McKinsey
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Report

The net-zero transition

What it would cost, what it could bring

McKinsey Global Institute
in collaboration with
McKinsey Sustainability and
McKinsey's Global Energy &
Materials and Advanced
Industries Practices

January 2022

McKinsey Global Institute

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MGI is led by McKinsey & Company senior partners James Manyika and Sven Smit, who serve as co-chairs, and Chris Bradley, Kweilin Ellingrud, Marco Piccitto, Olivia White, and Jonathan Woetzel, who serve as directors. Michael Chui, Mekala Krishnan, Anu Madgavkar, Jan Mischke, Jaana Remes, Jeongmin Seong, and Tilman Tacke are MGI partners. Project teams are led by the MGI partners and include consultants from McKinsey offices around the world. These teams draw on McKinsey’s global network of partners and industry and management experts. The MGI Council is made up of McKinsey leaders and includes Hemant Ahlawat, Michael Birshan, Andrés Cadena, Sandrine Devillard, André Dua, Katy George, Rajat Gupta, Eric Hazan, Solveigh Hieronimus, Acha Leke, Clarisse Magnin, Jurica Novak, Gary Pinkus, Hamid Samandari, Sha Sha, Oliver Tonby, and Eckart Windhagen. The Council members help shape the research agenda, lead high-impact research, and share the findings with decision makers around the world. In addition, leading economists, including Nobel laureates, advise MGI research.

In collaboration with McKinsey Sustainability and the Global Energy & Materials and Advanced Industries practices

McKinsey Sustainability is the firm’s client-service platform with the goal of helping all industry sectors transform to get to net zero by 2050 and to cut carbon emissions by half by 2030. McKinsey Sustainability seeks to be the preeminent impact partner and adviser for our clients, from the board room to the engine room, on sustainability, climate resilience, energy transition, and environmental, social, and governance (ESG). We leverage thought leadership, innovative tools and solutions, top experts, and a vibrant ecosystem of industry associations and knowledge partnerships to lead a wave of innovation and economic growth that safeguards our planet and advances sustainability.

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Preface

More than 10,000 years of continuous and accelerating progress have brought human civilization to the point of threatening the very condition that made that progress possible: the stability of the earth's climate. The physical manifestations of a changing climate are increasingly visible across the globe, as are their socioeconomic impacts. Both will continue to grow, most likely in a nonlinear way, until the world transitions to a net-zero economy, and unless it adapts to a changing climate in the meantime. No wonder, then, that an ever-greater number of governments and companies are committing to accelerate climate action.

At present, though, the net-zero equation remains unsolved: greenhouse gas emissions continue unabated and are not counterbalanced by removals, nor is the world prepared to complete the net-zero transition. Indeed, even if all net-zero commitments and national climate pledges were fulfilled, research suggests that warming would not be held to 1.5°C above preindustrial levels, increasing the odds of initiating the most catastrophic impacts of climate change, including the risk of biotic feedback loops. Moreover, most of these commitments have yet to be backed by detailed plans or executed. Nor would execution be easy: solving the net-zero equation cannot be divorced from pursuing economic development and inclusive growth. It would require a careful balancing of the shorter-term risks of poorly prepared or uncoordinated action with the longer-term risks of insufficient or delayed action. Indeed, a more disorderly transition could impair energy supply and affect energy access and affordability, especially for lower-income households and regions. It could also have knock-on impacts on the economy more broadly, potentially creating a backlash that would slow down the transition.

None of these challenges should come as a surprise. Achieving net zero would mean a fundamental transformation of the world economy, as it would require significant changes to the seven energy and land-use systems that produce the world's emissions: power, industry, mobility, buildings, agriculture, forestry and other land use, and waste. To bring about these changes, nine key requirements (encompassing physical building blocks, economic and societal adjustments, and governance, institutions, and commitment) would need to be fulfilled against the backdrop of many economic and political challenges.

This means addressing dozens of complex questions, including: what is the appropriate mix of technologies that need to be deployed to achieve emissions reductions while staying within a carbon budget, limiting costs, and delivering required standards of performance? Where are supply chain and infrastructure bottlenecks most likely to occur? Where might physical constraints, whether related to the availability of natural resources or the scale-up of production capacity, limit the pace of the transition? What levels of spending on physical assets would the transition require? Who would pay for the transition? How would the transition affect companies' markets and operations? What would it spell for workers and consumers? What opportunities and risks would it create for companies and countries? And how could consumers be encouraged to make changes to consumption and spending habits that will be necessary to ensure the transition?

In this report, we attempt to answer some of these questions, namely, those pertaining to the economic and societal adjustments. We provide estimates of the economic changes that would take place in a net-zero transition consistent with 1.5°C of warming. We seek to build and expand upon the vast external literature on the net-zero transition, in order to offer a more detailed and granular view of the nature and magnitude of the economic changes that it would entail. As a result, our estimates of the annual spending on physical assets for a net-zero transition exceed to a meaningful degree the $3 trillion–$4.5 trillion total spending estimates that previous analyses have produced.

This report is a first-order analysis of a hypothetical 1.5°C scenario. As such, it has several limitations.

First, it is not clear whether a 1.5°C scenario is achievable in the first place, nor what pathway the world would take to achieve it if it were. Indeed, some believe that 1.5°C is already out of reach, given the current trajectory of emissions and their potential to activate climatic feedback loops, as well as prevailing challenges with revamping energy and land-use systems. This research does not take a position on such questions. Instead, it seeks to demonstrate the economic shifts that would need to take place if the goal of 1.5 degrees is to be attained through a relatively orderly transition between now and 2050.

Second, this report is by nature and necessity limited in its scope. In particular it does not focus on such issues as technology breakthroughs, physical constraints related to scale-up capacity and the availability of natural resources, delayed-transition costs, the role of adaptation, or other imponderables or uncertainties, nor have we yet modeled the full range of economic outcomes likely under a net-zero transition. As a result, it is likely that real outcomes will diverge from these estimates, particularly if the net-zero transition takes a more disorderly path or restricting warming to 1.5°C proves unachievable. Spending requirements could be higher, for example due to the additional investment needed to maintain flexibility and redundancy in energy systems, or heightened physical risks and commensurate adaptation costs.

Third, this report does not explore the critical question of who pays for the transition. What is clear is that the transition will require collective and global action, particularly as the burdens of the transition would not be evenly felt. The prevailing notion of enlightened self-interest alone is unlikely to be sufficient to help achieve net zero, and the transition would challenge traditional orthodoxies and require unity, resolve, and ingenuity from leaders.

We nonetheless hope that our scenario-based analysis will help decision makers refine their understanding of the nature and the magnitude of the changes the net-zero transition would entail and the scale of response needed to manage it. We also hope that our attempts to describe as accurately as we can the challenges that lie ahead are seen as what they are: a call for more thoughtful and more decisive action, urgency, and resolve.

The report is joint research by McKinsey Sustainability, McKinsey's Global Energy and Materials Practice, McKinsey's Advanced Industries Practice, and the McKinsey Global Institute. McKinsey has long focused on issues of environmental sustainability, dating to client studies in the early 1970s. We developed our global greenhouse gas abatement cost curve in 2007, updated it in 2009, and have since conducted national abatement studies in countries including Brazil, China, Germany, India, Russia, Sweden, the United Kingdom, and the United States. Recent research on which we build in this publication includes the January 2020 report *Climate risk and response: Physical hazards and socioeconomic impacts,* a January 2021 article, "Climate math: What it takes to limit warming to 1.5°C," and two October 2021 articles, "Our future lives and livelihoods: Sustainable and inclusive and growing" and "Solving the net-zero equation: Nine requirements for a more orderly transition."

This research was led by Mekala Krishnan, a McKinsey Global Institute (MGI) partner in Boston; Hamid Samandari, a McKinsey senior partner in New York; Jonathan Woetzel, a senior partner and MGI director in Shanghai; Sven Smit, a senior partner in Amsterdam and co-chair of MGI; Daniel Pacthod, a senior partner in New York; Dickon Pinner, a senior partner in San Francisco; Tomas Nauclér, a senior partner in Stockholm; and Humayun Tai, a senior partner in New York. The research team was led in different periods by Annabel Farr, Danielle Imperato, Johanneke Tummers, Sophie Underwood, and Weige Wu. Team members: Wouter van Aanholt, Rishi Arora, Carolyne Barker, Ryan Barrett, Anna Benkeser, Mélanie Bru, Gene Chang, Jonas DeMuri-Siliunas, William Désilets, Julia Dhert, Spencer Dowling, William Edwards-Mizel, Karina Gerstenchlager, Jakob Graabak, Chantal de Graaf, Pragun Harjai, Laura Hofstee, Jania Kesarwani, Dhiraj Kumar, Joh Hann Lee, Youting Lee, Diego Miranda, Ian Murphy, Prit Ranjan, Shresth Sanghai, Lex Razoux Schultz, Ruben Robles, Kevin Russell, Nick Thiros, Ben D. Thomas, Sarah Vargese, Colin Varn, and Jan-Paul Wiringa.

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This report contributes to our mission to help business and policy leaders understand the forces transforming the global economy. As with all MGI research, it is independent and has not been commissioned or sponsored in any way by any business, government, or other institution.

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In brief

The net-zero transition: What it would cost, what it could bring

Governments and companies are increasingly committing to climate action. Yet significant challenges stand in the way, not least the scale of economic transformation that a net-zero transition would entail and the difficulty of balancing the substantial short-term risks of poorly prepared or uncoordinated action with the longer-term risks of insufficient or delayed action. In this report, we estimate the transition's economic effects on demand, capital allocation, costs, and jobs to 2050 globally across energy and land-use systems that produce about 85 percent of overall emissions and assess economic shifts for 69 countries. Our analysis is not a projection or a prediction and does not claim to be exhaustive; it is the simulation of one hypothetical, relatively orderly path toward 1.5°C using the Net Zero 2050 scenario from the Network for Greening the Financial System (NGFS), to provide an order-of-magnitude estimate of the economic transformation and societal adjustments associated with net-zero transition. We find that the transition would be universal, significant, and front-loaded, with uneven effects on sectors, geographies, and communities, even as it creates growth opportunities:

Capital spending on physical assets for energy and land-use systems in the net-zero transition between 2021 and 2050 would amount to about $275 trillion, or $9.2 trillion per year on average, an annual increase of as much as $3.5 trillion from today. To put this increase in comparative terms, the $3.5 trillion is approximately equivalent, in 2020, to half of global corporate profits, one-quarter of total tax revenue, and 7 percent of household spending. An additional $1 trillion of today's annual spend would, moreover, need to be reallocated from high-emissions to low-emissions assets. Accounting for expected increases in spending, as incomes and populations grow, as well as for currently legislated transition policies, the required increase in spending would be lower, but still about $1 trillion. The spending would be front-loaded, rising from 6.8 percent of GDP today to as much as 8.8 percent of GDP between 2026 and 2030 before falling. While these spending requirements are large and financing has yet to be established, many investments have positive return profiles (even independent of their role in avoiding rising physical risks) and should not be seen as merely costs. Technological innovation could reduce capital costs for net-zero technologies faster than expected.

In this scenario, the global average delivered cost of electricity would increase in the near term but then fall back from that peak, although this would vary across regions. As the power sector builds renewables and transmission and distribution capacity, the fully loaded unit cost of electricity production, accounting for operating costs, capital costs, and depreciation of new and existing assets, in this scenario could rise about 25 percent from 2020 until 2040 and still be about 20 percent higher in 2050 on average globally. Cost increases in the near term could be significantly higher than those estimated here, for example, if grid intermittency issues are not well managed. The delivered cost could also fall below 2020 levels over time because of the lower operating cost of renewables—provided that power producers build flexible, reliable, and low-cost grids.

The transition could result in a gain of about 200 million and a loss of about 185 million direct and indirect jobs globally by 2050. This includes demand for jobs in operations and in construction of physical assets. Demand for jobs in the fossil fuel extraction and production and fossil-based power sectors could be reduced by about nine million and four million direct jobs, respectively, as a result of the transition, while demand for about eight million direct jobs would be created in renewable power, hydrogen, and biofuels by 2050. While important, the scale of workforce reallocation may be smaller than that from other trends including automation. Displaced workers will nonetheless need support, training, and reskilling through the transition.

While the transition would create opportunities, sectors with high-emissions products or operations—which generate about 20 percent of global GDP—would face substantial effects on demand, production costs, and employment. In the NGFS Net Zero 2050 scenario, coal production for energy use would nearly end by 2050, and oil and gas production volumes would be about 55 percent and 70 percent lower, respectively, than today. Process changes would increase production costs in other sectors, with steel and cement facing increases by 2050 of about 30 and 45 percent, respectively, in the scenario modeled here. Conversely, some markets for low-carbon products and support services would expand. For example, demand for electricity in 2050 could more than double from today.

Poorer countries and those reliant on fossil fuels are most exposed to the shifts in a net-zero transition, although they have growth prospects as well. These countries are more susceptible to changes in output, capital stock, and employment because exposed sectors make up relatively large parts of their economies. Exposed geographies including in sub-Saharan Africa and India would need to invest 1.5 times or more than advanced economies as a share of GDP today to support economic development and build low-carbon infrastructure. The effects within developed economies could be uneven, too; 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. At the same time, all countries will have growth prospects, from endowments of natural capital such as sunshine and forests, and through their technological and human resources.

Consumers may face additional up-front capital costs and have to spend more in the near term on electricity if cost increases are passed through, and lower-income households everywhere are naturally more at risk. Consumer spending habits may also be affected by decarbonization efforts, including the need to replace goods that burn fossil fuel, like transportation vehicles and home heating systems, and potentially modify diets to reduce high-emissions products like beef and lamb. The up-front capital spending for the net-zero transition could yield lower operating costs over time for consumers. For example, total cost of ownership for EVs is expected to be lower than ICE cars in most regions by 2025.

Economic shifts could be substantially higher under a disorderly transition, in particular because of higher-order effects not considered here. The economic and social costs of a delayed or abrupt transition would raise the risk of asset stranding, worker dislocations, and a backlash that delays the transition. Even under a relatively gradual transition, if the ramp-down of high-emissions activities is not carefully managed in parallel with the ramp-up of low-emissions ones, supply may not be able to scale up sufficiently, making shortages and price increases or volatility a feature. Much therefore depends on how the transition is managed.

For all the accompanying costs and risks, the economic adjustments needed to reach net zero would come with opportunities and prevent further buildup of physical risks. Incremental capital spending on physical assets creates growth opportunities, in connection with new low-emissions products, support services, and their supply chains. Most importantly, reaching net-zero emissions and limiting warming to 1.5°C would reduce the odds of initiating the most catastrophic impacts of climate change, including limiting the risk of biotic feedback loops and preserving our ability to halt additional warming.

Government and business would need to act together with singular unity, resolve, and ingenuity, and extend their planning and investment horizons even as they take immediate actions to manage risks and capture opportunities. Businesses would need to define, execute, and evolve decarbonization and offsetting plans for scope 1 and 2 emissions and potentially expand those plans to include scope 3 emissions, depending on the nature of their operations, and the materiality, feasibility, and need of doing so. Over time, they would need to adjust their business models as conditions change and opportunities arise; integrate climate-related factors into decision-making processes for strategy, finance, and capital planning, among others; and consider leading action with others in their industry or ecosystem of investors, supply chains, customers, and regulators. Financial institutions in particular have a pivotal role to play in supporting large-scale capital reallocation, even as they manage their own risks and opportunities. Governments and multilateral institutions could use existing and new policy, regulatory, and fiscal tools to establish incentives, support vulnerable stakeholders, and foster collective action. The pace and scale of the transition mean that many of today's institutions would need to be revamped and new ones created to disseminate best practices, establish standards and tracking mechanisms, drive capital deployment at scale, manage uneven impacts, and support further coordination of efforts.

The goal of this research is to provide stakeholders with an in-depth understanding of the nature and magnitude of the economic and societal adjustments a net zero transition would entail. Our hope is that this analysis provides leaders with the tools to collectively secure a more orderly transition to net-zero by 2050. The findings serve as a clear call for more thoughtful and decisive action, taken with the utmost urgency. The rewards of the net-zero transition would far exceed the mere avoidance of the substantial, and possibly catastrophic, dislocations that would result from unabated climate change, or the considerable benefits they entail in natural capital conservation. Besides the immediate economic opportunities they create, they open up clear possibilities to solve global challenges in both physical and governance-related terms. These include the potential for a long-term decline in energy costs that would help solve many other resource issues and lead to a palpably more prosperous global economy. More importantly, they presage decisive solutions to age-old global economic and political challenges as the result of the unprecedented pace and scale of global collaboration that such a transition would have required. And while the immediate tasks ahead may seem daunting, human ingenuity can ultimately solve the net-zero equation, just as it has solved other seemingly intractable problems over the past 10,000 years. The key issue is whether the world can muster the requisite boldness and resolve to broaden its response during the upcoming decade that will in all likelihood decide the nature of the transition.

