to manage different demand at different times of the year and different times of day. Moreover, solar panels generate less power in the winter and none at night, complicating the problem if they become a larger part of the energy mix.

Fourth, because of the increase in wind and solar generation and the changing climate, planners and market designers must now accommodate weather volatility. For example, as Texas discovered during a severe freeze in 2021, some power plants and natural gas facilities are not winterized; that is, they stop working or suffer diminishing performance in extreme cold.[73]

A number of steps could start addressing these challenges in both regulated and deregulated markets for electricity. To build low-emissions assets affordably, power companies in regulated markets could either take on the job themselves, reducing costs through internal efficiency improvements, or issue competitive bids for other companies to do it. In deregulated markets, auctions for supply agreements will probably still be critical. In both kinds of markets, solar and wind power (or other forms of capital-intensive power) need to be able to compete on a level playing field with generation technologies that have relatively low capital costs but high fuel costs.

To help keep supply aligned with demand, a system depending on solar and wind power will also need to build a great deal of flexible capacity—that is, capacity that can provide electricity when wind and solar cannot.[74] (Flexible capacity is sometimes called resource adequacy, depending on the location and the length of time that the capacity covers.) Some of that flexible capacity would support wind and solar over the course of a day; for example, batteries could store solar power during the day and release it in the evening. In regulated markets, a procurement authority could require generators to make available a certain amount of such capacity. In deregulated markets, it could be attained by requiring assets to compete against each other to provide it.

Other kinds of flexible capacity would support electricity markets for more than a day in order to counteract seasonal and extreme events. For example, it may be necessary to maintain generation plants, which could run on fossil fuels today but eventually be retrofitted with carbon capture or shift to using low-emissions fuels. They would be used much less than they are today, so incentives would be needed for companies to maintain and run them, as well as the necessary support infrastructure, such as gas pipelines.[75]

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[72] Conversely, lower dependence on fuel inputs will reduce the risk of “commodity shocks,” in which a fuel commodity suddenly becomes scarce. Such shocks can significantly increase the price of electricity generation, and they can also eliminate access to the commodity entirely, jeopardizing the reliability of electricity. For example, in 2002, Bangladesh could not obtain supplies of natural gas that had been rerouted to Europe as a result of the shortage of gas there, and widespread outages resulted.

[73] Garrett Golding, “Texas electrical grid remains vulnerable to extreme weather events,” Federal Reserve Bank of Dallas, January 24, 2023.

[74] Note that flexible capacity does not necessarily call for fossil fuels; renewable resources often provide some capacity during critical times. Similarly, fossil fuels are not a sure bet at such times, as Texas’s experience in 2021 demonstrates.

[75] Running gas power plants to provide only backup capacity will entail numerous shifts. For example, gas pipelines, even if they carry less, may need even more investment, including investment in expanding the size of pipes so that they can provide adequate supply to generators at critical moments. Gas generators that will eventually shift to CCUS or hydrogen will also need investment.

Compensation mechanisms would have to change to give companies incentives to provide this kind of capacity. In regulated markets, planners could determine the amount of capacity needed and allow companies to build or maintain more assets to cover the need, compensating them with a regulated return on those assets. In deregulated markets, other compensation mechanisms, such as a price paid per gigawatt of flexible capacity, would provide incentives for companies to build or maintain assets well in advance of the need, because power capacity cannot be built overnight. Acceptable system risks would also need to be defined.

Flexibility will be critical regardless of the generation mix as more and more parts of the economy become electrified. Planning mechanisms will be necessary to determine the need—for example, which seasons and types of events present the greatest challenges and how much electricity will be needed to maintain reliability. A particularly important planning tool in determining how much capacity a resource can provide during critical times is probabilistic modeling, which can account for variations in demand for electricity and for intermittent supply.

Another way to reconcile the timing of supply and demand is to offer consumers and businesses incentives to shift their demand for electricity to times when there is more available supply. For example, EV charging does not have to happen in the evening. And data centers can align their demand to times and locations at which renewable sources of electricity are operating.[76]

Not only the generation of electricity but also its transmission faces a challenge: the transmission capacity necessary for the transition needs to be built. The challenge exists both for large-scale, high-capacity lines that would cover long distances and for smaller lines that would connect them to generators. There is no shortage of capital seeking to build large-scale transmission in many developed countries. The problem, rather, is planning procedures that assess only the reliability value of a single line. More modern planning procedures—which evaluate a portfolio of transmission lines and value several benefits, such as resiliency, access to clean energy, and economic development—are increasingly being adopted. Such procedures should balance costs and benefits among jurisdictions to account for their different approaches. Another reason for not building transmission capacity is permitting, as this report discussed earlier.

The distribution of electricity likewise faces a challenge in the transition. In many places, regulations provide utilities with most of their returns on the basis of their nondepreciated capital assets. That system gives the utilities an incentive to deploy more capital than they otherwise might. Several countries, such as Italy, are therefore planning to shift to models that reward total spending, not just capital spending. Such models could give utilities an incentive to be more capital efficient, which could lead to shifts in behavior, such as repairing assets (which does not always count as capital spending) rather than replacing them (which does).

Another area that could require market changes and planning focus is distributed energy resources, such as rooftop solar panels. Such resources could potentially reduce spending on transmission and distribution, and they could also provide small-scale flexible capacity. However, as use of distributed energy grows, its users will naturally depend less on utilities, requiring the utilities to plan carefully. Establishing clearer standards for compensating consumers for these resources will be vital.

Navigating risks and opportunities

If the world is to protect affordability and reliability during the net-zero transition, it will also have to navigate risks while moving from an old energy system to a new one. And to become more

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[76] Rasoul Rahmani, Irene Moser, and Antonio L. Cricenti, “Inter-continental data centre power load balancing for renewable energy maximisation,” *Electronics*, volume 11, number 10, 2022.

competitive, countries and companies will have to prepare for the many opportunities offered by the transition.

Principle 6: Manage existing and emerging energy systems in parallel. The net-zero transition will entail revamping how the world produces and uses energy. As that happens, the world will need to run two energy systems in parallel, smoothly ramping down the old, fossil fuels–based one while scaling up the new. Doing so well can help reduce emissions to net zero while ensuring reliable and affordable access to energy.

To help decision-makers better understand how to enable a smooth transition, we started by examining scenarios of demand for oil, gas, and coal from a range of sources, including the IEA, the IPCC, and McKinsey's *Global energy perspective 2023* (Exhibit 9).[77] Those scenarios have different warming outcomes by 2100, ranging from 1.5°C above preindustrial levels to about 3.0°C.

For oil demand, some of the scenarios show growth during the next few years, but then the picture changes. In all of the scenarios examined here, demand eventually starts to fall, and in most, it is lower by 2050 than it is today, though to varying extents. A key driver of the variation in projected demand for oil is the transportation sector—specifically, the use of EVs and the efficiency of transportation.

Gas demand is also expected to grow in the near term in some of the scenarios we examined. Over time, though, some scenarios show increases in demand between now and 2050, while others show declines. The overall impact on demand would depend on how various factors pushed it up or down. Faster declines could be caused by a more rapid increase in the use of renewable energy for power generation, growing electrification to replace the use of gas (particularly in heating systems in buildings), and a shift away from natural gas in industrial processes. But some transition-related solutions could push gas demand up: using gas to produce hydrogen, switching from coal to gas to generate electricity, and using gas power to provide firming capacity for renewable power generation. Using gas as a feedstock for chemicals could also increase demand.

And for coal demand, all scenarios show declines. The steepness of the declines depends in particular on how demand in India and China, the world's biggest consumers of coal, evolves.

Stakeholders approaching the management of two energy systems in parallel should therefore consider two implications. First, in scenarios in which warming is kept to the levels envisioned by the Paris Agreement, the process of shifting from the old energy system to the new means that oil, gas, and coal will play at least some part in the energy mix in the next few years. So it is vital that direct emissions from their operations be as small as possible.