Six characteristics of the net-zero transition

1 Universal

All carbon dioxide and methane emissions today come from **seven energy and land-use systems.**

2 Significant

Capital spending on physical assets for energy and land-use systems **will need to rise** by $3.5 trillion per year for the next 30 years, to an annual total of:

$9.2 trillion

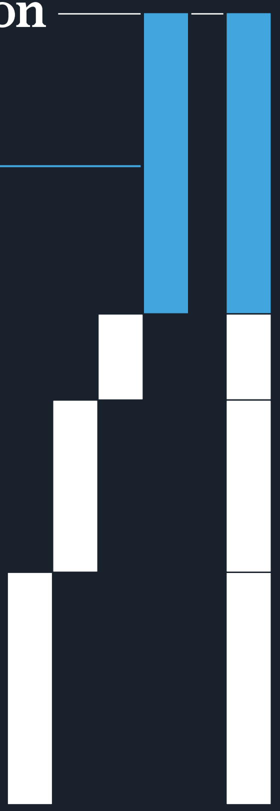
🟦 New spending
⬜ Current spending

$3.5 trillion
Increase in spending on **low-emissions assets vs. today**

$1 trillion
Spending reallocated **from high- to low-emissions assets**

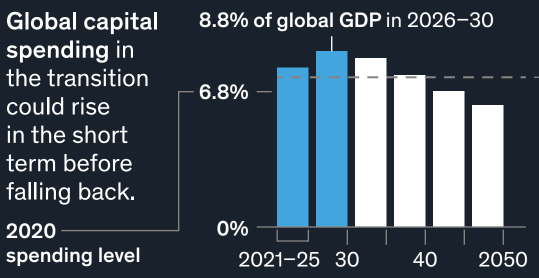
$2 trillion
Continued spending on **low-emissions assets**

$2.7 trillion
Continued spending on **high-emissions assets**



3 Front-loaded

Global capital spending in the transition could rise in the short term before falling back.



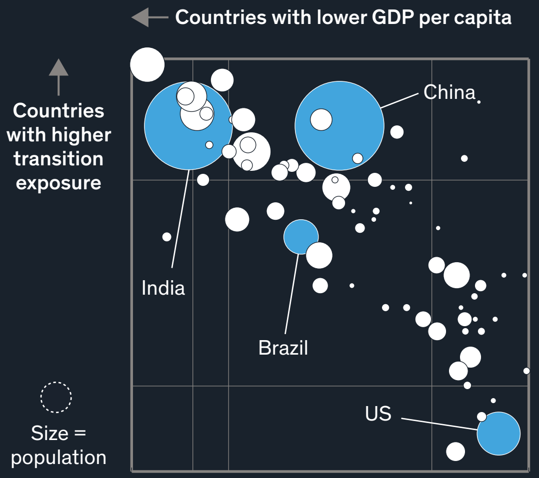
Cumulative spending of around

$275 trillion

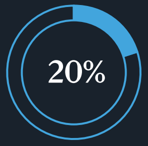
About 7.5% of global GDP across 2021–50

4 Uneven

Developing countries and fossil fuel-rich regions are more exposed to the net-zero transition compared with other geographies.



Some industry sectors are also more exposed.



Percentage of GDP generated by sectors with highest degree of exposure

5 Exposed to risks

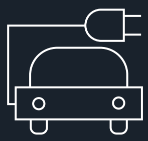
As high-emissions assets are ramped down and low-emissions ones ramped up in the transition, risks include rising energy prices, energy supply volatility, and asset impairment.

$2.1 trillion
Value in power assets alone that could be stranded by 2050

6 Rich in opportunity

The shift to a net-zero emissions world will create opportunities for businesses and countries. These could be in three areas:

Decarbonizing processes and products



Replacing high-emissions products and processes with low-emissions ones

New offerings to aid decarbonization
Including supply chain inputs, infrastructure, and support services

Estimates based on Net Zero 2050 scenario from Network for Greening the Financial System, which has an even chance of limiting warming to 1.5°C, a hypothetical scenario, not a prediction or projection. See technical appendix for further details on approach.

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Executive summary

As of this writing, in December 2021, more than 70 countries accounting for more than 80 percent of global CO_2 emissions and about 90 percent of global GDP have put net-zero commitments in place, as have more than 5,000 companies, as part of the United Nations' Race to Zero campaign.[1] Yet even if all the existing commitments and national climate pledges were fulfilled, estimates suggest that warming would exceed 1.5°C above preindustrial levels, increasing the odds of initiating the most catastrophic impacts of climate change, including biotic feedback loops.[2] Moreover, most of these commitments have yet to be supported by detailed plans or executed. Nor will execution be trivial, as it would require a careful balancing of shorter- and longer-term risks.

Today, while the imperative to reach net-zero is increasingly recognized, the net-zero equation is not solved. This state of affairs should not be surprising, given the scale of the task at hand. Achieving net-zero emissions by 2050 would entail a fundamental transformation of the global economy. To bring about these changes, nine key requirements encompassing the three categories of physical building blocks, economic and societal adjustments, and governance, institutions, and commitment would need to be fulfilled against the backdrop of many economic (for example, inflation) and political challenges (for example, polarization within and among countries).[3]

In this report, we focus on the second category, namely, understanding the nature and extent of the economic and societal adjustments. We simulate the global shifts in demand, capital allocation, costs, and jobs that would take place between now and 2050 in the context of a net-zero transition, examining potential gains and opportunities as well as losses and costs. Our analysis covers the energy and land-use systems that produce about 85 percent of overall emissions and takes a closer look at how the transition might affect 69 countries.

This analysis is not a projection or a prediction; it provides point estimates of specific economic transformations likely under a given hypothetical net-zero transition scenario from the Network for Greening the Financial System (NGFS), an organization set up by central banks and supervisors in December 2017 with the goal of strengthening the global response to climate change. (We describe our methodology and its limitations in Box E1, "Our research methodology: Approach, scenarios, limitations, and uncertainties.") This scenario has an even chance of limiting warming to 1.5°C; however, it is not clear whether the world will be able to keep the temperature increase to that level, or which of numerous pathways it may take in an effort to do so. This research does not take a position on such questions. Instead, it seeks to demonstrate the economic shifts that would need to take place if the goal of 1.5 degrees is to be attainable and a relatively orderly transition achieved.

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[1] Includes countries that have achieved their net-zero targets, or have put them in law, in policy documents, or made a declaration or a pledge. Net Zero Tracker, Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, and Oxford Net Zero, 2021. GDP data for 2019 from *World Development Indicators Data Bank,* World Bank. Emissions data for 2018 from Emissions Database for Global Atmospheric Research (EDGAR), v6.0, May 2021. "Race to Zero campaign," United Nations Framework Convention on Climate Change.

[2] Based on policies currently enacted into law, UNEP, Climate Action Tracker, and the International Energy Agency project that warming will be 2.6–2.7°C by 2100. In alternate scenarios, where current net-zero targets and 2030 pledges are fully implemented, these organizations project that warming would be restricted between 2.1 and 2.2°C. IEA lowers this estimate to 1.8°C if targets that are still under discussion are also fully implemented. *Emissions gap report 2021: The heat is on,* UNEP, 2021; *Warming projections global update,* Climate Action Tracker, November 2021; and *World energy outlook 2021,* International Energy Agency, October 2021. Estimates from the Network for Greening the Financial System (NGFS) similarly suggest that if current implemented policies continue, approximately 1,250 additional gigatons of CO_2 would enter the atmosphere by 2050, breaching the limit that scientists consider necessary to keep warming below 1.5°C. Based on an analysis of the NGFS Current Policies scenario, using the REMIND-MAgPIE 2.1/4.2 model. See also *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* Intergovernmental Panel on Climate Change (IPCC), 2021.

[3] Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.

Box E1

Our research methodology: Approach, scenarios, limitations, and uncertainties

We assess the net-zero transition along two dimensions: sectors and geographies. For the first, we examine energy and land-use systems that account for about 85 percent of global emissions: power, industry (steel and cement production), mobility (in particular, road transportation), buildings, agriculture and food, and forestry and other land use. We also looked at fossil fuels that supply energy to many of these systems. For the geographic dimension, we analyze effects in depth in 69 countries, which make up about 95 percent of global GDP.

We chose not to develop our own transition scenarios and rely instead on widely used scenarios created by other institutions. Specifically, we analyze potential effects under the Net Zero 2050 scenario defined by the Network for Greening the Financial System (NGFS). This hypothetical scenario mirrors global aspirations to cut emissions by about half by 2030 and to net zero by 2050 (Exhibit E1). It reaches net-zero CO_2 emissions by 2050 for the economy as a whole; this means there are some low residual gross CO_2 emissions in hard-to-abate sectors and some regions that are counterbalanced by CO_2 removals. We chose to work with the NGFS scenarios because they cover all major energy and land-use systems in a coherent manner, provide regional granularity, are designed for use in risk and opportunity analysis, and are becoming the standard scenarios used by financial institutions, regulators, and supervisors.[1]

In some cases, as a counterfactual for comparison, we also use the NGFS Current Policies scenario. This scenario projects the greenhouse gas emissions that would occur if only today's mitigation policies remain in place (based on an NGFS assessment of policies as of the start of 2020), and it anticipates a little over 3°C of warming by 2100.[2] The comparison allows us to account for how other factors such as GDP growth or population growth could affect the economy between now and 2050. We also collaborated with Vivid Economics to use the two NGFS scenarios to generate more granular sector variables where needed (for example, sales of new automobiles), in a manner that was based on and compliant with the NGFS scenarios. In such cases, we still refer to the specific sector variable as being based on the relevant NGFS scenario.

We performed the analysis as follows. First, we used the NGFS scenarios and downscaling by Vivid Economics to quantify changes in important variables in each energy and land-use system (for example, changes in power production by source). The downscaling was done to provide sectoral or technological granularity where not available from NGFS. We used this to assess changes in demand, and then assessed the implications for capital stock and investment, producer and consumer costs, and employment based on information about decarbonization technologies and their capital and operating costs, labor intensity, and effects on value chains. Where possible, we used region-specific costs and labor assumptions, as well as expected technology learning curves over time, based on McKinsey analysis.

Limitations of our approach and uncertainties. We recognize the limitations of the NGFS scenarios, as with any transition scenario, given that this is an emerging field of research. First, while some variables are explored at the sector level, the scenarios sometimes do not provide enough detail to explore how different types of activities will be affected, thus requiring downscaling to achieve the necessary sectoral granularity. Second, the models underpinning the NGFS scenarios may not capture important dynamics or constraints within a sector. For example, the model we used favors more economy-wide use of biomass in energy and industry (for example, hydrogen production) than may be considered feasible in other sector-specific decarbonization pathways. Third, although the models do capture ongoing learning and technological innovation, they may fail to sufficiently anticipate the emergence of disruptive technologies that may change decarbonization pathways and lower cost trajectories faster than anticipated. Fourth, while some NGFS scenarios have begun to incorporate damages from physical risks in the economic modeling, further work is needed to fully integrate physical risks into the decarbonization pathways. As a result, we have focused here on scenarios that do not incorporate physical risk. This approach also allows us to focus our analysis on the effects of the transition alone.[3] Finally, the scenarios reflect climate policies and technological trends in place before the COVID-19 pandemic and climate negotiations and pledges at COP26 in Glasgow in November 2021.

Our analysis largely consists of an analysis of first-order effects. Various uncertainties could influence the magnitude of outcomes highlighted here. While some of these factors could result in lower outcomes than those sized in this research, some factors suggest that additional costs and effects will likely occur as the transition unfolds. By the same token, the costs of physical climate risks could likely prove higher than those described here.

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[1] NGFS says this scenario "limits global warming to 1.5°C through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5 °C by the end of the century, with no or low overshoot (< 0.1 °C) of 1.5 °C in earlier years." We use the REMIND-MAgPIE scenario from NGFS (2021 release), which allows a CO_2 budget of about 440 gigatons (Gt) after 2020.

[2] For further details, see NGFS Scenarios Portal and Climate Scenarios Database, NGFS, June 2021.

[3] For further discussion of the uncertainties associated with modeling physical risks, see *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

Key uncertainties include the following:

- *Warming scenario and emissions pathway.* A higher warming scenario (for example, 2.0°C above preindustrial levels) may lead to smaller transition effects than a 1.5°C warming scenario, given the lower degree of emissions reduction and deviation from today's production and consumption patterns it entails (though physical risks would naturally be higher).
- *Sectors' decarbonization actions and activity levels.* Because the focus of our work is assessing the nature and magnitude of economic shifts and not identifying decarbonization actions, we used a prespecified net-zero scenario from NGFS. It is feasible that an alternate technology mix could result in lower costs and different shifts than those described here, and that further technological innovation could result in a different pathway with lower costs. It is also feasible that the path the world undertakes to decarbonize is different from the one described here. An alternate scenario may consist of more use of carbon capture and storage (CCS) technologies and a focus on decarbonizing the hydrocarbon value chain, for example, this could happen if capture costs fall, regulatory frameworks are put in place to incentivize CCS use, and markets mature for recycled CO_2 as a material feedstock.[4]
- *Magnitude of direct and indirect socioeconomic effects.* Some effects could be larger than described here, for example, if executing the transition is more complex than the scenario here suggests, and additional capital spending is needed to maintain flexibility and redundancy in energy systems. If supply of key materials or low-emissions sources of energy does not keep up with demand, this could result in shortages and price increases, which we have not considered in our quantification. Higher-order effects could magnify risks and increase costs, particularly in the short term. For example, depending on how the transition is financed, the effects on the overall economy could be substantially higher than sized here. Finally, effects could also be larger under an abrupt or delayed transition.
- *Economic and societal adjustments needed for the transition.* Costs and investments could be higher than sized here, for example to implement social support schemes to aid economic and societal adjustments. Similarly, additional costs may arise from delays, setbacks, and urgently needed adaptation measures, particularly if restricting warming to 1.5°C proves not to be possible. For our analysis, we quantify the scale of first-order effects and describe qualitatively the adjustments needed.

Aspects we did not cover. Topics we did not cover include the likelihood, validity, and comparative costs associated with various decarbonization scenarios; the comparative merits of different emissions-reduction technologies; constraints to implement and deploy decarbonization technologies (for example, scaling up supply chains); the actions needed to drive and incentivize decarbonization; quantification of higher-order economic effects of the transition, including on output, growth, value pools, valuations, trade flows, and human well-being; relative costs and merits of decarbonization and adaptation; and impacts that could result from physical climate hazards. We use benchmarks from the external literature and our past research to describe these latter possibilities. As discussed above, our analysis here represents first-order estimates. Fully quantifying the costs of rising physical risks and the transition is complex. It would require estimating impacts from rising physical risks and the cost of adaptation actions, building robust estimates of the impact of the net-zero transition on the economy that takes into account the higher-order effects described above, and doing so over time and while grappling with the various uncertainties described previously.

Full details of our methodology are in the technical appendix.

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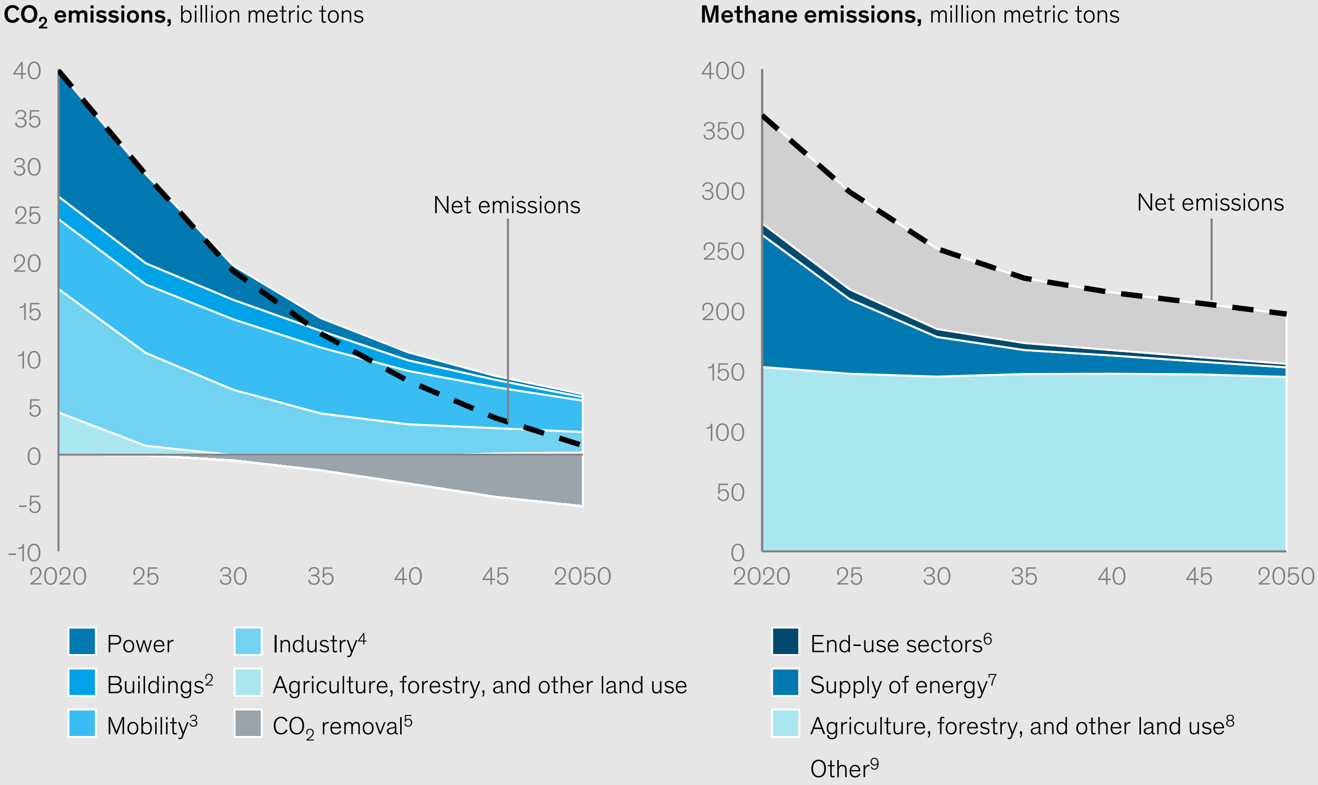
[4] For more on CCS, see also chapter 1.

Exhibit E1

Our analysis uses the Net Zero 2050 scenario from the Network for Greening the Financial System (NGFS).

Net Zero 2050 scenario pathway from NGFS[1]



1. The net-zero scenario is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE from the 2021 release of NGFS (phase 2).
2. CO_2 emissions from energy use in residential and commercial buildings.
3. CO_2 emissions from energy use in transportation sector (road, rail, shipping, and aviation).
4. CO_2 emissions from energy use in industry and industrial process emissions, energy conversion excluding electricity, fugitive emissions from fuels, and emissions from carbon dioxide transport and storage.
5. Total CO_2 emissions captured through bioenergy carbon capture and storage (BECCS). BECCS is deployed across multiple energy systems (eg, electricity generation, hydrogen production, and industry).
6. Methane emissions from energy use.
7. Methane emissions from energy conversion including electricity and fugitive emissions from fuels.
8. Methane emissions from agriculture, forestry, and other land use.
9. Methane emissions from all other sources (eg, waste).

Note: This is based on the NGFS database. Today's emissions may vary across other emissions databases depending on the methodology used.
Source: Network for Greening the Financial System scenario analysis 2021 phase 2 (Net Zero 2050 scenario) REMIND-MAgPIE model; McKinsey Global Institute analysis

Outcomes may well exceed our estimates here, particularly if the net-zero transition takes a disorderly path or if it proves impossible to restrict warming to 1.5°C (see Box E2, “Who will pay for the transition?”). We nonetheless hope such an exercise will help decision makers refine their understanding of the nature and the magnitude of the changes the net-zero transition would entail, and the scale of response needed to manage it.

Six characteristics of the net-zero transition emerge from our scenario-based analysis. First, the transition would be universal. Indeed, net-zero emissions can be achieved if and only if all energy and land-use systems that contribute to emissions are decarbonized, as these contributions are significant in all cases. All economic sectors and all countries would need to participate.

Second, the scale of the required economic transformation would be significant. In particular, we estimate that the cumulative capital spending on physical assets for the net-zero transition between 2021 and 2050 would be about $275 trillion. This means that spending would need to rise from about $5.7 trillion today to an annual average of $9.2 trillion through 2050, an increase of $3.5 trillion. Accounting for expected increases in spending, as incomes and populations grow, as well as for currently legislated transition policies, the required increase in spending would be lower, but still about $1 trillion.

Third, these effects would be front-loaded: spending would need to rise to almost 9 percent of GDP between 2026 and 2030 from about 7 percent today before falling. Likewise, we estimate that the delivered cost of electricity (across generation, transmission, distribution, and storage, and including operating costs, capital costs, and depreciation of existing and new assets) would rise by about 25 percent between 2020 and 2040 in the scenario modeled here before falling from that peak, although this would vary across regions.

Fourth, the transition would be felt unevenly among sectors, geographies, and communities, resulting in greater challenges for some constituencies than others.

Fifth, the transition is laden with short-term risks, even as the transition will help manage long-term physical risks. If poorly managed, it could increase energy prices, with implications for energy access and affordability, especially for lower-income households and regions. It would also have knock-on effects on the economy more broadly. If not well managed, there is a risk that the transition itself would be derailed.

Sixth is that, despite the challenges with making economic and societal adjustments, the transition would give rise to growth opportunities across sectors and geographies—and, critically, it would help avoid the buildup of physical risks.

This research aims to highlight the nature and magnitude of the economic transformation that a net-zero transition would require. While the challenges ahead are large, the findings of this research should be seen for what they are: a call for more thoughtful, decisive, and urgent action to secure a more orderly transition to net-zero emissions by 2050. Everyone would have a role to play, including governments, businesses, and individuals. To ease stakeholders’ adjustments to these effects, governments and businesses will likely need to adopt a long-term perspective and coordinate action in a spirit of unity, resolve, and cooperation and, at the same time, take near-term actions to manage their own risks and capture opportunities.

This research is a call for more thoughtful, decisive, and urgent action.

Box E2

Who will pay for the transition?

As discussed later in this report, the spending needed on physical assets for the net-zero transition is significant. It represents a substantial scale-up of spending relative to today's levels. It is also capital that will be spent very differently relative to today, with capital reallocated away from high-emissions assets and toward low-emissions ones. While some of this spending would eventually yield a return, various challenges with raising capital at this scale will need to be effectively managed. These include addressing technological uncertainty of investment, managing risk/return trade-offs, driving capital flows to developing countries, and ensuring demand for this capital exists in the sectors and geographies in which emissions reduction is most needed.

This raises the question of how to best pay for the transition. Various aspects to consider include who provides the financing (for example, public versus private actors, and the mix of financing provided by developed and developing countries), how capital is raised (for example, debt versus equity, through taxes on companies or consumers), and various combinations thereof. For example, public financing can come through raising taxes on companies, carbon taxes, taxes on consumers, or through taking on debt, to name a few approaches.

In deciding the optimal approach to financing the transition, stakeholders will need to consider three factors. First, which approach would raise capital at the speed and scale needed, and incentivize the deployment of this capital. Second, how financing can best include principles of equity, including what equity would require based on the history of emissions and who has the ability to pay. And finally, what are broader knock-on consequences of different financing approaches.

The latter is especially important, because it can profoundly influence the socioeconomic consequences of a net-zero transition. First, some ways of raising capital—for example, taxes on consumers—could curtail spending in other parts of the economy if not balanced, for example, with fiscal stimulus elsewhere. This in turn could have knock-on effects on corporate revenues for affected sectors, on job creation, and on growth more broadly. Second, the source of financing could exacerbate existing inequalities if not carefully managed. Developing countries, for example, may find it challenging to raise the capital needed for the transition on their own. Third, the type of financing could have a role in influencing the pace of the net-zero transition. Certain technologies, such as electric vehicle (EV) charging infrastructure, may require public financing at scale to reach the speed of deployment needed to achieve net-zero.

The results presented here do not factor in these considerations, as our focus is on sizing the magnitude of the need. However, the question of "who pays" is unavoidable as stakeholders undertake the economic transformation needed for the net-zero transition, and do so with the consequences mentioned above in mind.

Net-zero emissions can be achieved only through a universal transformation of energy and land-use systems

To stabilize the climate and limit physical climate risks, climate science tells us that it is necessary to reduce the addition of GHGs to the atmosphere to net zero (see Box E3, “Physical risks will continue to build up until net zero is achieved”). Seven energy and land-use systems act as direct sources of global emissions (Exhibits E2 and E3).[4] One system—forestry and other land use—also acts as a natural sink for carbon dioxide and would need to increase its rate of emissions absorption. The systems and their emissions footprints are the following:

- Power, consisting of electricity and heat generation: 30 percent of CO_2 emissions, and 3 percent of nitrous oxide (N_2O) emissions[5]
- Industry, consisting of various industrial processes, including production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal: 30 percent of CO_2 emissions, 33 percent of methane emissions, 8 percent of N_2O emissions
- Mobility, consisting of road, aviation, rail, maritime, and other forms of transportation: 19 percent of CO_2 emissions, and 2 percent of N_2O emissions
- Buildings, including heating and cooking: 6 percent of CO_2 emissions
- Agriculture, consisting of direct on-farm energy use and emissions from agricultural practices and fishing: 1 percent of CO_2 emissions, 38 percent of methane emissions, and 79 percent of N_2O emissions
- Forestry and other land use, primarily land cover change: 14 percent of CO_2 emissions, 5 percent of methane emissions, and 5 percent of N_2O emissions
- Waste, consisting of solid waste disposal and treatment, incineration, and wastewater treatment: 23 percent of methane emissions, 3 percent of N_2O emissions

Carbon dioxide in each case is emitted through the combustion of fossil fuels to produce energy (oil, gas, and coal), as well as through non-energy emissions (for example, emissions associated with industrial processes like the reduction of iron ore to produce steel and with deforestation). Based on current accounting methodologies, energy-related emissions make up as much as 83 percent of carbon dioxide emissions.[6]

Reaching net-zero emissions will require a transformation of the global economy.

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[4] UN Food and Agriculture Organization (FAO), 2020; “Energy use,” FAOSTAT; EMIT database, McKinsey Sustainability Insights, September 2021; and McKinsey Global Energy Perspectives.

[5] Heat generation includes heat from combined heat and power plants.

[6] Notably, this is based on the current system of emissions measurement, in which forestry emissions in particular are considered as net emissions, considering their role as both sources and sinks of greenhouse gases. Considering only their role as gross sources of emissions, and accounting for second-order effects of deforestation, would substantially increase the contribution of forestry as sources of emissions. For further details, see chapter 3.

Box E3

Physical risks will continue to build up until net zero is achieved

As average temperatures rise, acute hazards such as heat waves and floods increase in frequency and severity, and chronic hazards, such as drought and rising sea levels, intensify.[1] These hazards and changes could lead to rising, nonlinear, and systemic socioeconomic impacts, as described in our 2020 report on physical climate risk.[2] Most recently, the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR6) reaffirmed that continued GHG emissions will result in increasingly severe consequences for the Earth system and, potentially, abrupt and catastrophic changes that might occur as the climate passes tipping points.[3]

As physical climate risk spreads, it could trigger broader economic, financial, and social disruptions.[4] Estimates suggest that failing to limit the rise of greenhouse gas emissions could affect between 2 and 20 percent of global GDP by 2050 under a high-emissions (RCP 8.5) scenario.[5] The wide range reflects the intrinsic difficulty in making these estimates. The effect of hard-to-predict biotic feedback loops (for example, the thawing of permafrost) or knock-on economic effects (for example, from impacts on financial valuations) could push losses well beyond the high-end estimate.

To stabilize the climate and limit physical climate risks, climate science tells us that it is necessary to reduce the addition of GHGs to the atmosphere to net zero and limit warming to 1.5°C above preindustrial levels to reduce the odds of initiating the most dangerous and irreversible effects of climate change.[6] Global emissions of carbon dioxide are about 40 gigatons (GtCO_2) today. Emissions of CO_2 have risen significantly since 1970, though the rate of growth has slowed in recent years.[7] The IPCC AR6 report estimated that restricting all future net CO_2 emissions to 400–500 Gt, combined with substantial decreases in emissions of short-lived GHGs like methane, would result in a 50 to 67 percent probability of limiting warming to 1.5°C above preindustrial levels.[8] At current emissions rates, the carbon budget for 1.5°C of warming would thus likely be exceeded within about the next decade. Climate science tells us that the Earth system will continue to change along the journey to net zero and that some changes will continue even after we have stopped the planet from warming; thus, actions to reduce emissions will also need to go hand-in-hand with adaptation.[9] Decisions taken over the next decade will thus be crucial.

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[1] Noah S. Diffenbaugh and Christopher B. Field, "Changes in ecologically critical terrestrial climate conditions," *Science,* volume 341, number 6145, August 2013; Seth D. Burgess, Samuel Bowring, and Shu-zhong Shen, "High-precision timeline for Earth's most severe extinction," *Proceedings of the National Academy of Sciences,* volume 111, number 9, March 2014.

[2] *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[3] *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* Intergovernmental Panel on Climate Change (IPCC), 2021.

[4] See Box 1 in *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[5] Making estimates of this kind is challenging, and we have not attempted to do so in our research. The ranges here come from a review of the literature focused on quantifying the various impacts of physical climate effects on real GDP or GDP growth. For detailed sources, see chapter 1 and the bibliography.

[6] "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

[7] Emissions data for other greenhouse gases are less frequently reported. In 2019, annual emissions were 364 megatons of methane (CH_4), and 10 megatons of nitrous oxide (N_2O). See also Global Carbon Budget, 2021; EMIT database by McKinsey Sustainability Insights, September 2021. For more on the impact of the pandemic, see Corinne Le Quéré et al., *Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement,* Global Carbon Project, March 2021.

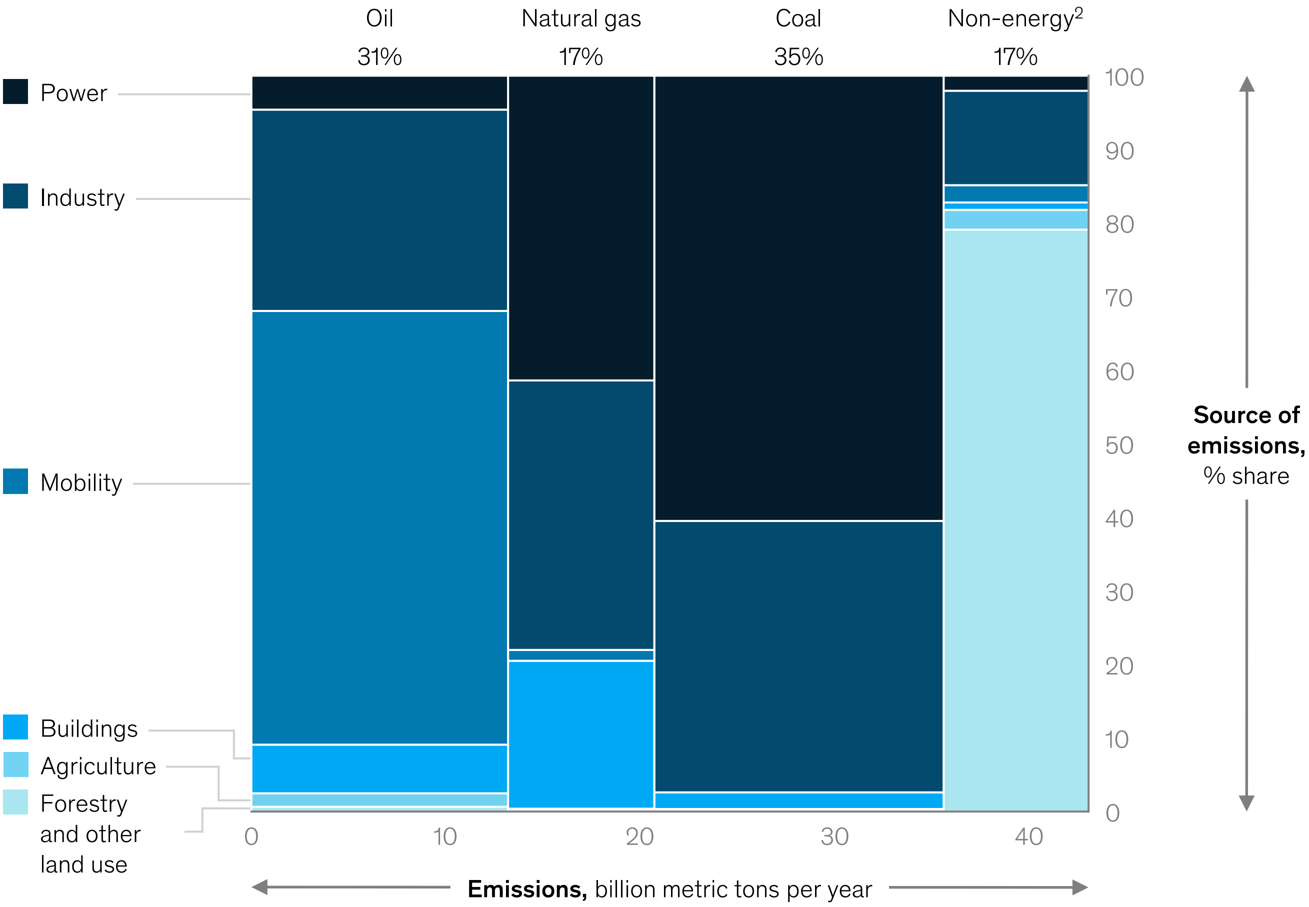
[8] Restricting future net emissions to 1,150–1,350 GtCO_2 would result in a 50–67 percent probability of limiting warming to 2.0°C. At current emissions rates, the carbon budget for 1.5°C of warming would be exceeded in approximately the next decade, and the 2.0°C budget would be exceeded in about three decades.

[9] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters,* volume 13, number 1, January 2018.

Exhibit E2

Energy use accounts for 83 percent of the CO_2 emitted across energy and land-use systems.

CO_2 emissions per fuel and energy and land-use system, 2019, share[1]



1. Includes all fossil fuel CO_2 sources as well as short-cycle emissions (eg, large-scale biomass burning, forest fires). Power includes emissions from electricity and heat generation (i.e., from combined heat and power plants); Industry includes various industrial processes, including production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal; Mobility includes emissions from road, aviation, rail, maritime, and other forms of transportation; Buildings includes emissions from heating, cooking, and lighting of commercial and residential buildings; Agriculture includes emissions from direct on-farm energy use and fishing; Forestry includes net flux of CO_2 from land use and land cover change but not the opportunity cost of lost carbon capture. The global CO_2 emissions in this exhibit represent the total emissions of the full sectors, not of the subsectors considered in this report. Based on 2019 emissions.
2. In addition to energy-related CO_2 emissions, anthropogenic emissions include industry process emissions and deforestation.