Second, these numerous scenarios show that although demand for oil and gas will be lower in 2050 than it is today—substantially lower, on a 1.5°C trajectory—the decline will not be immediate. In the interim, it will be important for demand to be met with enough supply so that access to energy is reliable and affordable. At the same time, however, it will be absolutely critical to ensure that reliance on the old system, to the extent needed, does not slow momentum toward the new.

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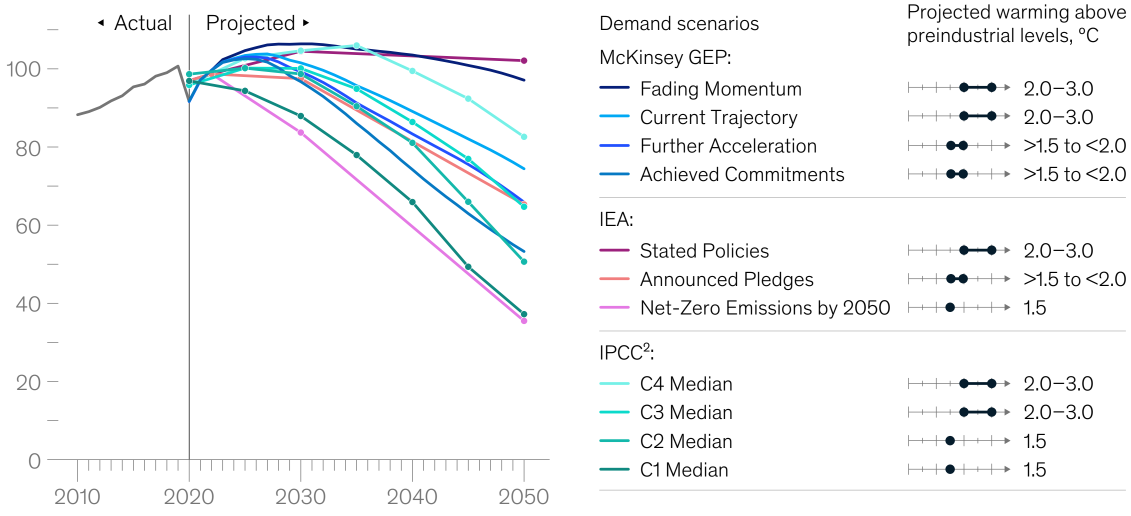
[77] *See World energy outlook 2023*, International Energy Agency, October 2023; "World energy balances," International Energy Agency, August 2023; "AR6 Scenario Explorer and Database hosted by IIASA," International Institute for Applied Systems Analysis, 2022; and *Global energy perspective 2023*, McKinsey & Company, October 2023. The scenarios are for fossil fuels used for energy production but also for other uses. By oil demand here, we mean demand for a range of liquids, including crude oil, natural gas liquids, biofuels, coal-to-liquids, gas-to-liquids, methyl tert-butyl ether, refinery gains, and low-emissions fuels.

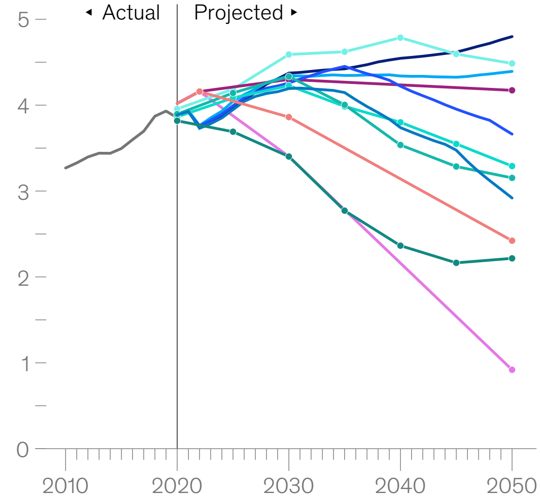
Exhibit 9

Demand for oil, gas, and coal declines by 2050 in many scenarios, but the outlook varies widely.

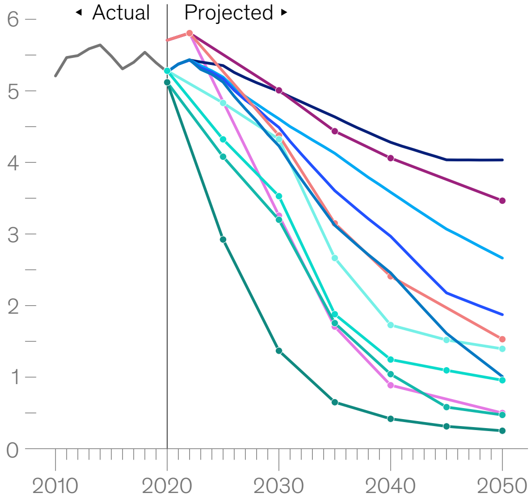
Oil and other liquid fossil fuels, daily average,[1] barrels, million



Natural gas, annual,
cubic meters, trillion



Coal, annual,
metric tons of coal equivalent, billion



Note: All non-McKinsey data come directly from public sources. For some scenarios, data for 2020 may vary from actual data because they may come from models, including models built some years ago. Data may also vary among scenarios because of different assumptions about the energy content of fuels, the specific mix of fuel types within each category, and other factors. We have used linear interpolation between the published data points, which are indicated by dots. Values from the Intergovernmental Panel on Climate Change (IPCC) were provided in exajoules (EJ), which we converted by using the following conversion factors: 1 EJ per year = 0.517 million barrels of oil per day, 28.9 billion cubic meters of gas per year, and 34.12 metric megatons of coal equivalent per year. We derived those conversion factors by using the reported 2022 demand in exajoules and the reported volume measures in *World energy outlook 2023*, International Energy Agency, October 2023.

[1] Includes the following: for McKinsey GEP scenarios, crude oil, natural gas liquids (NGLs), coal-to-liquids (CTLs), gas-to-liquids (GTLs), methyl tert-butyl ether (MTBE), refinery gains, and low-emissions fuels; for IEA scenarios, crude oil, NGLs, CTLs, GTLs and additives, refinery gains, and low-emissions fuels. For IPCC scenarios, we used the conversion factor described above.

[2] Each of the four IPCC lines shows the median value of a range of scenarios. In the C1 and C2 scenarios, warming by 2100 is limited to 1.5°C above preindustrial levels, but in the C2 scenario, it first overshoots that limit, whereas in the C1 scenario, it does not. In the C3 and C4 scenarios, there are a 67% and a 50% likelihood, respectively, of limiting warming by 2100 to 2.0°C above preindustrial levels.