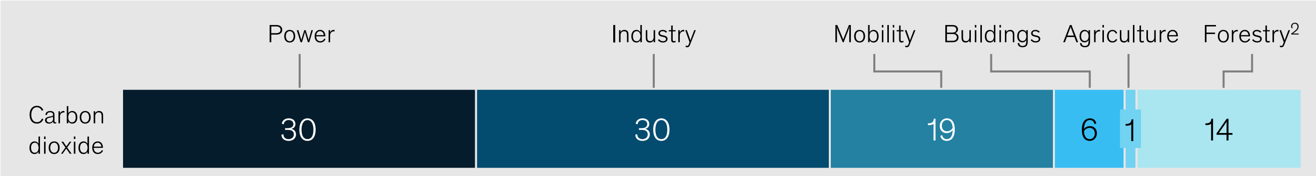
Note: This is based on the McKinsey EMIT database that draws on a variety of bottom-up sources. Depending on the emissions database used, data per sector and the economy as a whole may vary. Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021, data for 2019); International Energy Agency; McKinsey Global Energy Perspectives; McKinsey Global Institute analysis

Exhibit E3

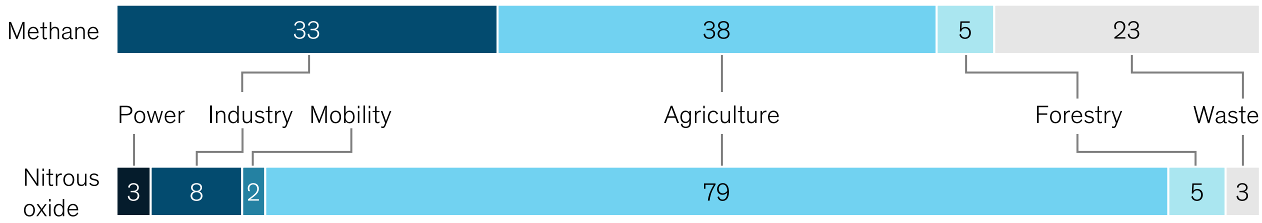
Power and industry are major energy consumers and together generate about 60 percent of CO_2 emissions.

Share of emissions[1] **per energy and land-use system,** 2019, %



Subsectors' share of system emissions, %

Power	Industry	Mobility	Buildings	Agriculture	Forestry[2]
Electricity 97 Heat 3	Steel 26 Cement 20 Oil and gas extraction 15 Chemicals 12 Coal mining 6 Other 20	Road 75 Aviation 13 Maritime 11 Rail 1 Other <1	Residential 70 Commercial 30	Farming 96 Fishing 4	Forestry 100



1. Includes all fossil fuel CO_2 sources as well as short-cycle emissions (eg, large-scale biomass burning, forest fires). Power includes emissions from electricity and heat generation (i.e., from combined heat and power plants); Industry includes various industrial processes, including production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal; Mobility includes emissions from road, aviation, rail, maritime, and other forms of transportation; Buildings includes emissions from heating, cooking, and lighting of commercial and residential buildings; Agriculture includes emissions from direct on-farm energy use and fishing; Forestry includes net flux of CO_2 from land use and land cover change but not the opportunity cost of lost carbon capture; Waste includes emissions from solid waste disposal and treatment, incineration, and wastewater treatment. The global CO_2 emissions in this exhibit represent the total emissions of the full sectors, not of the subsectors considered in this report. Based on 2019 emissions.
2. Forestry and other land use.

Note: This is based on the McKinsey EMIT database that draws on a variety of bottom-up sources. Depending on the emissions database used, data per system and the economy as a whole may vary. Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021, data for 2019); McKinsey Global Institute analysis

Effective decarbonization actions include shifting the energy mix away from fossil fuels and toward zero-emissions electricity and other low-emissions energy carriers such as hydrogen; adapting industrial and agricultural processes; increasing energy efficiency and managing demand for energy; utilizing the circular economy; consuming fewer emissions-intensive goods; deploying carbon capture, utilization, and storage (CCS) technology; and enhancing sinks of both long-lived and short-lived greenhouse gases. Avoiding deforestation and enabling forest restoration are particularly important for restoring and enhancing GHG sinks.[7] Recent McKinsey research on what it would take to achieve a 1.5°C pathway examined a range of scenarios and found that the above actions would need to be deployed across all sectors in the economy and would require emissions-reduction efforts beginning today.[8]

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[7] Estimates suggest that over a 30-year period, a tree can store an additional 60 to 85 percent as much carbon as is released when the tree is cut down or burned, and that overall secondary emissions and forgone carbon sequestration resulting from deforestation can be three to nine times higher than the direct emissions alone. Research indicates that forgone carbon sequestration and forest degradation are highly underestimated in current evaluations of deforestation emissions. For details, see chapters 1 and 3.

[8] Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," McKinsey & Company, April 2020. See also "Curbing methane emissions: How five industries can counter a major climate threat," McKinsey & Company, September 2021.

A key feature of any transition to net-zero emissions is its universality, across energy and land-use systems and throughout the global economy. This is for two reasons. First, each of these energy and land-use systems contributes substantially to emissions. Thus, every one of these systems will need to undergo transformation if the net-zero goal is to be achieved. Second, these systems are highly interdependent; actions to reduce emissions must thus take place in concert and at scale across systems, economic sectors, and geographies. For instance, electric vehicles are valuable only to the extent that low-emissions electricity production has been achieved. All sectors of the economy participate in these energy and land-use systems across global value chains. Similarly, all countries contribute to emissions, either directly or through their role in value chains. Reaching net-zero emissions will thus require a transformation of the global economy.

A net-zero transition would have a significant and often front-loaded effect on demand, capital allocation, costs, and jobs

Decarbonizing the energy and land-use systems described previously will be possible only if nine system-level requirements are met. They encompass physical building blocks, economic and societal adjustments, and governance, institutions, and commitment (see Box E4, "The net-zero 'equation' and system-level requirements to help solve it").

This report focuses on the economic and societal adjustments needed for a net-zero transition. We illustrate the significant adjustments that would need to be made through an analysis of the nature and the magnitude of the transition on demand, capital allocation, costs, and jobs. Various other knock-on effects could also ensue and affect, for example, value pools, financial valuations, GDP, and global trade flows. While we do not quantify these, we discuss some of them qualitatively throughout the report.[9] Specific aspects include the following:

— **Demand:** Changes in policies, technologies, and consumer and investor preferences under a net-zero transition could increase demand for low-emissions goods and services and lower demand for high-emissions ones, in turn causing changes across value chains.

— **Capital allocation:** Decarbonizing the global economy and securing low emissions going forward would require significant capital spending on the formation of new physical assets and the transformation of existing ones.

— **Costs:** Operating and production costs would change as low-emissions processes are implemented, investment is made, and energy consumption shifts toward low-emissions sources.

— **Jobs:** Workforce requirements would evolve as markets are reshaped and organizations institute new operational practices and processes.

Our analysis using the NGFS Net Zero 2050 scenario is a hypothetical simulation, not a projection or a prediction. Our perspectives on demand, investment, costs, and jobs below represent a consistent and interdependent view of the world under this scenario. The analysis is not exhaustive, and we acknowledge its limitations and uncertainties.

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[9] We have focused on quantifying the direct shifts, given the vast uncertainties involved in modeling these higher-order effects, and because their outcome could vary based on specific actions taken to manage them. For further details on our methodology, see Box E1.

Box E4

The net-zero 'equation' and system-level requirements to help solve it

Prior research by McKinsey Sustainability makes the point that achieving net zero is akin to solving an equation—one that balances sources and sinks of emissions by reducing GHG emissions as much as possible while increasing GHG stores to remove any remaining emissions from the atmosphere.[1] To help solve this equation, that research identified nine fundamental, interrelated system-level requirements for a net-zero transition. Our research in this report uses these requirements as a starting point. We place them into the following three groups:

Physical building blocks, encompassing (1) technological innovation; (2) ability to create at-scale supply chains and support infrastructure; and (3) availability of necessary natural resources. Past McKinsey research suggests that there is a line of sight to the technologies needed to limit warming to 1.5°C above preindustrial levels, although continued innovation is still needed.[2] Further innovation, both to develop new technologies that can be deployed at scale and to reduce their costs, will be needed nonetheless. For example, under a 1.5°C pathway, the number of solar panels installed globally per week would be approximately eight times higher than the number today. The rate of wind-turbine installations would need to increase fivefold.[3] And natural resources, including raw materials such as copper, nickel, rare-earth metals, land, and water, would also need to be carefully managed to ensure sufficient availability and minimize bottlenecks, and prevent price spikes and inflation. Building out supply chains to support the kind of step change in deployment needed requires not only significant capital and the right capabilities but also extensive coordination.

Economic and societal adjustments, comprising (4) effective capital reallocation and financing structures; (5) management of demand shifts and near-term unit cost increases; and (6) compensating mechanisms to address socioeconomic impacts. As we discuss in this research, an orderly transition to net zero would require significant changes to capital allocation. Companies and countries would need to manage the demand shift and cost changes from a wholesale revamping of energy and land-use systems, even as the implications for individuals and communities for livelihoods and expenditures could be substantial.

Governance, institutions, and commitment, consisting of (7) governing standards, tracking and market mechanisms, and effective institutions; (8) commitment by, and collaboration among, public-, private-, and social-sector leaders globally; and (9) support from citizens and consumers. The pace, scale, and systemic nature of the required transition mean that all stakeholders will need to play a role, working together in new ways. Securing an orderly transition will require leaders who have the commitment and capabilities to develop coherent, reliable, and workable policies and help their organizations navigate the changes that lie ahead. The transition is also unlikely to occur without the support of citizens and consumers, and in some cases, consumers may need to fundamentally shift behaviors to reduce their own emissions.

As stakeholders have increased their commitments to net zero, moving to action has not proven easy or straightforward. This is for five reasons: first, the scale and pace of the step-up in spending needed on physical assets, given that entire energy and land-use systems evolved over a century or two and would need to be transformed over the next 30 years; second, the collective and global action required, particularly as the burdens of the transition would not be evenly felt; third, the near-term shifts needed for longer-term benefits; fourth, the shifts needed in business practices and lifestyles that have evolved over decades; and fifth, the central role of energy in all economic activity, which means that transformation would need to be carefully managed. Indeed, the transition involves the transformation of the most important systems supporting our lives and well-being. Even small disturbances to these systems could affect daily lives, from raising producer and consumer costs to impairing energy access, and could lead to delays and public backlash. Together, these factors highlight why the prevailing notion of enlightened self-interest alone is unlikely to be sufficient to help achieve net zero.

In this report, we focus on the second of these groupings of requirements, the economic and societal adjustments, to better understand these challenges and how stakeholders can respond. There is a real risk that transition costs could be unbearable to many in the absence of compensating measures; for example, if companies and countries do not manage the shifts in demand or cost impacts to their existing products and services, or if communities are left behind as the world transitions to a net-zero economy.

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[1] Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.

[2] See, for example, Paolo d'Aprile, Hauke Engel, Godart van Gendt, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, December 2020. Our work on decarbonization in Europe found that more than 85 percent of today's emissions in Europe can be abated with already demonstrated technologies, including 28 percent that are mature and 32 percent that are in the early-adoption phase (although it is important to note that the pathway to deploying these technologies is still uncertain and would require addressing the other requirements mentioned here).

[3] See also Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly,* April 2020.

Demand: In the net-zero scenario examined here, high-emissions products would see shrinking demand, while uptake of low-emissions products would create growth opportunities

Our analysis suggests that under the NGFS Net Zero 2050 scenario, changes in policies, technologies, and consumer and investor preferences would lead to considerable shifts in demand for various goods and services (Exhibit E4). By 2050, oil and gas production volumes would be 55 percent and 70 percent lower, respectively, than they are today. Coal production for energy use would nearly end by 2050. Similarly, the transition would affect demand for products that use fossil fuels. Demand for internal combustion engine (ICE) cars would eventually cease as sales of battery-electric and fuel cell-electric cars increase from 5 percent of new car sales in 2020 to virtually 100 percent by 2050.

In other sectors, demand could shift, with a substitution of products manufactured with emissions-intensive operations to lower-emission alternatives. For example, steel production would increase by about 10 percent relative to today, but with low-emissions steel rising from one-quarter of all production to almost all production by 2050. In the agriculture and food system, the dietary shifts necessary for a net-zero transition would, over time and in the case of some consumers, move protein demand from emissions-intensive beef and lamb to lower-emissions foods like poultry.

In other areas, in particular those related to low-emissions energy sources, demand would grow.[10] Power demand in 2050 would be more than double what it is today. Production of both hydrogen and biofuels would increase more than tenfold between 2021 and 2050.[11] Other industries, such as those that manage carbon with nature-based solutions or carbon capture and storage technologies, could also grow (see also discussion later on opportunities from the transition). For example, forestry and other land use would contribute to sequestering approximately nine metric gigatons of CO_2 by the middle of the century.

Capital allocation: About $275 trillion of cumulative spending on physical assets would be needed through 2050 under the NGFS Net Zero 2050 scenario

Shifts in demand during the net-zero transition would trigger the retirement or transformation of some existing physical assets and the acquisition of new ones. Our analysis suggests that these moves would influence spending on physical assets in two ways. First, spending would increase significantly relative to today. Second, a portion of the capital that is now being spent on high-emissions assets would be spent on low-emissions assets, including those with CCS installed.[12]

Our analysis of the NGFS Net Zero 2050 scenario suggests that about $275 trillion in cumulative spending on physical assets, or approximately $9.2 trillion per year, would be needed between 2021 and 2050 across the sectors that we studied (Exhibit E5).[13]

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[10] Increased energy access relative to today and growing population and incomes globally would also drive some of the increase described here.

[11] For hydrogen, this excludes captive production for industrial end uses such as refineries and chemicals.

[12] Our analysis divides high-emissions assets from low-emissions assets and enabling infrastructure. Low-emissions assets have a relatively low emissions footprint; the term does not always mean carbon neutral. This segmentation was done to allow us to size the scale of capital reallocation needed for the net-zero transition. In doing so, we recognize that the demarcation between high and low emissions is not always clear. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, geothermal, biomass, gas with CCS, and nuclear power along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using EAF, DRI with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or fossil fuel kilns with CCS; zero-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass, including heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; land restoration.

[13] Based on analysis of systems that account for about 85 percent of overall GHG emissions today. This estimation includes spend for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (for example, for vehicles and alternate methods of steel and cement production), and various forms of land use (for example, GHG-efficient farming practices). This includes both what is typically considered investment in national accounts and spend, in some cases, on consumer durables such as personal cars. We typically consider spending to replace physical assets at the point of emissions (for example, cars for mobility); additional spending would also occur through the value chain. We have not sized this, to minimize double counting.

Exhibit E4

The NGFS Net Zero 2050 scenario entails a transformation of energy and land-use systems. (1 of 2)

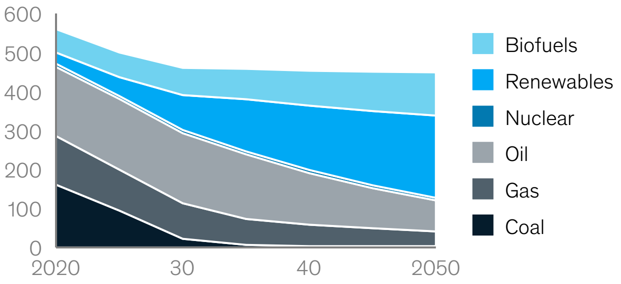
Not exhaustive

Activity level trajectory, 2020–50[1]

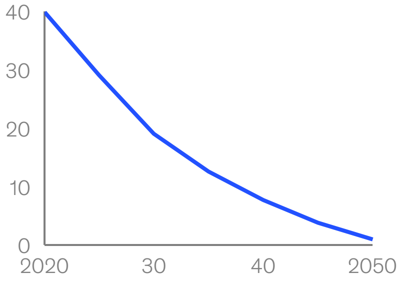
Emissions trajectory, 2020–50[1]

Overall

Primary energy, Exajoule

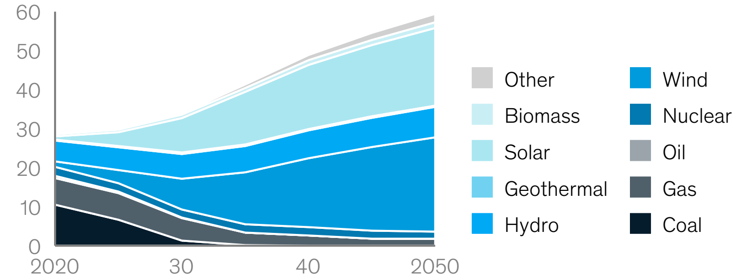


Global CO_2 emissions, billion metric tons[2]

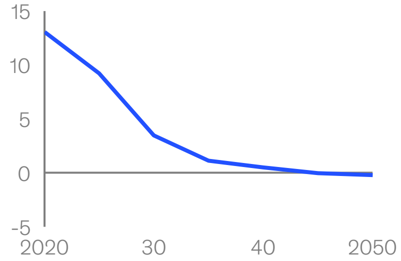


Power

Electricity generation by source, Peta-Watt hours

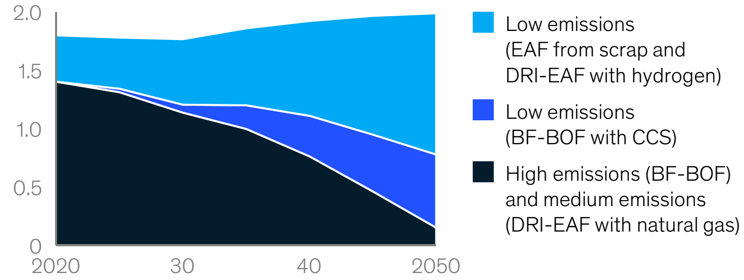


Electricity generation CO_2 emissions, billion metric tons

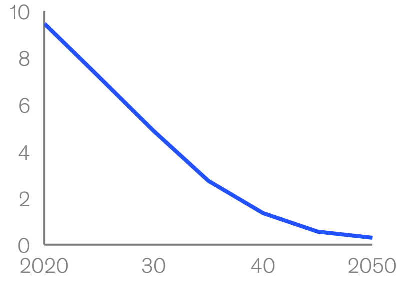


Industry:
Steel

Steel production, billion metric tons

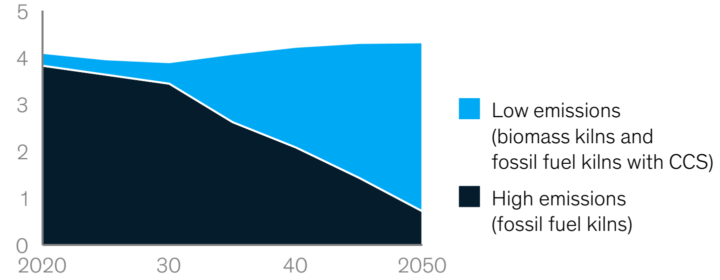


Industrial process and energy demand, CO_2 emissions, billion metric tons[3]



Industry:
Cement

Cement production, billion metric tons



1. Based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE. In some instances, variables were downscaled by Vivid Economics. This represents global activity levels and emissions. In the Net Zero 2050 scenario, different systems reach zero emissions at different times.
2. The overall trajectory of CO_2 emissions will be influenced in large part by the trajectory and mix of primary energy use. However, other factors, for example rates of afforestation and deforestation as well as industrial processes, will also play a role.
3. Emissions for the entire industry system, not only for cement and steel.