Source: International Energy Agency (IEA), World Energy Balances; publicly available data from IEA, *World energy outlook 2023*; “AR6 Scenario Explorer and Database hosted by IIASA,” International Institute for Applied Systems Analysis, 2022; McKinsey’s *Global energy perspective 2023* (GEP); McKinsey analysis

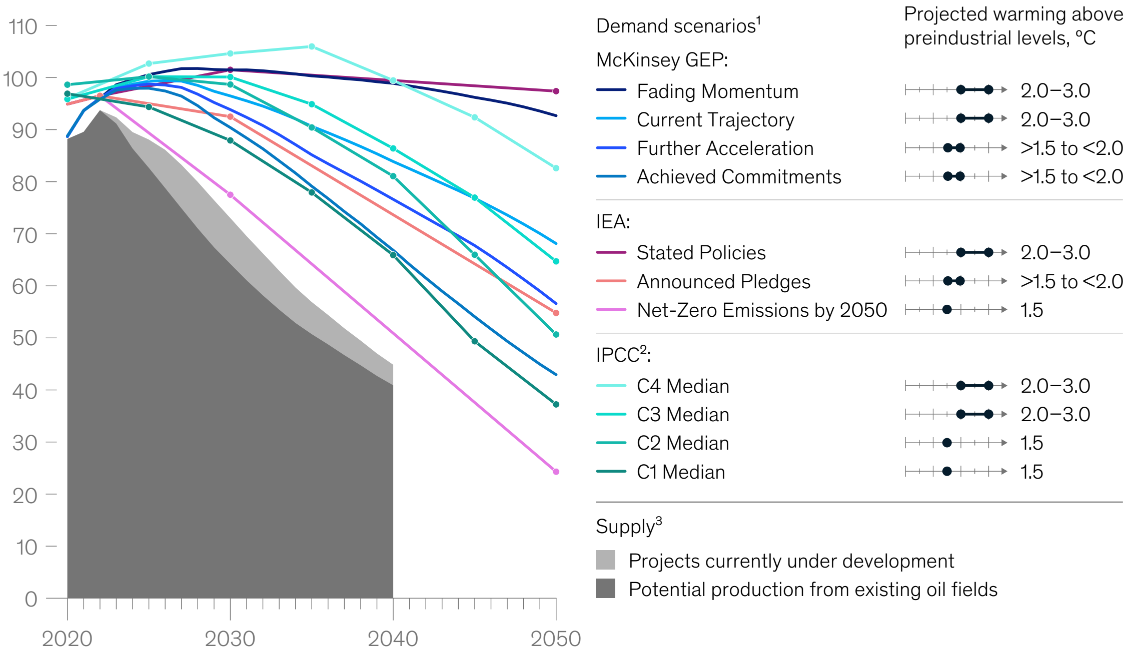
McKinsey & Company

In addition to studying demand for oil, we examined expectations of supply.[78] Specifically, we looked at the potential production of crude oil and natural gas liquids from existing oil fields (accounting for their expected depletion as well as for future production there that can be enabled by maintenance and other measures) and from projects currently under development (Exhibit 10).[79] We found that at

Exhibit 10

The world's ability to meet future oil needs with existing resources varies among demand scenarios.

Supply and demand of crude oil and natural gas liquids, daily average, barrels, million



Note: All non-McKinsey data come directly from public sources. We have used linear interpolation between the available data points, which are indicated by dots. Values from the Intergovernmental Panel on Climate Change (IPCC) were provided in exajoules (EJ), which we converted by using the following conversion factor: 1 EJ per year = 0.517 million barrels of oil per day. We derived that conversion factor by using the reported 2022 demand in exajoules and the reported volume measures in *World energy outlook 2023*, International Energy Agency, October 2023.

[1] For McKinsey GEP scenarios and IEA scenarios, includes crude oil and natural gas liquids. For IPCC scenarios, we used the conversion factor described above.

[2] Each of the four IPCC lines shows the median value of a range of scenarios. In the C1 and C2 scenarios, warming by 2100 is limited to 1.5°C above preindustrial levels, but in the C2 scenario, it first overshoots that limit, whereas in the C1 scenario, it does not. In the C3 and C4 scenarios, there are a 67% and a 50% likelihood, respectively, of limiting warming by 2100 to 2.0°C above preindustrial levels.

[3] Includes production from existing oil fields and projects under development. Existing oil fields consist of those that are currently producing; we account for their expected depletion as well as for future production that can be enabled by maintenance and other measures, such as infill drilling. Projects under development include those that are in the post–final investment decision (FID) stage. The analysis excludes major pre-FID project redevelopments and expansions, as well as new investments in shale oil, unconventional wet gas, and associated natural gas liquids. It also assumes that existing sanctions regimes continue and that some spare capacity remains in the system. Supply was modeled only until 2040 because uncertainty about future sources of production made modeling challenging after that point.

Source: International Energy Agency (IEA), World Energy Balances; publicly available data from IEA, *World energy outlook 2023*; "AR6 Scenario Explorer and Database hosted by IIASA," International Institute for Applied Systems Analysis, 2022; Rystad Energy; McKinsey's *Global energy perspective 2023* (GEP); McKinsey Energy Solutions; McKinsey analysis

McKinsey & Company

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[78] Supply was modeled only until 2040 because uncertainty about future sources of production made modeling challenging after that point.

[79] Existing oil fields consist of those that are currently producing; we account for their expected depletion as well as for future production that can be enabled by maintenance and other measures, such as infill drilling. Projects under development include those that are in the post–final investment decision (FID) stage. The analysis excludes major pre-FID project redevelopments and expansions, as well as new investments in shale oil, unconventional wet gas, and associated natural gas liquids. It also assumes that existing sanctions regimes continue and that some spare capacity remains in the system.

least through 2040, some shortfall could exist between that production and potential demand for oil, even with the substantial decline in demand for oil expected on a 1.5°C trajectory.[80]

And depending on how demand for gas evolves, new infrastructure may be needed, in particular for pipelines and for facilities that transform gas into liquefied natural gas (LNG) and then back. In the United States, for example, new pipeline infrastructure may be needed in parts of the country to supply gas to support renewable power systems. Likewise, Asia has only modest gas reserves of its own, so it may need new facilities to service LNG imported from abroad.

These analyses point to a number of solutions that could help manage two energy systems effectively in parallel. First and foremost, it will be critical to scale up the new energy system as quickly as possible. This could be done by expanding alternative energy sources, changing end-use sectors, and improving energy efficiency, as we have described in depth elsewhere in this report. But more is needed.

One important step is to reduce Scope 1 and 2 emissions from fossil fuel operations to the extent possible.[81] Estimates suggest that such emissions of methane from oil and gas operations could be reduced by 35 percent at nearly no net cost.[82] Methane emissions could be reduced by fixing leaky connections and updating operating procedures to reduce venting at wells, pipes, and tanks.[83] Other measures could include reduced flaring, electrification of equipment, and use of carbon capture.

Another step is for decision-makers to undertake fossil fuel–related investments in ways that provide as much energy as necessary and prevent price volatility but also maintain momentum toward net zero and do not risk locking in the use of fossil fuels. Increasing the efficiency and effectiveness of existing operations to maximize production—for instance, through improved management of reservoirs—is one opportunity. Another, to the extent new projects are needed, is deploying capital in a modular fashion. That is, rather than investing in projects that require large, up-front capital outlays in return for long useful lifetimes, companies could identify opportunities for which capital can be deployed in segments. Also, projects with low emissions intensity could be prioritized.

Principle 7: Compete for opportunities created by the transition, using comparative advantage as a guide. As the transition unfolds, and as demand for high-emissions products and their components falls, jobs and output in some parts of the economy may be harmed.[84] Other parts of the economy could gain. By 2050, the transition could result in a gain of about 200 million jobs and a loss of about 185 million jobs globally.[85] Countries will need to consider how to support vulnerable workers and industries.

But even as the transition reduces demand and affects some parts of the economy, it will also create new opportunities for countries and companies to participate in a net-zero economy. Some

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[80] The 1.5°C scenarios that we examined are from the IEA and the IPCC.

[81] Scope 1 emissions come from sources that are controlled or owned by an organization; Scope 2 emissions are those "associated with the purchase of electricity, steam, heat, or cooling." See US Environmental Protection Agency, Center for Corporate Climate Leadership, "Scope 1 and Scope 2 inventory guidance," August 21, 2023.

[82] *Emissions from oil and gas operations in net zero transitions*, International Energy Agency, June 2023. See also *Curbing methane emissions: How five industries can counter a major climate threat*, McKinsey & Company, September 2021.

[83] Methane emissions from the energy sector are highly concentrated in a few countries, which could create barriers to emissions reduction if those countries do not actively pursue it. According to the International Energy Agency, the five biggest methane emitters for energy-related uses are China, Russia, the United States, Iran, and India, which together account for over half of the global total. Of those countries, only the United States has signed the Global Methane Pledge. See "Methane tracker," International Energy Agency, February 2023.

[84] For example, see Pia Andres et al., "Stranded nations? Transition risks and opportunities towards a clean economy," *Environmental Research Letters*, volume 18, number 4, March 2023.

[85] *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.

of those opportunities are direct ones involving low-emissions products and processes: improving the energy efficiency of heating systems, building wind and solar farms, manufacturing EVs, and so on. Those opportunities will in turn create others, such as extracting and refining new materials needed for the transition, crafting new financing mechanisms, and building infrastructure, such as EV charging stations. As we discussed above, many net-zero technologies are already commercially mature, while others are in the early market stage and ripe for further development. Building and scaling up new green businesses can boost jobs, exports, and economic output (in both developed and developing countries); they can also create value for companies.

As countries and companies begin to explore these areas, they should be guided by their potential to gain comparative advantage. For example, some countries may have outsize access to sunshine or wind; those countries might choose to produce green hydrogen, which relies on access to low-cost renewable power, or to follow energy-intensive courses, such as running data centers. Other countries may have deposits of mineral resources needed in the transition. Others may be able to take advantage of their geographic location to participate in new global trade networks, such as those for low-emissions fuels. In other cases, countries and companies may have technical know-how that can help them manufacture the goods that the transition will require. A good example is South Korea, which has taken advantage of its expertise in battery manufacturing to become a leader in grid-scale energy storage, capturing 50 percent of the global market in 2018 with support from government initiatives.[86] (For more on how priorities during the transition could vary, see Box, “Customizing net-zero strategies for different countries.”)

Numerous measures can help countries capture opportunities. Investing in education and training programs could equip workforces with skills that green industries need. Creating ecosystems that enable local innovation could encourage the development of new ideas, products, and services within a country. And designing new initiatives carefully and holistically, with an eye toward how they interact with one another, will be important, because climate policy is intertwined with many other kinds of policy, including national security policy, industrial policy, innovation policy, and labor market policy.

Companies too can take steps to position themselves well and benefit from opportunities. Those steps include creating customer partnerships to build new markets, reallocating capital across their portfolios to emerging areas, and scaling up new green businesses. Our past research has identified many companies that are doing so.[87]

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[86] *Korea’s energy storage system development: The synergy of public pull and private push*, World Bank Group Korea Office, January 2020.

[87] Laura Corb, Anna Granskog, Tomas Nauclér, and Daniel Pacthod, “Full throttle on net zero: Creating value in the face of uncertainty,” McKinsey & Company, September 2023.

Box

Customizing net-zero strategies for different countries

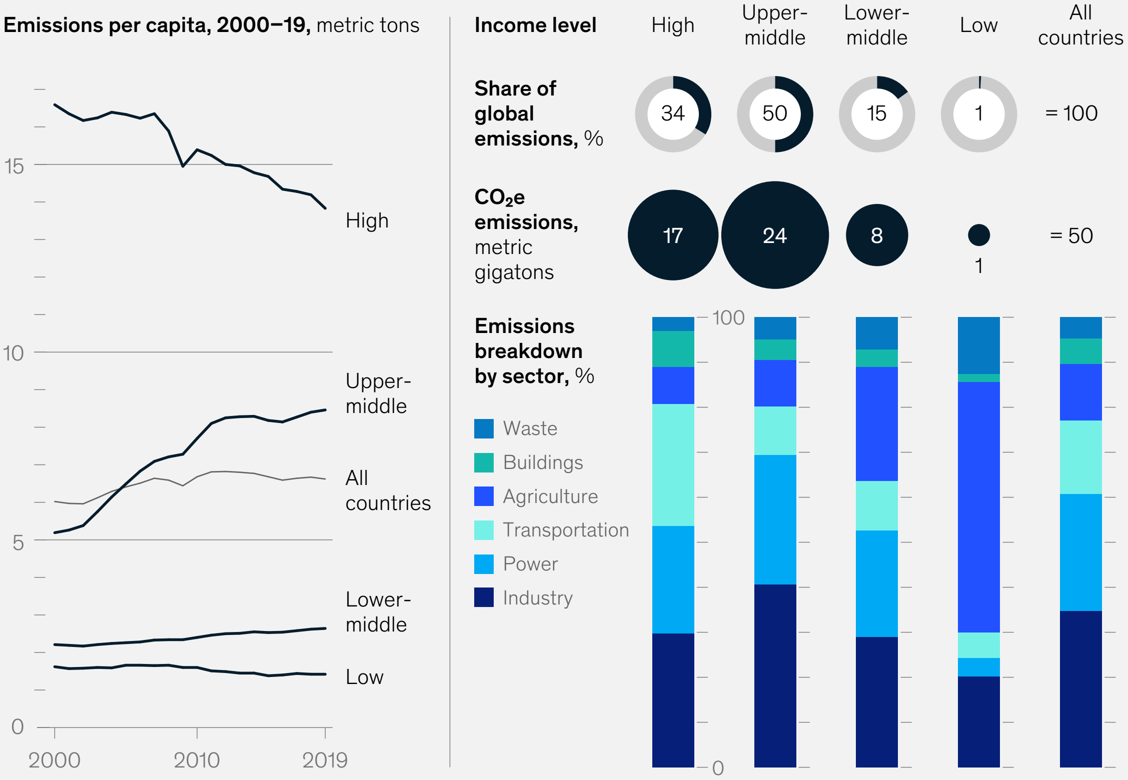
Every country will face different challenges and imperatives on its net-zero journey. Although detailed country strategies are beyond the scope of this work, here we highlight a few characteristics that could help inform such strategies.[1]

Emissions. Today, most GHG emissions come from high-income countries, which emit 34 percent of the total, and upper-middle-income countries, which emit about 50 percent.[2] Emissions per capita have been rising for that second group, though their per capita emissions remain well below those of high-income countries (Exhibit 1).[3] Low-income countries emit less than 5 percent of the total.[4]

Exhibit 1

The quantity and source of emissions vary by countries' income.

Global CO$_2$e emissions by country income level, 2019[1]



Note: **Industry** includes emissions from industrial processes for cement, chemicals, metals, and mining, as well as oil and gas processes such as upstream processes, refining, and pipeline transportation. **Power** includes emissions from electricity generation and heat generation. **Transportation** includes emissions from road vehicles, rail, aviation, and maritime transportation. **Agriculture** includes emissions from crop residues, enteric fermentation, fishing, manure, on-farm energy use, rice, and synthetic fertilizers. **Buildings** includes emissions from cooking and heating in commercial and residential buildings. **Waste** includes emissions from the biological treatment of solid waste, solid waste disposal, wastewater treatment and discharge, and the incineration or open burning of waste. Data about emissions from land use, land-use change, and forestry are most reliably available at the regional level, so we did not consider those emissions in this country-by-country analysis; globally, they amounted to about 4.2 metric gigatons in 2019.

[1] CO$_2$e, or carbon dioxide equivalent, includes not only carbon dioxide but also other greenhouse gases. CO$_2$e is calculated with a measure called global warming potential, which indicates how much energy the emissions of one ton of a greenhouse gas will absorb in relation to the emissions of one ton of CO$_2$ over a given period—in this case, 100 years. Country groupings by income level are from the World Bank's classifications for calendar year 2019. See "New country classifications by income level: 2020–2021," Data Blog, World Bank, July 1, 2020.

Source: Food and Agriculture Organization of the United Nations, "FAOStat"; World Bank; McKinsey EMIT database (v2021); McKinsey analysis

McKinsey & Company

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[1] For a range of near-term actions that countries and regions around the world could take, see *The energy transition: A region-by-region agenda for near-term action*, McKinsey & Company, December 2022.