Source: NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2); Vivid Economics; McKinsey Sustainability Insights; McKinsey Global Institute analysis

Exhibit E4 (continued)

The NGFS Net Zero 2050 scenario entails a transformation of energy and land-use systems. (2 of 2)

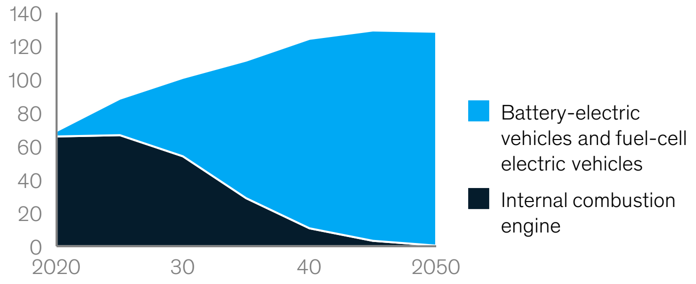
Not exhaustive

Activity level trajectory, 2020–50[1]

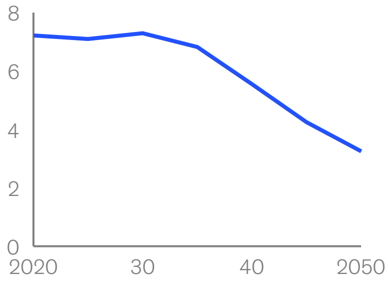
Emissions trajectory, 2020–50[1]

Mobility

Total new passenger cars sold per year, million

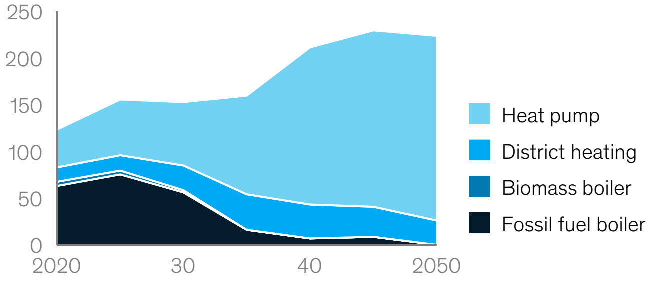


Transportation CO_2 emissions, billion metric tons[2]

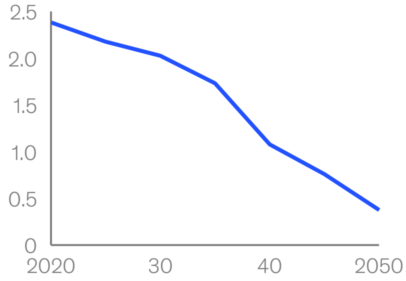


Buildings

Total heating systems sold per year, million

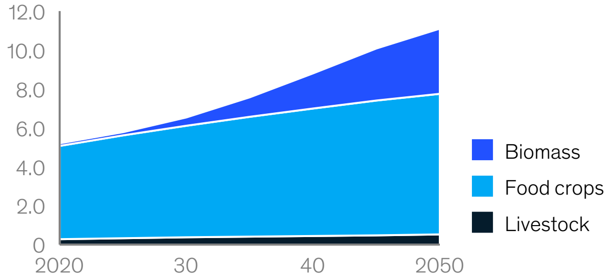


Buildings CO_2 emissions, billion metric tons

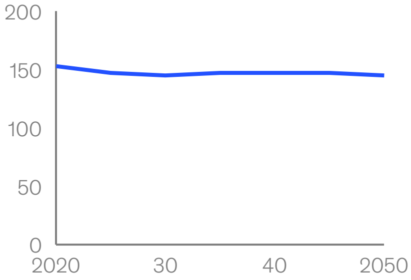


Agriculture

Agriculture production, %, billion metric tons dry matter

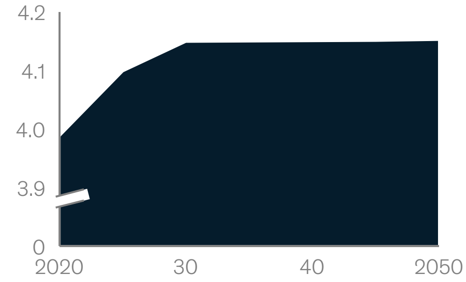


Agriculture, forestry, and other land use (AFOLU) methane emissions, million metric tons[3]

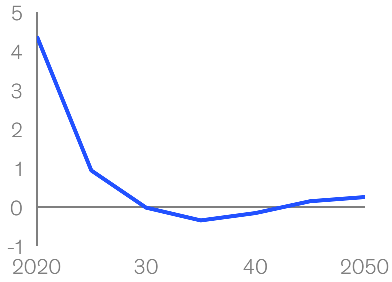


Forestry and other land use

Forest cover, billion hectares



AFOLU CO_2 emissions, billion metric tons[4]



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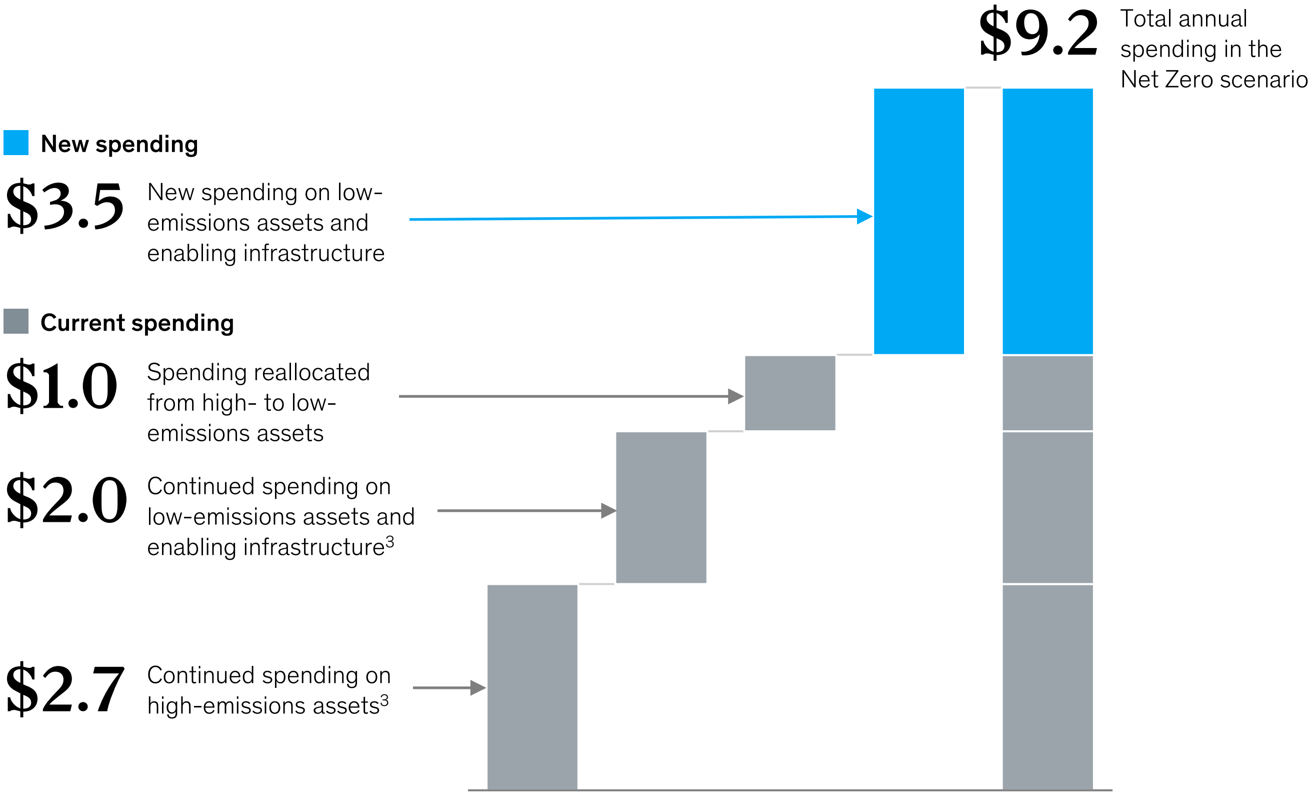
1. Based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE. In some instances, variables were downscaled by Vivid Economics. This represents global activity levels and emissions. In the Net Zero 2050 scenario, different systems reach zero emissions at different times.
2. Includes road transportation, aviation, freight, and rail.
3. Methane emissions from agriculture, forestry, and other land use are mostly influenced by agriculture, but they also include a small amount of emissions from forestry and other land use.
4. Carbon dioxide emissions are mostly influenced by forestry and other land use, but they also include a small amount of emissions from agriculture. Afforestation contributes to cumulatively sequestering approximately nine metric gigatons of carbon dioxide by 2050 in the NGFS Net Zero scenario.

Source: NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2); Vivid Economics; McKinsey Sustainability Insights; McKinsey Global Institute analysis

Exhibit E5

Spending on physical assets for energy and land-use systems in the NGFS Net Zero 2050 scenario would rise to about $9.2 trillion annually, or about $3.5 trillion more than today.

Annual spending on physical assets for energy and land-use systems[1] **in the Net Zero 2050 scenario,**[2] **average 2021–50,** $ trillion



1. We have sized the total spending on physical assets in power, mobility, fossil fuels, biofuels, hydrogen, heat, CCS (not including storage), buildings, industry (steel and cement), agriculture, and forestry. Estimation includes spend for physical assets across various forms of energy supply (eg, power systems, hydrogen, and biofuel supply), energy demand (eg, for vehicles, alternate methods of steel and cement production), and various forms of land use (eg, GHG-efficient farming practices).
2. Based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall CO_2 emissions today. Spend estimates are higher than others in the literature because we have included spend on high-carbon technologies, agriculture, and other land use, and taken a more expansive view of the spending required in end-use sectors.
3. Our analysis divides high-emissions assets from low-emissions assets. High-emissions assets include assets for fossil fuel extraction and refining, as well as fossil fuel power production assets without CCS; fossil fuel heat production, gray-hydrogen production; steel BOF; cement fossil fuel kilns; ICE vehicles; fossil fuel heating and cooking equipment; dairy, monogastric, and ruminant meat production. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, geothermal, biomass, gas with CCS, and nuclear power along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using EAF, DRI with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or fossil fuel kilns with CCS; low-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass, including heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; and land restoration.

Source: McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

This represents spending related specifically to the deployment of new physical assets and to the decarbonization of existing assets. It does not include spending to support other adjustments—for example, to reskill and redeploy workers, compensate for stranded assets, or account for the loss of value pools in specific parts of the economy. Spending could also be higher than sized here, for example, in order to build redundancy into energy systems during the transition to avoid supply volatility. Other research to date that has sized investment needs for the transition has largely focused on estimating required energy investment. Here we expand this to include additional spending categories.[14] As a result, our estimates exceed to a meaningful degree the $3 trillion to $4.5 trillion of annual spending for the net-zero transition that others have estimated.[15]

The amount of cumulative spending is equivalent to about 7.5 percent of GDP from 2021 to 2050. The required spending would be front-loaded, rising from about 6.8 percent of GDP today to about 9 percent of GDP between 2026 and 2030 before falling. In dollar terms, the increase in annual spending is about $3.5 trillion per year, or 60 percent, more than is being spent today, all of which would be spent in the future on low-emissions assets. This incremental spending would be worth about 2.8 percent of global GDP between 2020 and 2050. To put this in comparable terms, the increase is approximately equivalent, in 2020, to half of global corporate profits, one-quarter of total tax revenue, 15 percent of gross fixed capital formation, and 7 percent of household spending.

The second aspect, the reallocation of spending, would also be significant. At present, $3.7 trillion—or 65 percent of total spending—goes annually toward high-emissions assets, such as coal-fired power plants and vehicles with internal combustion engines. In this net-zero scenario, about $1 trillion of today's spend on high-emissions assets would need to be reallocated to low-emissions assets. Of the overall $9.2 trillion needed annually for a net-zero transition over the next 30 years, $6.5 trillion—or 70 percent of total spending—would be on low-emissions assets, reversing today's trend. Three sector groups—mobility, power, and buildings—would account for approximately 75 percent of the total spending on physical assets in this net-zero scenario (see the next section for a detailed discussion of spending needed by sector).

> **Our estimates exceed to a meaningful degree the $3 trillion to $4.5 trillion of annual spending for the net-zero transition that others have estimated.**

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[14] We broadened the analysis to include a more comprehensive view of spending by households and businesses on assets that use energy (for example, the full cost of passenger cars and heat pumps), capital expenditures in agriculture and forestry, and some continued spend in high-emissions physical assets like fossil fuel–based vehicles and power assets.

[15] See *Net Zero by 2050: A roadmap for the global energy sector,* IEA, 2021; *NGFS climate scenarios for central banks and supervisors,* NGFS, 2021; Christoph Bertram et al., "Energy system developments and investments in the decisive decade for the Paris Agreement goals," *Environmental Research Letters,* volume 16, number 7, June 2021; David McCollum et al.,"Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals," *Nature Energy,* volume 3, June 2018; *Making mission possible: Delivering a net-zero economy,* Energy Transitions Commission, September 2020; and *Better growth, better climate: The new climate economy report,* The Global Commission on the Economy and Climate, 2014.

If we consider the likely evolution of this spending given population growth, GDP growth, and current momentum toward the net-zero transition, the capital outlay would be smaller but remain significant. If we take as a basis the NGFS Current Policies scenario—which accounts for expected income and population growth, as well as currently legislated policies and expected cost reductions in key low-emissions technologies—the incremental annual spend in a net-zero scenario would be about $0.9 trillion rather than the $3.5 trillion increase noted above (Exhibit E6).[16] Approximately 50 percent of the $8.3 trillion in annual spending in the Current Policies scenario would be on low-emissions assets, which highlights that already some shift to low-emission spending is anticipated in this scenario from existing technological trends and policies today.

The transition could also lead to asset stranding, whereby existing physical assets are either underutilized or retired before the end of their useful life. In the context of the net-zero transition, the capital stock associated with fossil fuels and emissions is worth many trillions of dollars, a significant share of the total global capital stock—and even more capital stock depends indirectly on these assets.

Stranding large portions of this capital stock in a disorderly or abrupt way could impede value generation in many industrial sectors and indeed the global economy and would therefore need to be carefully managed. In power alone, for example, we estimate that some $2.1 trillion worth of assets could be stranded by 2050. About 80 percent of these stranded assets would pertain to fossil fuel–based power plants in operation today, primarily coal-fired plants in countries such as China and India that are relatively new (less than 15 years old) and would normally have many more years of productive life.[17]

Moreover, many assets that could be stranded are capitalized on the balance sheets of listed companies. Early retirement of these assets would potentially lead to the reduction of (currently perceived) value and to bankruptcies and credit defaults, with potential knock-on effects on the global financial system. And markets may well pronounce their verdict before the actual stranding has taken place. Unsurprisingly, then, the possibility of asset stranding has prompted concerns about financial-sector risk and the need to build the capabilities to quantify and manage it.[18]

While the scale of the capital that would need to be deployed in a net-zero transition is substantial, it is important to put it in context. First and foremost, as we discuss later, the economic adjustments involved in reaching net zero in a coordinated and orderly manner would prevent the further buildup of physical risks and the additional costs arising from a more disorderly transition. Second, in the long run, the up-front capital expenditures for a net-zero transition could result in operating savings for some sectors through reduced fuel consumption, improved material and energy efficiency, and lower maintenance costs.

The up-front capital expenditures for a net-zero transition could result in operating savings for some sectors in the long run.

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[16] The NGFS Current Policies scenario projects the greenhouse gas emissions that would occur if only today's policies remained in place, and it anticipates about 3°C of warming by 2100. See Box E1 and the technical appendix.

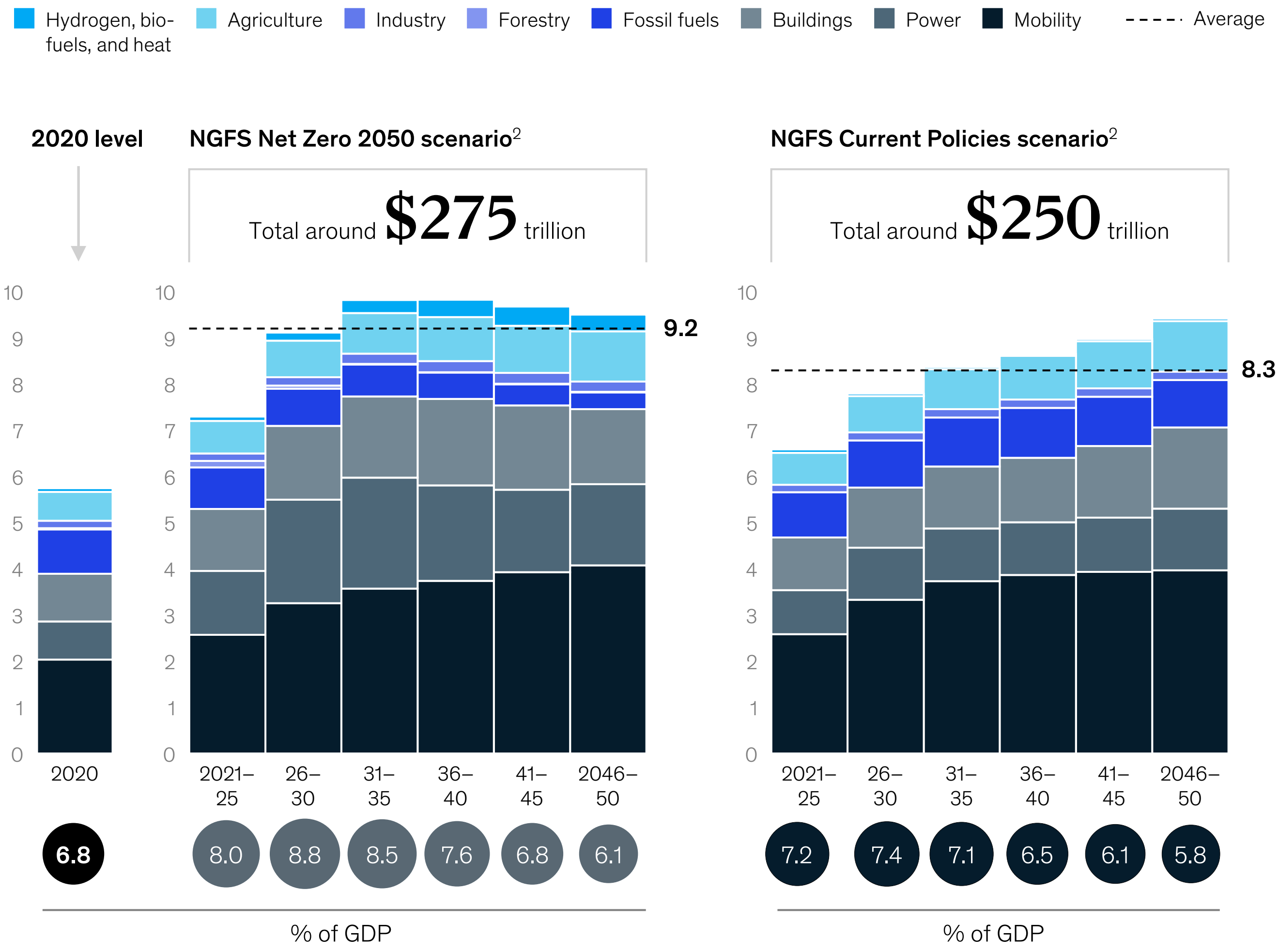
[17] Our definition of stranded assets represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years. Other research has found similar effects on the power sector, and other sectors. See, for example, *Stranded assets and renewables: How the energy transition affects the value of energy reserves, buildings and capital stock,* International Renewable Energy Agency, 2017; David Nelson et al., *Moving to a low-carbon economy: The impact of policy pathways on fossil fuel asset values,* Climate Policy Initiative, October 2014; and Jean-Francois Mercure et al., "Reframing incentives for climate policy action," *Nature Energy,* November 2021.

[18] See, for example, David Nelson et al., *Moving to a low-carbon economy: The impact of policy pathways on fossil fuel asset values,* Climate Policy Initiative, October 2014.

Exhibit E6

The NGFS Net Zero 2050 scenario would entail around $275 trillion in cumulative investments over 30 years—around $25 trillion more than the Current Policies scenario.

Annual spend on physical assets for energy and land-use systems,[1] $ trillion per year



1. We have sized the total spending on physical assets in power, mobility, fossil fuels, biofuels, hydrogen, heat, CCS (not including storage), buildings, industry (steel and cement), agriculture, and forestry. Estimation includes spend for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (for example, for vehicles, alternate methods of steel and cement production), and various forms of land use (for example, GHG-efficient farming practices). This includes both what are typically considered "investments" in national accounts and spend, in some cases, on consumer durables such as personal cars. Annual average over 5-year periods.
2. Scenario based on the Network for Greening the Financial System Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Current policies is based on the NGFS Current Policies scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall CO_2e emissions today. Our analysis includes a more comprehensive view of spending by households and businesses on assets that use energy, capital expenditures in agriculture and forestry, and some continued spend in high-emissions physical assets. See technical appendix.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

It is also important to recognize that capital spending is not merely a cost. Much of this investment is already cost-effective and comes with a return. For example, research analyzing other net-zero scenarios has found that about 40–50 percent of spending can come with a positive investment case.[19]

Various challenges will need to be managed in the short run to achieve such outcomes. They include raising capital and securing financing at this scale, managing technological uncertainty of investment, considering risk/return trade-offs, and driving capital flows to both developed and developing countries. Raising and deploying capital could be more challenging for specific sectors and geographies.

Capital spending is not merely a cost: much of this investment is already cost-effective and comes with a return.

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[19] McKinsey research finds that about half of the required investments to reach net-zero emissions in Europe have a positive investment case. This means that switching to the relevant low-emissions technology would represent a cost saving at the cost of capital for each sector and segment. See Paolo D'Aprile, Hauke Engel, Godart van Gend, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020. The IEA also examined the actions required to be taken by consumers in the IEA Net Zero 2050 scenario such as switching to low-emissions vehicles. They find that 40 percent would result in overall cost savings relative to an Announced Polices scenario where governments follow through on their climate targets and commitments. See *World economic outlook,* IEA, 2021. On the macroeconomic level, higher levels of public and private investment could provide economic stimulus, leading to negligible net negative impacts, or even modest net positive impacts, on GDP growth (though as discussed, much depends on how the transition is financed and managed). For example, the European Commission found in conducting an impact assessment for proposed 2030 net-zero-aligned emissions targets for the European Union that raising policy ambition would result in a cumulative impact of between -0.7 percent and +0.55 percent on GDP by 2030 compared to a baseline forecast. See *Impact assessment: Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people,* Commission Staff Working Document SWD/2020/176, September 2020.

Costs: Steel, cement, and power would see cost increases in the Net Zero 2050 scenario, due to shifts in production processes and capital expenditures, while total cost of ownership of EVs would fall

The transition's financial implications reach beyond spending on physical assets. Production costs, which reflect changing operating costs as well as capital costs for new investment and asset depreciation, would also shift as processes are changed and high-emissions assets are replaced or retrofitted. And any changes in production costs could possibly affect the costs of consumer goods, if costs are passed through. We examine these effects in turn.

In the steel and cement sectors, production costs, including operating costs, capital charges, and depreciation, could rise by about 30 percent and 45 percent, respectively, from their current levels, though continued innovation could lower these estimates. In the power sector, our analysis indicates that the global average delivered cost of electricity across generation, transmission, distribution, and storage would increase before falling from their peak, in the scenario modeled here. The impact would be front-loaded: costs would increase by about 25 percent by 2040, including operating costs, capital costs, and depreciation of new and existing assets, from 2020 levels (Exhibit E7). This is for two main reasons: firstly, investments will be needed in building renewables and grid and storage capacity, creating capital costs and depreciation charges. Secondly, some fossil-based power assets would continue to incur capital costs, even if they are underutilized or retired prematurely.[20] This analysis represents a global average perspective. The picture could look different across regions depending on the current state of the power system, the availability of natural resources like sunshine and wind, and the age of fossil power fleets, among other factors. It is conceivable that innovation and economies of scale could drive down capital and grid spending. Delivered cost of electricity in the first half of the century could then be lower than anticipated in the scenario.

On the other hand, impacts could be significantly higher than those sized here (though it is important to note that costs as sized here are not the same as consumer electricity prices). Various factors could contribute to this, including potential grid intermittency issues as renewable assets are scaled up, shortage of fossil fuel–based capacity to serve peak loads and provide backup for renewables, and shortage of coal and gas inputs for fossil fuel power plants, to name a few. The potential impacts of such outages would be even greater with electricity being used more extensively across the economy than today under a net-zero transition, for example for heating, mobility, and industry. If the shift from high-emissions fossil fuel–based power assets and the ramp-up of low-emissions assets that replace them is not well managed, this could increase both energy prices and volatility and there could be challenges with reliable power. (See Box E5, "How rising energy prices can create risk.")

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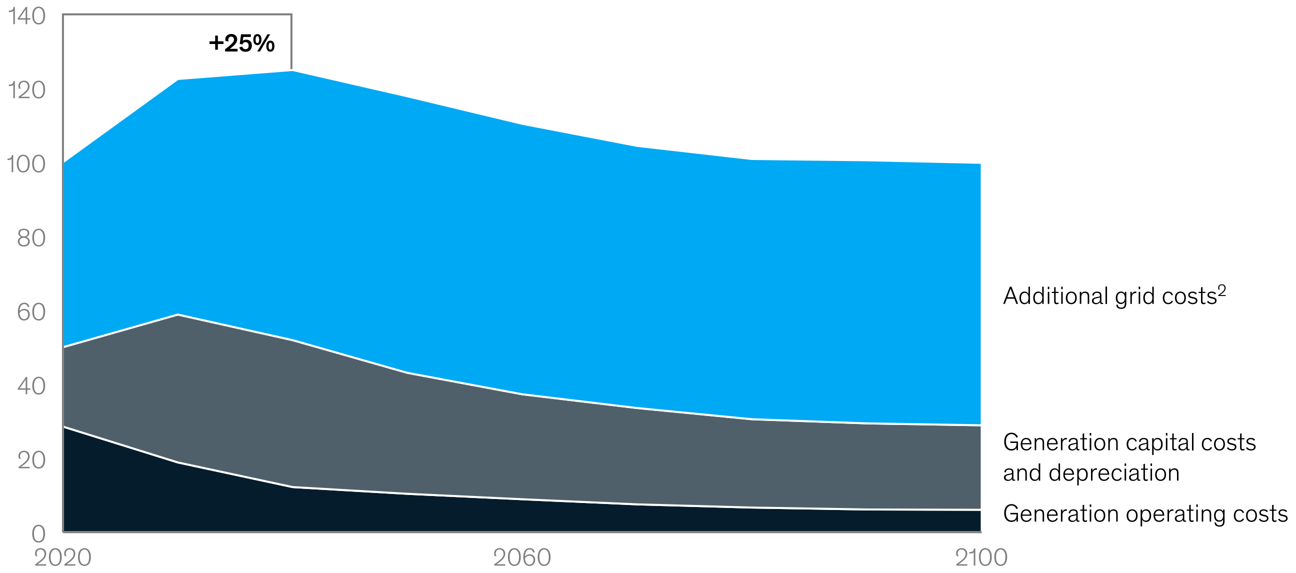
[20] To assess cost changes for power, we first quantified the change in three main cost drivers: power generation capital charge and depreciation (at a weighted average cost of capital of 6.5 percent), power generation operating costs, and transmission, distribution, and storage investments. These were then translated into a delivered cost of electricity by dividing by electricity production in each time period. This metric indicates how the underlying costs are changing for the entire power sector. Our methodology is broader than other studies focused on the levelized cost of energy for new assets which often highlight the competitive cost position of renewables in the power mix. Our analysis also takes into account infrastructure spending on grids, capital charges, and depreciation of legacy assets even if they are prematurely retired or underutilized. See also Rupert Way et al., *Empirically grounded technology forecasts and the energy transition,* Institute for New Economic Thinking Oxford, working paper number 2021-01, September 2021. Note that our metric is different from the actual cost paid by consumers, and eventual energy prices for consumers could look substantially different. Consumer electricity prices depend on a multitude of factors, including decisions on how the power system transformation is paid for and over what time frame. For example, a key question is how to best manage coal generation decommissioning and write-down costs. Moreover not all expected changes in delivered costs are due to decarbonization. For instance, some transmission and distribution investments would happen regardless, as countries increase electricity access. This analysis does not take into account short-term variations in supply and demand, subsidies, or taxes.

Exhibit E7

Global average delivered cost of electricity in the NGFS Net Zero 2050 scenario would rise in the short run and then fall back from its peak.

Delivered cost of electricity,[1] $ per MWh, index (100 = 2020), NGFS Net Zero 2050 scenario, global average



1. This metric represents a full system cost for power, across generation, transmission, and storage. It includes operating costs, capital costs, and depreciation. To assess cost changes for power, we first quantified the change in three main cost drivers: power generation capital charge (at a weighted average cost of capital of 6.5 percent), power generation operating costs, and transmission, distribution and storage investments. These were then translated into the delivered cost of electricity by dividing by electricity production in each time period. This metric indicates how the underlying costs are changing for the power sector and is not the same as consumer electricity prices. The trends described here are global averages and would vary across regions.
2. Transmission and distribution plus storage.

Source: Network for Greening the Financial System scenario analysis 2021 phase 2 (Net Zero 2050 scenario) REMIND-MAgPIE (phase 2) model; Vivid Economics; World Resources Institute Power Plant Database; McKinsey Power Solutions; McKinsey Global Institute analysis

In the scenario modeled here, costs would subsequently decrease from the 2040 peak; for example, by 2050, operating costs for generation could drop by more than 60 percent relative to 2020 as the energy mix shifts to renewables. Some of the reduction in operating and other costs for generation would be offset by an increase in the operating and other costs associated with grid flexibility, transmission, and distribution. As a result, delivered cost of electricity in this scenario would still be about 20 percent higher in 2050 than 2020 levels. In the long run, there is more uncertainty about how delivered cost of electricity could evolve, and costs could at some point be lower than 2020 levels, depending on innovations to power technologies, grid design, and evolution of the power system to manage flexibility issues.

Other sectors could see overall cost decreases. A key example of this is mobility. Our analysis suggests that the total cost of ownership for electric cars could be cheaper than ICE cars in most regions by 2025, as we describe in more detail below.[21] Medium-duty BEV trucks covering 200–300 km a day are expected to reach total cost parity with ICEs by around 2025, with heavy-duty long-haul trucks reaching parity by 2030 in Europe and later in other regions.

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[21] Total cost of ownership accounts for purchase price, operating costs, for instance fuel and maintenance costs, and resale value; based on three years of ownership of a new car.

Box E5

How rising energy prices can create risk

Global energy prices surged in the third quarter of 2021, providing a glimpse of the speed with which market imbalances can feed through to consumers and prompt swift government reactions including subsidies to low-income households.

Natural gas price benchmarks in Europe and Asia were ten times higher in October 2021 than one year prior, while US month-ahead natural gas prices reached their highest level since 2008. International coal prices were also sharply higher, at five times their fall 2020 levels.[1] Rising primary fuel prices sparked large increases in consumer electricity prices in Germany, Spain, and elsewhere in Europe. In the United States, gasoline pump prices of $3.50 per gallon were the highest in seven years.[2] Deteriorating margins for energy providers and electricity-intensive industries such as fertilizer production forced several companies to curtail operations.[3]

Energy prices are already a highly critical topic given the centrality of energy to consumers and economic activity—even under normal circumstances. For example, according to the European Commission, 31 million Europeans live in energy poverty and are unable to adequately heat their homes.[4] To help alleviate price rises, India, Japan, South Korea, the United Kingdom, and the United States announced in November 2021 they would be tapping into their respective strategic oil reserves.[5] Some governments also initiated subsidy programs. These included the US making available a $4 billion budget for the Low Income Energy Assistance Program, providing aid to more than five million families.[6] Italy and Spain capped home energy bills and redirected utility company profits to subsidize low-income households and small enterprises.[7]

A confluence of factors led to the price fluctuations, including a rebound in consumer activity as lockdowns related to the COVID-19 pandemic eased along with persistent labor and supply chain shortages. In some instances, weather events exacerbated the situation, including low wind speeds in the North Sea, a cold snap in Texas that led to a gas production shut-in, drought in Brazil that depleted hydropower reservoir levels to 25 percent below their five-year average, and flooding of Chinese coal mines that exacerbated shortages driven in part by the recent freeze on coal imports from Australia.[8]

Such events, while not directly attributed to a net-zero transition, nonetheless shine a light on supply chain and grid vulnerabilities. In doing so, they can serve as a cautionary preview of potential future energy market volatility that can be triggered by rapid simultaneous shifts on the supply and demand sides of the global energy and materials landscape.
For example, as reliance on renewables grows and investment in fossil fuel–based power generation declines, tight supply for raw material inputs for technologies like solar panels and batteries may compound energy price volatility given long lead times in the capital-intensive mining sector. As the world acts on net-zero pledges, periods of energy price volatility like those in the last months of 2021, among others, thus serve as a reminder of the importance of careful transition management.