[2] Those calculations refer to emissions of CO$_2$ and other GHGs. Non-CO$_2$ emissions were converted into CO$_2$ equivalents according to their 100-year global warming potential.

[3] These calculations exclude anthropogenic emissions from forestry and other land use because those data are most reliably available at the regional level and this is a country-level analysis. Those emissions amounted to 4.2 metric gigatons in 2019. See "FAOStat," Emissions totals, Food and Agriculture Organization of the United Nations, May 2023.

[4] Country groupings by income came from the World Bank's classifications for fiscal year 2019. See "New country classifications by income level: 2020–2021," Data Blog, World Bank, July 1, 2020.

Customizing net-zero strategies for different countries (continued)

The nature of emissions also varies from country to country. A large share of high-income countries' emissions is from energy production, buildings, and transportation. In upper-middle-income countries, emissions resulting from energy production and industrial use are high. In low-income countries, emissions are relatively low from energy use but high from agriculture. Therefore, the priority for some countries may be energy-related emissions; for others, emissions from agriculture. But all countries will need to consider where there are opportunities to deploy underused lower-cost solutions and where transition solutions may be most appropriate (see principle 1).

All countries will also need to consider their opportunities to pursue three priorities simultaneously—emissions reduction, economic development, and adaptation to the risks posed by climate change—as well as tensions among those three priorities. For example, for the many low-income countries that have relatively low emissions today, the key priority might be driving economic growth and job creation now and striving to do so in ways that could also keep future emissions low.

Existing energy systems. Countries' current capacity to produce energy also varies. In 2020, 4.6 billion people, all of them in developing (that is, low- and middle-income) countries, consumed less than 50 gigajoules of energy apiece—far less than the 140-gigajoule average in high-income countries (Exhibit 2).[5]

Developing countries also typically have less firming capacity that could one day support wind and solar power. The age of high-emissions assets also varies among countries. Emerging economies often have younger coal-burning power plants, for example, and less incentive to prematurely decommission them. The same point applies to young, high-emitting assets in other sectors, such as steel furnaces.

In developing countries, therefore, designers of future energy systems must consider not only the emissions of such systems but also how to deliver affordable access to energy, address the lack of firming capacity, and tackle the risk of stranded assets. But the mix of energy solutions could vary substantially among countries. Steps to consider include switching cooking fuels from wood or charcoal to gas and electricity; building low-cost solar and wind power, either as part of electric grids or as distributed energy resources, and especially in places where the need for firming capacity would not substantially raise costs; building gas power, including gas power that could replace coal power where feasible, and ideally in a way that can provide long-term firming or clean capacity as well as near-term energy access; and considering other low-emissions alternatives, such as geothermal power and hydropower.

Also, after analyzing a scenario from the Network for Greening the Financial System, we found that developing countries would need to spend up to three times as much as developed ones, measured as a share of GDP, on low- and high-emissions assets for energy, materials, and land-use systems (both for the transition and for economic development) to reach net zero by 2050.[6] That spending is largely used to build power systems. Yet financing is harder for those countries. So scaling up blended finance could be a particularly important solution (see principle 3).

Developed countries, by contrast, have more power assets that can provide firming capacity. So their priorities might include removing constraints on the supply of inputs needed for the transition (see principle 4) and revamping energy markets (principle 5).

Economic activity and endowments. Existing economic activity and jobs may be put at risk by the transition. Developing countries and fossil fuel–rich regions are the most vulnerable to both kinds of losses.[7] But all countries will need to consider how to support affected workers and industries. They will also need to consider how they can benefit from transition-related opportunities by taking advantage of their natural endowments (see principle 7) and reducing technology costs (principle 2). For example, India, which has 300 days of sunshine per year, is prioritizing building a solar power industry, and some estimates suggest that it could become the second-largest producer of solar components by 2026.[8]

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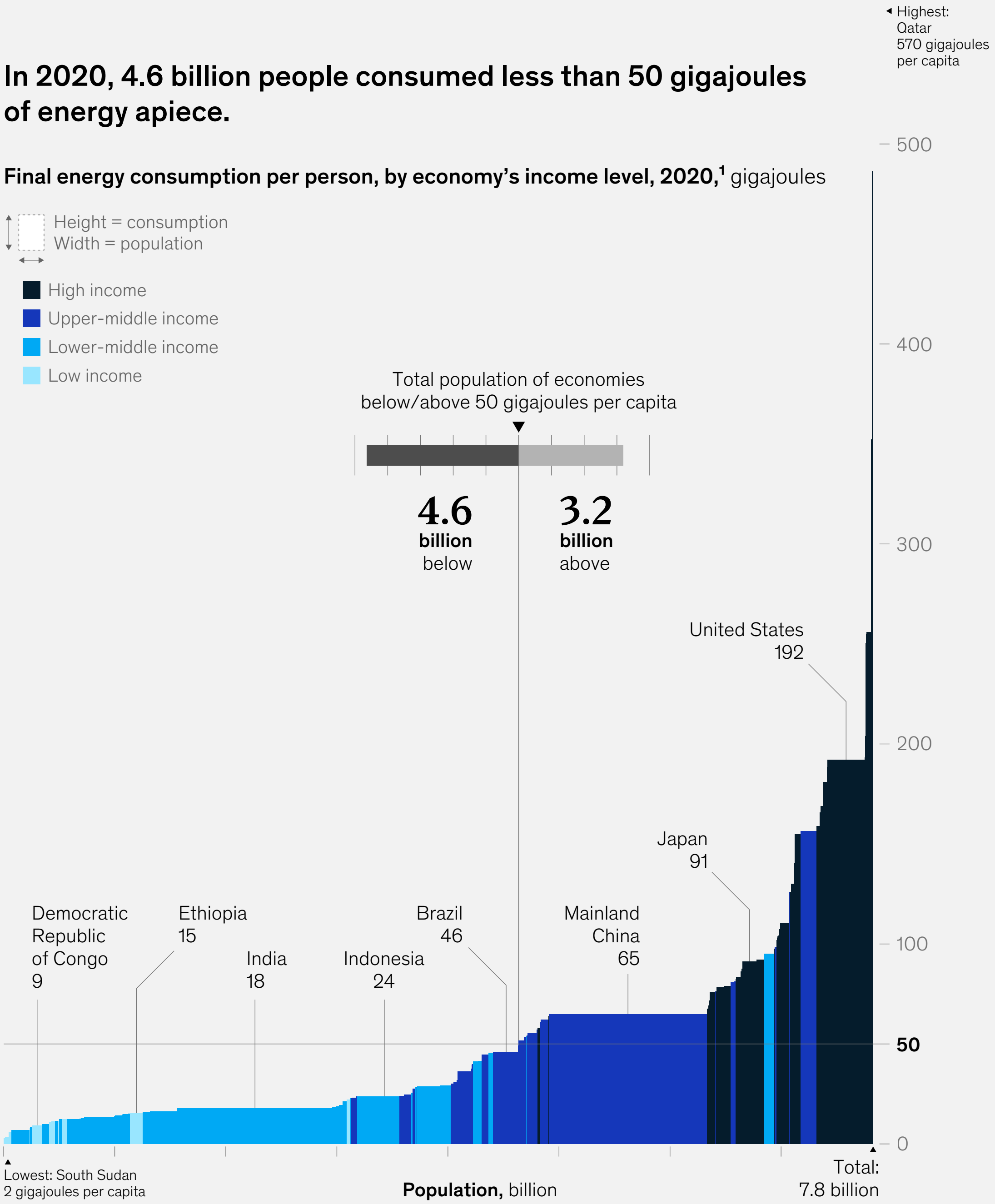
[5] Those estimates are based on information in DataBank, the World Bank, 2023; "Final renewable energy consumption," International Renewable Energy Agency, July 2023; "World energy balances," International Energy Agency, August 2023; and *Global energy perspective 2023*, McKinsey & Company, October 2023.
[6] *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022.
[7] Ibid.
[8] *India's photovoltaic manufacturing capacity set to surge*, Institute for Energy Economics and Financial Analysis and JMK Research & Analytics, April 2023.