Exposure to these risks would also increase with electrification as a key pillar of the transition. Power outages, whether due to the energy mix, weather or operator error, would have far-reaching consequences where households and businesses are depending on a reliable source of electricity for day-to-day needs such as heating, cooling, appliances, vehicles, and industrial applications. As the mix of the power system shifts to renewables in the net-zero transition we have analyzed here, various factors could influence the delivered cost of electricity, and also electricity prices for consumers. First, as already noted, the delivered cost of electricity would initially rise in the Net Zero 2050 scenario as power generation assets are replaced and transmission, distribution, and storage capacity is built. Increases in these costs could even be higher than calculated here, with implications for prices and with more volatility, for the various reasons discussed previously. Second, storage and transmission costs, which constitute a substantial portion of the cost of electricity, could feed through to consumers in an uneven way, with some paying more while others experience savings. This will depend in part on a range of localized factors including existing transmission and distribution capacity and the need for long duration storage. Finally, market design could be an important factor: as the power system changes, power markets may need to change with it. Today, power is sold through the spot market, in which prices are set according to production costs of the marginal power producer, and through bilateral purchase agreements between power producers and consumers. Capacity markets have historically accounted for a relatively small share of power sales, but they may play a larger role in the future to fully compensate flexible producers that help balance the grid. New market mechanisms may be needed to encourage some marginal fossil fuel power producers to decommission their plants earlier. Key questions remain about how this would be paid for, and also how cost increases, if any, would affect end consumers.

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[1] Carlos Fernández Alvarez and Gergely Molnar, "What is behind soaring energy prices and what happens next?" International Energy Agency, October 2021.

[2] US retail gasoline price data, all grades, all formulations, US Energy Information Administration.

[3] Carlos Fernández Alvarez and Gergely Molnar, "What is behind soaring energy prices and what happens next?" International Energy Agency, October 2021.

[4] *State of the energy union 2021*, European Commission, October 2021.

[5] Zolan Kanno-Youngs, Stanley Reed and Jim Tankersley, "The United States and other world powers will tap oil reserves," *New York Times,* November 23, 2021.

[6] *Biden administration deploys American Rescue Plan funds to protect Americans from rising home heating costs; calls on utility companies to prevent shut offs this winter,* White House Fact Sheet, November 18, 2021.

[7] "Italy sets aside more than 3 bln euros to curb energy bills," Reuters, September 23, 2021; "Spain targets energy firms as European bills surge," BBC News, September 14, 2021.

[8] Joe Wallace, "Energy prices in Europe hit records after wind stops blowing," *Wall Street Journal,* September 13, 2021. Carlos Fernández Alvarez and Gergely Molnar, "What is behind soaring energy prices and what happens next?" International Energy Agency, October 2021.

Consumers would face additional up-front capital costs and may need to spend more in the near term on electricity if cost increases are passed through; lower-income households everywhere are naturally more at risk

The net-zero transition could also affect consumer spending. Consumers may face higher prices and up-front capital costs in the near term and may need to adjust their spending if significant emissions reductions are to be achieved, although the extent of the impact could vary depending on the composition of consumers' spending baskets and whether companies pass on costs, among other factors.[22] Low-income households are particularly at risk. Over time, all consumers could see some benefits.

First, consumers' spending habits may be affected by decarbonization efforts. For example, they may need to replace goods that burn fossil fuels, like transportation vehicles and home heating systems that rely on fossil fuels, and potentially modify diets to reduce beef and lamb consumption.

Second, any rise in electricity prices would affect consumers, particularly lower-income consumers, whose spend on energy makes up a large share of wallet. However, this depends on how cost recovery is allocated among consumers, up to and including the extent any increases in delivered cost of electricity are passed through to end consumers.

Third, consumers would incur up-front capital costs related in particular to the mobility and buildings transition. For example, as ICE vehicles are phased out, households would shift spending to EVs, which cost more than comparable ICE cars because of their large batteries. Even though, in the long term, consumers could benefit over the life of the asset—for example, because of the lower total cost of ownership for EVs or savings from energy efficiency measures in homes. McKinsey analysis suggests that the total cost to own an EV, which takes into account purchase price, maintenance, fuel cost, and resale value, would be cheaper than an ICE car in most regions by 2025. For example, the total cost of ownership for battery-electric cars in Europe may be cheaper compared to that of ICEs by 2025, and the United States by 2030.[23] A faster decline in battery prices or local subsidies could accelerate this break-even point. Even so, the higher up-front costs may prove challenging for lower-income households. Food costs are one area where consumer costs could fall if the dietary shifts required to decarbonize the agriculture and food sectors manifest—that is, if eating habits move away from emissions-intensive and higher-cost ruminant protein like beef and lamb to other forms of protein like poultry.[24]

Finally, higher production costs could also affect the price of consumer goods and services in other areas. Higher costs for low-emissions shipping could be passed on to the consumer for goods shipped internationally; however, the extent to which this will flow through to higher costs for consumers will likely be country- and product-specific.[25] Likewise, rising costs in hard-to-abate sectors such as steel and cement could raise the cost of end products, though this will depend on the fraction of the cost of these materials in final goods and services.[26] All of these could be addressed through a range of compensating mechanisms to ease the transition.

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[22] A comprehensive accounting of the effects on consumers would be complex, since effects vary based on such factors as a consumer's spending basket, whether companies pass through any additional operating or capital costs, and the transition's effect on government revenues and subsidies. Effects on consumers are likely to vary by region. For example, developing countries could have a higher proportion of their total spend basket affected by the climate transition, due to higher spending on energy. Individuals' incomes could also be affected by shifts in livelihood or any changes in taxation as a result of the transition.

[23] McKinsey Center for Future Mobility Electrification Model (2021), price benchmarks in key markets.

[24] Derek Headey and Harold Alderman, "The relative calorific prices of healthy and unhealthy foods differ systematically across income levels and continents," *Journal of Nutrition,* volume 149, issue 11, November 2019.

[25] For example, research has highlighted that the cost of jeans may only rise by 1 percent but this might vary for other product types. See *Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness,* Hydrogen Council and McKinsey & Company, February 2021.

[26] See Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel, "The zero-carbon car: Abating material emissions is next on the agenda," McKinsey & Company, September 2020.

Jobs: The net-zero transition analyzed here could lead to a reallocation of labor, with about 200 million direct and indirect jobs gained and 185 million lost by 2050

Our analysis of the NGFS Net Zero 2050 scenario suggests that the transition could result in an increase in demand for about 162 million direct and indirect jobs (referred to as “job gains”) and a decrease in demand for about 152 million direct and indirect jobs (referred to as “job losses”) in operations and maintenance by 2050 across different sectors of the economy. In addition, about 41 million jobs could be gained and 35 million lost related to direct and indirect jobs associated with spending on physical assets needed for the net-zero transition by 2050 (Exhibit E8).[27] Jobs in the latter category, linked to shifts in capital spending, are likely to be more transitory than those in the former, related to operations and maintenance, as discussed below. Together, this results in 202 million direct and indirect jobs gained and 187 million lost by 2050, as a result of the net-zero transition modeled here. When considering job losses and gains here, we only consider those which are directly attributable to the net-zero transition, rather than other factors like income or population growth. The effect on jobs would be especially notable not so much for its overall size in terms of net losses or gains as for its concentrated, uneven, and re-allocative nature.

The size of the job dislocation in the scenario analyzed here needs to be put in perspective with job dislocations from other trends. For example, previous research by the McKinsey Global Institute suggests that automation, remote work, and e-commerce trends could lead to job losses of about 270 million to 340 million across eight countries between 2018 and 2030, with commensurate job gains—considerably more than our estimates for net-zero transition-related job losses and gains globally.[28]

One notable characteristic in our analysis of the job losses and gains during the net-zero transition would be their concentration in specific sectors and geographic regions. Job gains would be largely associated with the transition to low-emissions forms of production, for example to renewable-power production, while the losses would particularly affect workers in fossil fuel–intensive or otherwise emissions-intensive sectors, a significant reallocation of jobs across the economy. In the NGFS Net Zero 2050 scenario, demand for direct operations and maintenance jobs in the fossil fuel extraction and production sector and the fossil fuel–based power sector could be lower by about nine million and about four million jobs, respectively—equivalent to about 70 percent and 60 percent of today’s workforce in those respective sectors, due to the net-zero transition. Jobs in the agriculture and food sectors could also be reallocated as demand for animal protein is affected under a net-zero transition. About 34 million direct jobs, mainly in livestock and feed-related jobs, could be lost by 2050, including 19 million in ruminant meat farming. These could be partially offset by a gain of 12 million direct jobs, including for example ten million in poultry farming.

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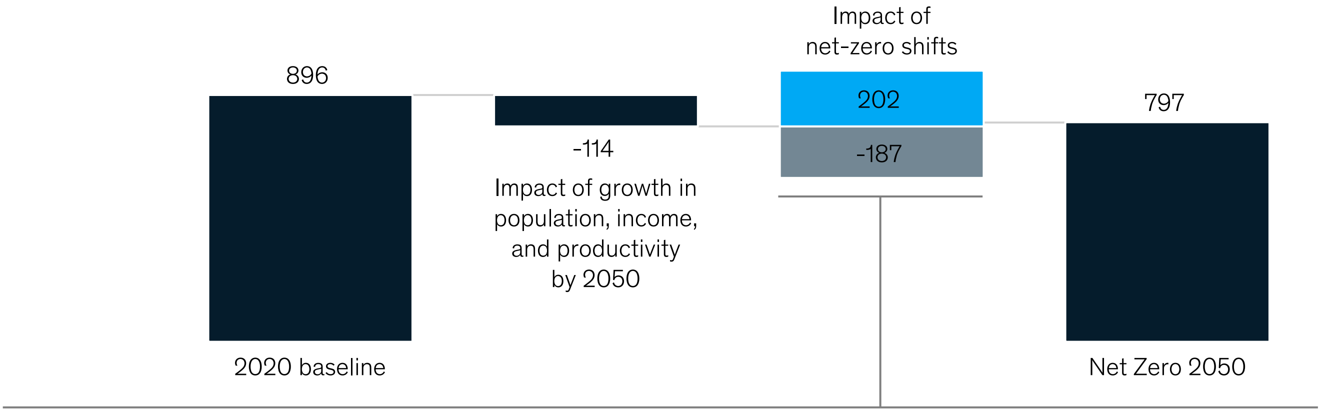
[27] By “direct” jobs we mean jobs in the specified sector, as opposed to “indirect” jobs, which refers to the upstream jobs that produce inputs for production in the sector. Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar and wind power driving increases in solar and wind power jobs and decreases in coal and gas power jobs). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. Job losses and gains could in reality manifest as job shifts. Our methodology does not account for any higher order impacts and assumes an orderly transition, for example, without constraints created from financing the transition. For further details, see technical appendix.

[28] For more information, see *The future of work after COVID-19,* McKinsey Global Institute, February 2021. It is important to note that other factors could influence the job numbers presented here, potentially leading to greater reallocations. These include whether the transition is orderly or disorderly, whether financing for the transition limits investment in other parts of the economy, and fiscal and monetary policy decisions, which we do not model.

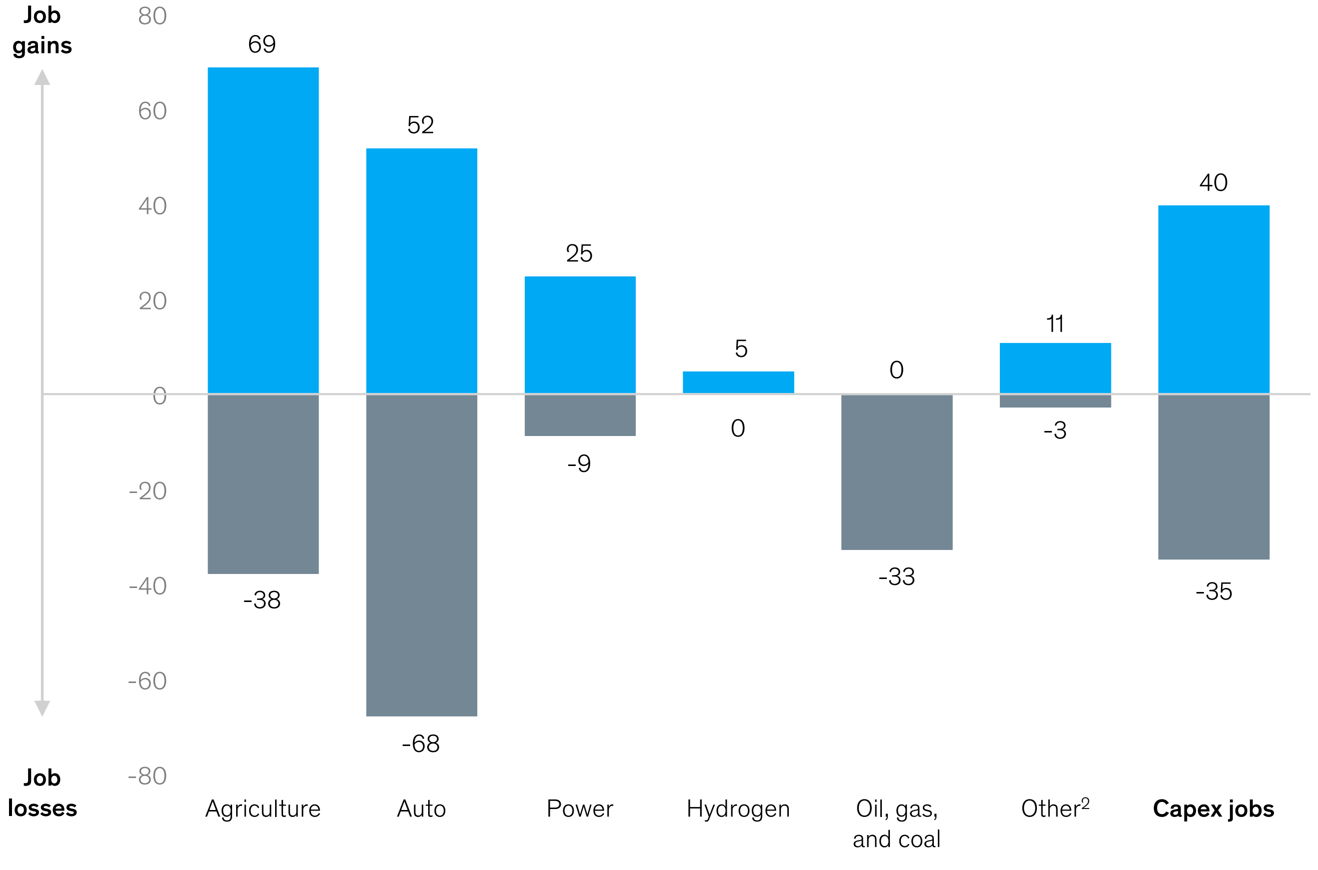
Exhibit E8

In the NGFS Net Zero 2050 scenario, about 200 million direct and indirect jobs could be gained and 185 million lost by 2050.

Total job shifts, direct and indirect, by 2050, million[1]



Total job shifts by sector,[1] direct and indirect, by 2050, million



1. Includes all direct and indirect jobs; based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall emissions today; a job is counted as a gross loss or a gain if it involves a shift in sector or subsector for a worker (indicating a changing job function), or geography of an existing job. Operations and maintenance jobs consist of those related to the operations and maintenance activities in the sector (direct jobs), and their supply chains (indirect jobs). Capex jobs are those arising from capital investment in the sector, associated with manufacturing and construction (direct jobs), and their supply chains (indirect jobs), and are not included in the 2020 baseline number. While calculating indirect jobs, we include upstream jobs from all other sectors of the economy such as financial services, wholesale trade, retail trade, transportation, etc, but exclude a set of sectors for which we have done bottom-up calculations, including: Agriculture, forestry and fishing, mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. Impacts of a net-zero transition consist of job losses and gains directly associated with the transition, and do not include other macroeconomic forces like population or income growth. See technical appendix.
2. Other comprises mineral, forestry, cement, carbon abatement, steel, and biofuels.

Note: Figures may not sum to total because of rounding.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

Low-emissions sectors, by contrast, would likely see job gains. For example, the renewable power sector could see an increase in demand for approximately six million direct operations and maintenance jobs by 2050 driven by the net-zero transition. As mentioned above, job gains could also occur as a result of capital outlays, particularly during the earlier years of the transition. In construction, manufacturing, and other industries associated with the build-out of low-emissions physical assets, net job gains (job gains minus job losses) could be as high as about 37 million by 2030 and could still be about five million by 2050 (which further emphasizes the potential transitory nature of these jobs). The transition might also create still more jobs, as past diffusion of new technologies has done.[29]

One notable characteristic in our analysis of the job losses and gains during the net-zero transition would be their concentration in specific sectors and geographic regions.