Customizing net-zero strategies for different countries (continued)

Exhibit 2

In 2020, 4.6 billion people consumed less than 50 gigajoules of energy apiece.

Final energy consumption per person, by economy's income level, 2020,[1] gigajoules



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[1] Groupings by income level are from the World Bank's classifications for calendar year 2020. See "New country classifications by income level: 2021–2022," Data Blog, World Bank, July 1, 2021. Consumption estimates are those published in *Global Energy Perspective 2023*, McKinsey & Company, October 2023.

Source: International Energy Agency, World Energy Balances; International Renewable Energy Agency, Final Renewable Energy Consumption, 2023; World Bank; McKinsey's *Global energy perspective 2023*; McKinsey analysis

McKinsey & Company

An illustration shows how following those principles could accelerate the world’s current trajectory

As the world embarks on the transition’s next phase, applying the principles described above could help reduce emissions while ensuring affordability, reliability, and industrial competitiveness.

To demonstrate that point, we conducted a set of analyses. They illustrate what might happen as a result of deploying lower-cost solutions (as in principle 1) and driving down the cost of more expensive ones (as in principle 2) to different degrees. Specifically, they provide rough assessments of the corresponding capital spending on low- and high-emissions technologies, as well as of emissions and warming levels.[88] As we proceed from analysis to analysis, we show how progressively greater deployment of low-cost technologies, steeper cost declines of low-emissions technologies, and higher low-emissions spending lead to less and less warming, until finally we reach warming of 1.5°C.

A few words about our methods are in order. (For more detail, see the technical appendix.) To measure the implications of the two principles for affordability, we used capital spending on low-emissions assets, not operating spending. We did so for a number of reasons. First, the current challenge facing the world is to deploy capital toward low-emissions technologies; as we mentioned earlier, the amount of capital currently being spent on the transition remains far short of what is necessary to limit warming to 1.5°C. As we also mentioned earlier, even if the capital

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[88] In quantifying investment, we include what is typically considered investment in national accounts, such as investment in solar and wind power capacity, as well as some spending on what are typically considered consumer durables, such as electric vehicles. Our analysis distinguishes high-emissions assets and technologies from low-emissions ones. Low-emissions assets emit relatively low amounts of GHGs but are not necessarily carbon neutral. Examples of low-emissions assets are solar and wind farms and electric vehicles. In some cases, we also include enabling infrastructure, such as the transmission and distribution infrastructure needed for renewable power or the charging infrastructure needed for electric vehicles. Examples of high-emissions assets are fossil fuel–based power and vehicles with internal combustion engines. In this analysis specifically, we consider the investment needed for one transition solution—namely, switching coal power to gas power—as low-emissions capital spending. We do that because our analysis regards that switch as a way of lowering emissions. For a detailed list of abatement solutions and technologies considered in this analysis, see the technical appendix.

cost of low-emissions technologies declines as quickly as expected, only 50 percent of the capital spending on those technologies needed by 2030 to eventually achieve net zero is likely to take place under current policy frameworks; any additional spending would therefore depend on greater societal commitment, such as increased public spending or additional policies.[89] Second, capital spending is more relevant to low-emissions technologies than operating spending is, because many of those technologies cost more to build than to operate; the reverse is true for high-emissions technologies. In reality, some spending on operating costs would also be needed, particularly in the illustrative analyses that include greater use of high-emissions assets, which tend to have higher operating costs.

These are only illustrative analyses, and much more work would be needed to comprehensively and rigorously evaluate the implications of the measures we have applied here, consider additional ones, perform a broader and more careful assessment of costs, and design robust transition scenarios. Also, the analyses are intended to be not options that a decision-maker could choose among but rather an illustration of how different actions can together achieve the goals of the Paris Agreement. Nonetheless, we believe the exercise can help us understand the potential implications of applying the two principles in full measure.

Our analyses are as follows (Exhibit 11).

— *Maintain current capital spending.* Our first step was to establish a starting point from which to build subsequent analyses. We considered a starting point in which the current amount of spending on low-emissions technologies would continue, though it would grow over time with GDP; on average in this illustrative analysis, about $2.5 trillion would be spent annually between 2021 and 2050.[90] And the cost of those technologies would continue to decline.[91] (In reality, as low-emissions technologies become more cost competitive with traditional alternatives, spending on those technologies could grow more quickly than GDP. We did not consider that effect because the goal of this analysis was to establish a baseline for the rest of our work.) In total, about $8 trillion would be spent each year from 2021 to 2050, on average, on both high- and low-emissions technologies. Emissions of CO_2 in 2050 would be higher than 2020 levels. Warming by 2100 could be roughly 3.5°C to 4.0°C above preindustrial levels, according to the relationship between emissions and temperature published by the IPCC.[92] (For more detail, see the technical appendix.)

— *Unlock lower-cost solutions first.* Next, we considered what would happen if average spending on low-emissions technologies were about 10 percent higher than in the previous analysis. All of the increased spending would be allocated to lower-cost solutions—specifically, improving energy efficiency, reducing methane emissions in fossil fuel production, reducing GHG emissions in agriculture and land use, and switching power generation from coal to gas.[93] As a result, our illustrative analysis suggests, emissions of CO_2 in 2050 would be lower than 2020 levels by about 10 percent, and warming by 2100 could be roughly 3.0°C above preindustrial levels.

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[89] *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023. That 50 percent includes both a continuation of today's spending levels and increased spending likely under current policy frameworks.

[90] These estimates are higher than others in the literature because we have taken an expansive view of the spending required in end-use sectors and because we have considered agriculture and land use.

[91] We assume that those rates would be 80 percent as fast as the rates that are expected in typical current policy scenarios.

[92] See "Technical summary" in *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2023.

[93] As this report mentioned earlier, other costs, such as stranded asset risks, may also exist for transition solutions, such as switching power generation from coal to gas. This analysis does not consider those costs. We ensured that the magnitude of abatement from the low-cost solutions was within bounds identified in the literature.

Exhibit 11

A set of illustrations shows the effects of spending on low-cost solutions and accelerating the cost declines of low-emissions technologies.

	Maintain current capital spending	Unlock lower-cost solutions first	Accelerate cost declines too	And spend even more	Net-zero emissions by about midcentury	
Capital spending on low-emissions technology Annual average, 2021–50, multiple of "maintain current capital spending" analysis	1.0×	1.1×	1.25×	1.5×	3.0×	2.0×
Capital spending on low- and high-emissions technology Annual average, 2021–50, multiple of "maintain current capital spending" analysis	1×	~1×	~1×	~1–1.1×	~1.2–1.3×	~1–1.1×
Increased abatement from lower-cost solutions[1]		✓	✓	✓ ✓	✓	✓ ✓
Reduction in low-emissions technology costs Rate of reduction,[2] multiple of "maintain current capital spending" analysis	1.0×	1.0×	2.0×	2.0×	1.5×	2.0×
Emissions outcome Reduction in CO_2 emissions, 2020 to 2050[3]	*n/a (increase)*	▼~10%	▼~30%	▼~60%	▼~100%	▼~100%
Estimated warming Warming above preindustrial levels by 2100, based on IPCC methods	3.5–4.0°C	~3.0°C	~2.5°C	< 2.0°C	~1.5°C	~1.5°C

Note: These are only illustrative analyses. They are intended to be not options that a decision-maker could choose among but rather an illustration of how different actions can together achieve the goals of the Paris Agreement. Our analysis focuses on capital spending on low-emissions assets, not operating spending; for more details, see the technical appendix. In quantifying capital spending, we include what is typically considered investment in national accounts, as well as some spending on consumer durables, such as electric vehicles. Our analysis distinguishes high-emissions assets and technologies from low-emissions ones. Low-emissions assets emit relatively low amounts of GHGs but are not necessarily carbon neutral. Examples of low-emissions assets are solar and wind farms and electric vehicles. In some cases, we also include enabling infrastructure, such as the transmission and distribution infrastructure needed for renewable power or the charging infrastructure needed for electric vehicles. Examples of high-emissions assets are fossil fuel–based power and vehicles with internal combustion engines. In this analysis specifically, we consider the investment needed for one transition solution—namely, switching coal power to gas power—as low-emissions capital spending. We do that because our analysis regards that switch as a way of lowering emissions. Numbers have been rounded.

[1] Such solutions include increased energy efficiency, reduced methane emissions from fossil fuel operations, shifting from coal to gas to generate electricity, and measures related to emissions from agriculture, forestry, and other land use.

[2] The rate of cost declines is an exogenous input into this analysis. We assume that the rate for the "maintain current capital spending" analysis would be 80% as fast as the rate that is expected in typical current policy scenarios. We assume that some part of the spending on low-emissions technology would be allocated to driving down the cost of more expensive solutions. See the technical appendix for details.

[3] Rounded to the nearest 10%.

Source: McKinsey analysis

McKinsey & Company

— *Accelerate cost declines too.* Next, we considered what would happen if average spending on low-emissions technologies were 25 percent higher than in the first analysis. Some of that increased spending would be allocated to the lower-cost solutions just described. Some would be allocated to investment in R&D and market stimulation, and some to the early deployment of some higher-cost solutions, to help drive down the cost of such solutions. We assumed that those efforts could reduce costs twice as quickly as in the first analysis.[94] We recognize that this is an ambitious assumption, but we have made it to test the potential impact that such a measure could have on overall spending needs and warming levels. As a result of these measures, emissions of CO_2 would be further tempered: by 2050, they would be about 30 percent lower than 2020 levels. And warming could reach roughly 2.5°C above preindustrial levels by 2100.

— *And spend even more.* Here, we considered what would happen if average spending on low-emissions technologies were 50 percent higher than in the first analysis. As in the previous analysis, some of that increased spending would be allocated to lower-cost solutions, and some would be allocated to driving down the cost of more expensive solutions, again making the reduction in the cost of technology twice as large as in the first analysis. As a result, emissions of CO_2 by 2050 would be about 60 percent lower than 2020 levels, and warming by 2100 could be less than 2.0°C above preindustrial levels.

— *Net-zero emissions by about midcentury.* In none of the analyses described so far does the world achieve warming of 1.5°C above preindustrial levels. So we conducted two further analyses in which the world would succeed in reducing net emissions of CO_2 to zero by about 2050.[95] The analyses consider two ways to achieve that goal. In one case, average spending on low-emissions technologies each year would be three times as high as it is in the first analysis. Some of that increased spending would be allocated to lower-cost solutions. And the cost of more expensive solutions would be driven down 1.5 times as quickly as in the first analysis.[96] In the other case, average spending on low-emissions technologies each year would be twice as high as it is in the first analysis. Slightly more of the increased spending would be allocated to lower-cost solutions. And far greater efforts would be made to drive down the cost of more expensive solutions, so that that cost would fall twice as quickly as in the first analysis. As a result, once again, net-zero emissions of CO_2 would be reached by about 2050 and warming could be limited to 1.5°C above preindustrial levels by the end of the century.

Though they are only illustrative, our analyses allow us to make four observations.

First, spending on lower-cost solutions holds promise for reducing emissions and improving warming outcomes. Second, accelerating the cost declines of low-emissions technologies does the same, by more effectively using the capital that is deployed. In fact, these illustrative analyses suggest that if it was possible to unlock lower-cost solutions, double the rate of cost declines, and spend even one and a half times as much as the world is spending today on low-emissions technologies, as in the fourth analysis laid out above, the world could substantially bend the current

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[94] That assumption is in line with the conclusions stated in Rupert Way et al., “Empirically grounded technology forecasts and the energy transition,” *Joule*, volume 6, number 9, September 2022. For more detail, see the technical appendix.

[95] These two analyses are meant to show how applying the two principles more or less extensively could shift the low-emissions capital spending needed to achieve a 1.5°C outcome. Therefore, in the initial one, low-cost solutions are applied to a lesser extent than in the subsequent one, and the rate of cost reduction is slower. Neither analysis is a least-cost-optimized 1.5°C analysis of the sort performed by integrated assessment models, which try to minimize combined capital and operating costs.

[96] That rate of cost decline is in line with many typical 1.5°C scenarios.

trajectory of emissions. Doing so could potentially even limit warming to less than 2.0°C, in contrast to 3.5°C to 4.0°C without those measures.[97]

Third, limiting warming to 1.5°C would require spending two to three times as much as the world is spending today on low-emissions technologies. Here again, prioritizing lower-cost solutions and driving cost declines could help reduce low-emissions spending—potentially by as much as one-third, the difference between spending in our two illustrative analyses that limit warming to 1.5°C.

Finally, the total amount of spending on low- and high-emissions technologies together increases as we move from the first analysis to those with steeper emissions reductions, though much more slowly than does spending on low-emissions technologies alone. That indicates a substantial reallocation of spending from high- to low-emissions technologies.

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[97] Again, by the amount that the world is spending today, we mean the current amount but growing over time with GDP. Also, bringing down the cost of high-cost technologies has a second benefit, though it is not modeled here: it could help make low-emissions technologies more cost competitive with high-emissions ones, thus helping drive capital to them and increasing the likelihood of their adoption. For more details, see *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023.

Embracing a change of mindset can help the world move closer to its net-zero goals

The principles we have described could be applied in many other ways. But all of them depend on a needed change of mindset about the transition.

As stakeholders consider how to execute the next phase of the transition, in addition to making commitments to reach net zero in the future, they should commit to making more and more progress every year. By clearly defining near-term goals, they can illuminate the immediate next steps of the transition, helping turn the aspirations of the Paris Agreement into tangible action.

As we have discussed throughout this report, rather than considering emissions reduction alone, stakeholders should do so while bearing in mind affordability, reliability, and industrial competitiveness. Those objectives are important both in their own right and in accelerating progress toward net zero.

And stakeholders should approach the transition with a sense of participation and collaboration, because all of them have roles to play. Governments can create an environment that supports the transition to new technologies, develop an integrated view of how energy supply systems would transform in tandem with demand, and safeguard domestic competitiveness while also encouraging global cooperation. The social sector can help ensure that no single group is disproportionately burdened as the transition unfolds. Individual consumers, employees, and citizens will play a part. Companies will be the parties enacting the transition by building assets, developing products, and radically changing processes. Their strategy for value creation will have to include both guarding against risks and unleashing innovation to capture opportunities. All of these actors will have to work together to reimagine and execute the transition.

Guided by the principles described in this report, they might begin by asking a few provocative questions:

- How can lower-cost solutions be deployed to abate ten metric gigatons of GHGs by 2030?

- What would it take to double the rate at which expensive solutions become cheaper?
- Where might the worst bottlenecks occur, and how could they be preempted?
- How could a thoughtful portfolio of net-zero opportunities be constructed—and one that also mirrors each stakeholder's comparative advantage?

The answers to such questions might dramatically increase the world's likelihood of reaching global net-zero goals.

Technical appendix

This report describes illustrative analyses in which more lower-cost solutions are deployed while the cost of expensive solutions is simultaneously driven down. The goal of the analyses was to demonstrate that those two approaches could help reduce emissions and make the net-zero transition more affordable. Here, we offer information about how we created the analyses.

Methods

Because the goal of the analyses was not to design a robust pathway to net zero, we chose to conduct a relatively simple assessment. Our methods should therefore not be compared with more elaborate analyses, such as those used in making full-scale integrated assessment models. We performed the following steps.

1. *Defining the unit capital cost of abatement for each solution from 2021 to 2030.* The unit capital cost is the cost in dollars of abating one ton of CO_2 equivalent.

2. *Projecting the unit capital cost through 2100.* We projected a trajectory of unit capital costs by using assumptions about the rates at which unit capital costs change each year. To determine how quickly those rates might be increased in order to further drive down costs, we drew on ranges of values from the academic literature. Specifically, we considered cases in which cost declines happen rapidly as a result of measures such as R&D, learning-by-doing, and economies of scale.[98]

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[98] In our "maintain current capital spending" analysis, we assumed that the pace of cost declines would be 80 percent as fast as the pace expected in typical current policy scenarios. To estimate how much the pace could accelerate in the other analyses, we made assumptions that costs could fall up to twice as quickly as in the "maintain current capital spending" analysis. Those assumptions are ambitious, but we have made them to test the potential impact that such a measure could have on overall spending needs and warming levels. They are in line with the higher-end conclusions stated in Rupert Way et al., "Empirically grounded technology forecasts and the energy transition," *Joule*, volume 6, number 9, September 2022. That research examines potential rates of cost declines for many technologies. It finds that technology costs could decline substantially more quickly in an ambitious transition scenario than in one akin to a current policy scenario: for solar power, 1.5 times as quickly; for wind power, 1.3 times as quickly; and for less mature technologies, such as electrolyzers, many times more quickly (the values are based on median-to-median comparisons among scenarios). If, instead of assessing the ambitious scenario in relation to a current policy scenario, we assessed it in relation to our "maintain current capital spending" analysis, those factors would become 1.9, 1.6, and far higher, respectively.

3. *Defining analyses.* We defined various analyses by allocating capital investment to various low-emissions technologies and to various periods from 2021 to 2100.[99] To do that, we first set the level of overall capital spending on low-emissions technologies for each analysis, basing it on various multiples of today's spending level. We then allocated any investment beyond today's level to different low-emissions technologies—first to lower-cost technologies and then to higher-cost ones.[100] In each case, we also assessed whether the resulting spending profiles were reasonable by comparing them with those in established scenarios from other organizations. We accounted for investments in both building new assets and replacing existing ones at the end of their lives. We also roughly accounted for spending that would be needed to drive R&D and other measures to lower the costs of technologies. To do so, we examined various historical benchmarks for R&D spending, as well as incentives for R&D and early-stage deployment in measures such as the Inflation Reduction Act. We also conducted a sensitivity analysis and found that our overall conclusions still held, even under different (reasonable) assumptions for how much might be spent on R&D and other measures to drive cost reductions.

4. *Deriving additional capital investments required in high-emissions technologies.* We used the capital investment in low-emissions technologies to determine the additional capital investment required in high-emissions technologies. To do that, we assessed how much the spending on low-emissions technologies quantified above could meet underlying demand for energy and other products—and how much demand would remain and need to be met by spending on high-emissions technologies. Together, those two spending values determined the total spending in each analysis.

5. *Calculating abatement in each analysis.* We calculated the abatement achieved on the basis of how much capital was allocated to each low-emissions technology and that technology's expected unit capital cost of abatement.

6. *Estimating the trajectory of net emissions and resulting warming in 2100.* We determined the trajectory of net emissions in each analysis by subtracting the abatement it would achieve from total emissions for each decade (an amount that would increase with economic and population growth). We converted greenhouse gases other than CO_2 into carbon dioxide equivalent according to their potential to increase global warming over 100 years. We estimated warming by 2100 using the relationship between cumulative emissions and temperature described by the IPCC.[101]

In performing those steps, we relied on data from a variety of sources. They include *Net zero by 2050: A roadmap for the global energy sector*, International Energy Agency, October 2021; "NGFS Phase 3 scenario explorer," Network for Greening the Financial System, 2022; *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change, 2022; and *Global Energy Perspective 2023*, McKinsey & Company, October 2023. We also used other McKinsey proprietary information about decarbonization solutions and their capital

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[99] In quantifying investment, we include what is typically considered investment in national accounts, such as investment in solar and wind power capacity, as well as some spending on what are typically considered consumer durables, such as electric vehicles. Our analysis distinguishes high-emissions assets and technologies from low-emissions ones. Low-emissions assets emit relatively low amounts of GHGs but are not necessarily carbon neutral. Examples of low-emissions assets are solar and wind farms and electric vehicles. In some cases, we also include enabling infrastructure, such as the transmission and distribution infrastructure needed for renewable power or the charging infrastructure needed for electric vehicles. Examples of high-emissions assets are fossil fuel–based power and vehicles with internal combustion engines. In this analysis specifically, we consider the investment needed for one transition solution—namely, switching coal power to gas power—as low-emissions capital spending. We do that because our analysis regards that switch as a way of lowering emissions.

[100] The lower-cost technologies were improving energy efficiency, reducing methane emissions in fossil fuel production, reducing GHG emissions in agriculture and land use, and switching power generation from coal to gas. Those technologies have relatively lower capital costs per unit of abatement, and in many cases, they also have lower total (capital and operating) costs per unit of abatement.

[101] See "Technical summary" in *Climate change 2021—The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2023.

costs, as well as various sources for investment in different categories of technologies; for details about those, see *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023. For each of our analyses, we validated that abatement potentials, unit cost trajectories, and overall investment levels were in line with those in other comparable analyses in the literature.

Though some of our analysis in this research was based on data from other organizations, it is not endorsed by any of them. We gratefully acknowledge their input, but the conclusions and any errors are our own.

Limitations

Our analyses had various limitations.

We narrowly defined affordability as the magnitude of capital spending. We considered capital spending, not operating spending, for a number of reasons. First, the current challenge facing the world is to deploy capital toward low-emissions technologies; as this report mentioned earlier, the amount of capital currently being spent on the transition remains far short of what is necessary to limit warming to 1.5°C. As this report also mentioned earlier, even if the capital cost of low-emissions technologies declines as quickly as expected, only 50 percent of the capital spending on those technologies needed by 2030 to eventually achieve net zero is likely to take place under current policy frameworks; any additional spending would therefore depend on greater societal commitment.[102] Second, capital spending is more relevant to low-emissions technologies than operating spending is, because many of those technologies cost more to build than to operate; the reverse is true for high-emissions technologies. In reality, some spending on operating costs would also be needed, particularly in our analyses that include greater use of high-emissions assets, which tend to have higher operating costs. Although we chose to focus on capital spending, future analysis could expand our work to include operating costs (as well as other measures of affordability, such as the cost of energy).

Also, we considered only the amount of spending needed on low-emissions solutions, not whether they would be cost competitive with traditional alternatives. Driving down the capital costs of technologies can both reduce the total spending needed and ensure that more solutions are cost competitive.

Other factors not considered in our analyses include the impact of stranded assets; transition frictions, which could raise costs; the amount of spending, considered in detail, needed to drive down technology costs; and cost declines resulting from economies of scale rather than from R&D or from the learning that happens as companies start to build and deploy a product.

Our analyses are decade-by-decade figures rather than yearly ones. Also, there may be increased uncertainty in the later years of the analyses.

For each solution, the rate at which unit capital cost declines is exogenous. That is, we treat it as an input, and its value is based on data from major published scenarios and research literature.

Finally, we grouped low-emissions technologies into 12 categories. Our analyses were therefore relatively coarse, and future research might consider approaching the same questions in greater detail.

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[102] *From poverty to empowerment: Raising the bar for sustainable and inclusive growth*, McKinsey Global Institute, September 2023. That 50 percent includes both a continuation of today's spending levels and increased spending likely under current policy frameworks.

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