Job losses that affect entire sectors or subsectors and those that are geographically concentrated in specific communities or regions will create particular needs for economic and societal adjustments during the transition.[30] For example, in 44 US counties, more than 10 percent of the workforce is employed in the coal, oil, and gas extraction, mining, and refining sectors, the fossil fuel–based power sector, and the automotive sector (Exhibit E9). Similarly, automotive production is a relatively large share of employment in Germany, Japan, Mexico, and South Korea (see also discussion later on how countries are exposed to the net-zero transition and could benefit from transition opportunities).

Disruptions would be substantially higher under a more disorderly transition

How the transition is managed will be decisive. The effects described here reflect the NGFS Net Zero 2050 scenario, in which gradual yet substantial reductions in emissions take place, resulting in a relatively orderly transition. However, the complexity of the transformation may well lead to the reality being more disorderly, and indeed it may not be feasible to limit warming levels to 1.5°C. This makes the case for action even more critical.

The key risks are threefold: the first concerns the choice of pathway to arrive at net-zero emissions, and whether this will be smooth or abrupt. The second relates to the measures taken by stakeholders to ease the adjustments needed for a net-zero transition. The third has to do with a range of constraints that could prove challenging even if the pathway chosen is a relatively smooth and gradual one.

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[29] One study found that 0.56 percent of new jobs in the United States each year are in entirely new occupations that did not previously exist. See Jeffrey Lin, "Technological adaptation, cities, and new work," *Review of Economics and Statistics,* volume 93, number 2, May 2011. See also *Jobs lost, jobs gained: What the future of work will mean for jobs, skills, and wages,* McKinsey Global Institute, December 2017.

[30] As an example, analysis by McKinsey & Company in collaboration with the Greater Houston Partnership finds that Houston could lose up to 650,000 jobs by 2050 under a 1.5°C pathway, if no action is taken to respond to the changing energy landscape. However, with decisive action to lead in the energy transition, Houston could gain up to 560,000 additional jobs. For further details, see *Houston: Leading the transition to a low-carbon world,* Greater Houston Partnership, June 2021.

Exhibit E9

More than 10 percent of the employment in 44 US counties is in coal mining, oil and gas extraction and refining, fossil-based power, and automotive manufacturing.

Low ▨ High

▨ Counties[1] with >10% of county employment in the examined sector

Coal mining

	% of	
County	County employment	Sector employment
McDowell, WV	18	3
Buchanan, VA	18	5
Boone, WV	16	3
Campbell, WY	15	17
Greene, PA	14	8
Mingo, WV	13	3
Wyoming, WV	11	2
Harlan, KY	8	2
Leslie, KY	8	1
Logan, WV	8	4
Knott, KY	7	1
Perry, KY	6	3
Pike, KY	6	5
Raleigh, WV	6	8
Letcher, KY	6	1
Bell, KY	4	1
Nicholas, WV	3	1
Somerset, PA	3	3
Floyd, KY	3	1
Wise, VA	3	1

Oil and gas extraction

	% of	
County	County employment	Sector employment
Upton, TX	41	0
Irion, TX	34	0
Dunn, ND	26	0
Hutchinson, TX	25	1
Reagan, TX	25	0
Hemphill, TX	22	0
Sterling, TX	20	0
Crockett, TX	16	0
Midland, TX	15	7
Winkler, TX	15	0
Woods, OK	14	0
Duchesne, UT	14	0
Burke, ND	14	0
Woodson, KS	12	0
Stephens, TX	12	0
Eddy, NM	11	2
Crane, TX	11	0
Richland, MT	10	0
Mountrail, ND	9	0
Lincoln, WY	9	0

Fossil-based power

	% of	
County	County employment	Sector employment
Stewart, TN	11	4
Indiana, PA	2	8
Dunklin, MO	1	1
Imperial, CA	1	6
Berkeley, SC	1	4
Sumner, TN	0	3
Schuylkill, PA	0	2
Anderson, TN	0	2
Oswego, NY	0	1
Cambria, PA	0	1
Clermont, OH	0	1
Northampton, PA	0	2
Darlington, SC	0	0
Colbert, AL	0	0
Madison, IL	0	1
Delaware, PA	0	3
Hamilton, OH	0	6
Lancaster, NE	0	2
Prince, MD	0	3
Dearborn, IN	0	0

Automotive manufacturing

	% of	
County	County employment	Sector employment
Clay, IL	31	0
DeKalb, TN	27	0
Crenshaw, AL	26	0
Washington, KY	26	0
Elkhart, IN	25	7
Howard, IN	25	2
LaGrange, IN	21	1
Marion, KY	18	0
Noble, IN	17	1
Madison, OH	15	1
Marshall, OK	15	0
Giles, TN	13	0
Champaign, OH	13	0
Shelby, OH	12	1
Calhoun, MI	11	1
Perry, IN	11	0
Nelson, KY	10	0
Tishomingo, MS	10	0
Gibson, IN	9	0
Shelby, KY	9	0

1. Top 20 US counties by % local employment in coal mining, oil and gas extraction and refining, fossil-based power, and automotive manufacturing. Based on an analysis of 3,273 counties and county equivalents (parishes, census area, municipalities) across the United States, Puerto Rico, and Virgin Islands.

Source: US Bureau of Labor Statistics

Some pathways to net-zero emissions assume that the decline in emissions begins immediately and progresses gradually to 2050, with appropriate measures in place to manage disruptions and limit costs. Others assume that reduction of emissions begins later and progresses more quickly to achieve the same amount of cumulative emissions. The latter could involve significant and abrupt changes in policy, high carbon prices, and sudden changes to investment practices—along with greater socioeconomic effects and a larger-scale response.[31] Making job transitions would be more challenging, and there could be greater risk of stranded assets.

Second, if actions are not taken to manage transition disruptions, this could lead to more challenges, especially for vulnerable communities—for example, if rises in energy costs are passed through to low-income households, or if displaced workers are not provided appropriate support to reskill and redeploy.

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[31] See also *Inevitable Policy Response 2021: Policy Forecast,* Principles for Responsible Investment, March 2021.

Finally, even if the pathway chosen is relatively orderly, given the scale of the transformation required, supply may not be able to scale up sufficiently, making shortages and price increases or volatility a feature. Rapidly scaling up demand for low-emissions assets and other products needed for the transition, without corresponding scale-up of supply, could lead to supply/demand imbalances, shortages, price increases, and inflation.[32] As already noted, a mismatch or mistiming between the ramping down of high-emissions activities and the ramping up of low-emissions activities could create energy price volatility and issues with reliability that could potentially result in a backlash that delays the transition. Another risk is that stakeholders maintain two parallel energy systems in a manner that is inefficient and not cost effective. Thus the transformation of the energy system needs to be carefully managed. And there may be other constraints, including accessing the volume of financing required in the initial phases of the transition when many of the investments would be front-loaded.

There could also be other costs incurred and investment needed beyond those mentioned in this report, for example related to the reskilling of workers, or economic diversification efforts. A key area where additional spend would be needed is related to adaptation investments. Adaptation action is needed to manage a continually increasing level of physical risk, irrespective of the decarbonization measures required to achieve net-zero emissions. Key adaptation measures include actions to protect people and assets, for example installing "gray" infrastructure such as sea walls, building resilience and backups in systems with actions like increasing global inventories and diversifying supply chains, and reducing exposure where necessary, for example by relocating assets from regions.

To illustrate the difference between transition pathways, we analyzed two NGFS scenarios consistent with limiting warming to less than 2.0°C from preindustrial levels. In the "Below-2°C scenario," where emissions reductions start immediately on a pathway to 2.0°C of warming, our analysis suggests that only a relatively small amount of additional coal power capacity is added, about $150 billion between 2020 and 2050. Of this, $100 billion would be prematurely retired or underutilized. But in the scenario where emissions reductions toward 2.0°C warming start later, a substantially larger amount of capacity would be added; as much as $600 billion would be invested in coal-power capacity, with as much as $400 billion prematurely retired or underutilized.

Perhaps the greatest risk from delaying emissions reductions is physical climate risk. The longer it takes to initiate emissions reduction, the more of the world's remaining carbon budget would be used up—leaving less time to cut emissions and increasing the risk that warming is not restricted to 1.5°C or even 2.0°C.

While significant, these economic adjustments would create growth opportunities and prevent further buildup of physical risk

The changing demand outlook combined with the $3.5 trillion in incremental annual spending on physical assets in the NGFS Net Zero 2050 scenario, noted above, would create substantial growth opportunities for companies and countries in the near term. We describe the opportunities for countries later in this summary. The opportunities for companies are in the three main areas described below.

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[32] For example, see "The raw materials challenge: How the metals and mining sector will be at the core of enabling the energy transition," McKinsey & Company, January 2022. The research describes a scenario based on the current pipeline of projects and without measures to incentivize further supply, in which copper and nickel demand in 2030 could exceed supply by 5 million to 8 million and 700,000 to one million metric tons, respectively. See also 2022 *global outlook: Thriving in a new market regime,* Blackrock Investment Institute, 2022.

Decarbonized forms of legacy products and processes: Companies that reduce the emissions intensity of their processes and products could gain advantages as the transition progresses. In some cases, decarbonizing processes and products can make them more cost-effective. For example, improving the energy efficiency of heating systems in steel plants lowers both emissions and operating costs. Even when decarbonizing adds to operating costs, companies can benefit from taking this step—for instance, if consumers are willing to pay more for low-carbon products or if companies are subject to carbon-pricing mandates.

Low-emissions products and processes that replace established high-emissions options: Carmakers might produce EVs instead of ICE vehicles, for example. Steelmakers can implement low-carbon production processes such as direct reduced iron–electric arc furnaces (DRI-EAF) powered by green hydrogen.[33] Utilities might set up wind or solar farms to generate renewable electricity, while energy companies could introduce biofuels and hydrogen.

Inputs, physical capital, infrastructure, and support services: New offerings will be needed to support production in the other two categories. These offerings include inputs such as lithium and cobalt for battery manufacturing, physical capital such as solar panels and batteries, and infrastructure such as EV charging stations and hydrogen refueling stations.[34] Technical services such as forest management, engineering and design, and power-system integration will help with the management of low-carbon assets. Services such as financing, risk management, certification, emissions measurement and tracking solutions, and worker training will also be needed.

The incremental capital spending on physical assets, which we estimate at about 3 percent of GDP annually through 2050, as discussed previously, and the broader economic transformations under a net-zero transition would have another essential feature: most importantly, reaching net-zero emissions and limiting warming to 1.5°C would prevent the buildup of physical risks and reduce the odds of initiating the most catastrophic impacts of climate change, including limiting the risk of biotic feedback loops and preserving the ability to halt additional warming.[35]

Rapidly scaling up demand for low-emissions assets and other products needed for the transition, without corresponding scale-up of supply, could lead to supply shortages and price increases.

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[33] DRI is produced from the chemical reduction of iron ore into iron by either a reducing gas or elemental carbon produced from natural gas or coal, which can be used as an input, along with high-grade steel scrap, in the EAF method of steel production. Steel production in integrated blast furnaces or basic oxygen furnaces today uses iron ore and requires coal as a reductant. See Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey & Company, June 2020.

[34] For example, see "The raw materials challenge: How the metals and mining sector will be at the core of enabling the energy transition," McKinsey & Company, January 2022. The research finds that requirement for additional supply will come not only from relatively large-volume raw materials—for example, copper for electrification and nickel for battery EVs, which are expected to see significant demand growth beyond their current applications—but also from relatively niche commodities, such as lithium and cobalt for batteries, tellurium for solar panels, and neodymium for the permanent magnets used both in wind power generation and EVs. Some commodities—most notably steel—will also play an enabling role across technologies, as additional infrastructure is needed.

[35] See Box E3 in the executive summary, chapter 1, and the bibliography for a detailed list of the academic literature and broader discussion related to physical climate risks.

Sectors are unevenly exposed to the transition; those with high-emissions products or operations would be especially affected

We find that, while all sectors of the economy are exposed to a net-zero transition because of their participation in energy and land-use systems, some are more exposed than others. The sectors with the highest degree of exposure directly emit significant quantities of greenhouse gases (for example, the coal and gas power sector) or sell products that emit greenhouse gases (such as the fossil fuel sector). Approximately 20 percent of global GDP is in these sectors. A further 10 percent of GDP is in sectors with high-emissions supply chains, such as construction. Other sectors accounting for about 70 percent of GDP have less pronounced direct exposure. They are nevertheless dependent on the highly exposed sectors, for example through interconnected economic and financial systems, and therefore could be affected by the transition.

In this section, we describe the economic shifts for some of the most affected sectors. Together they account for about 85 percent of global GHG emissions through their operations or products, and we present our analysis of the economic changes they would likely experience in the Net Zero 2050 scenario.[36]

Fossil fuels. As noted earlier, combustion of fossil fuels produces 83 percent of global CO_2 emissions. The sector is seeking to decarbonize its own emissions through energy efficiency, electrification, and managing fugitive methane emissions.[37] At the same time, it faces significant demand shifts from potential shifts in the energy mix under a net-zero transition, with a reduction in demand for fossil fuels and growing demand for other energy sources such as electricity, hydrogen, and biofuels. In the scenario analyzed here, oil and gas production volumes in 2050 would be 55 percent and 70 percent lower, respectively, than today. Coal production for energy use would be nearly eliminated. Under the net-zero transition, demand for jobs within the fossil fuel extraction and production sector could be lower by about nine million direct jobs by 2050. In response, McKinsey research suggests that a number of oil and gas companies are adapting to the low-carbon transition by becoming resource specialists, becoming diversified energy players, or turning themselves into low-carbon pure plays.[38]

Power. To decarbonize, the global power sector would need to phase out fossil fuel–based generation and add capacity for low-emissions power to meet the additional demand arising from both economic development and the growing electrification of other sectors. It would require substantial annual capital spending from 2021 to 2050, which we estimate at about $1 trillion in power generation, $820 billion in the power grid, and $120 billion in energy storage in the NGFS Net Zero 2050 scenario. Opportunities would arise not only for power producers but also for providers of equipment, electricity-storage hardware, and related services. Our analysis suggests that by 2050, under a net-zero transition, approximately six million direct jobs could be added in operations and maintenance for renewable power and approximately four million direct jobs could be

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[36] We estimate how much exposure these sectors have to the transition by measuring their direct emissions (scope 1 emissions, which indicate exposure to potential demand shifts, investment needs, and cost changes from having to alter production processes), emissions from products (downstream scope 3, which may affect demand, for example, if consumers shift their preferences, and in turn also affect the capital investments made by the sector and its costs), supply chain emissions (upstream scope 3, which may expose the sector to cost shifts as its core inputs are affected by the transition), and emissions from purchased electricity (scope 2 for electricity use, which could indirectly expose the sector to the effects of changes in the world's energy mix).

[37] See Paul Gargett, Stephen Hall, and Jayanti Kar, "Toward a net-zero future: Decarbonizing upstream oil and gas operations," McKinsey & Company, December 2019.

[38] Chantal Beck, Donatela Bellone, Stephen Hall, Jayanti Kar, and Dara Olufon, "The big choices for oil and gas in navigating the energy transition," McKinsey & Company, March 2021.

lost in fossil fuel–based power. The build-out of power infrastructure and the capital spending associated with the net-zero transition could produce as many as 27 million direct jobs in the early years of the transition, and about 16 million direct jobs associated with construction and manufacturing activity in 2050. Asset stranding could be large. Our analysis suggests that about $2.1 trillion of the sector's capital stock could be stranded by 2050 in the Net Zero 2050 scenario.[39] Eighty percent of this amount is today's capacity, while 20 percent is capacity that would be built between 2021 and 2050.[40]

Mobility. Our analysis of mobility focuses on the road transportation segment, which accounts for about 75 percent of all mobility emissions.[41] Decarbonization would involve replacing ICE vehicles with battery-electric vehicles or vehicles powered by hydrogen fuel cells. In the Net Zero 2050 scenario, annual spending would be $3.5 trillion on both vehicles and to build charging and fueling infrastructure between 2021 and 2050. About 13 million direct ICE-related jobs would be lost in the Net Zero 2050 scenario, although some of this loss would be offset by gains of about nine million direct jobs related to EV manufacturing by 2050 with the difference between losses and gains driven in large part by the relatively higher productivity of zero-emissions vehicle manufacturing.

Industry. We focus on two sectors, steel and cement, that together account for approximately 14 percent of global CO_2 emissions and 47 percent of industry's CO_2 emissions.[42] While technology pathways are still emerging, steel and cement production could be decarbonized by installing CCS equipment or switching to processes or fuels—such as hydrogen—that can have zero or low emissions. Production costs in both sectors could increase by more than 30 percent by 2050 compared with today, though this could be lower with continued innovation.

Buildings. In the net-zero scenario, the buildings sector would decarbonize by improving energy efficiency—for example, through the use of insulation—and by replacing fossil fuel–powered heating and cooking equipment with low-emissions systems. The average annual spending on physical assets between 2020 and 2050 would be $1.7 trillion per year. Decarbonization of buildings could result in a net gain of about half a million direct jobs by 2050 under a net-zero transition, driven by retrofitting buildings with insulation. The buildings sector's biggest adjustment during this transition would be managing the up-front capital costs for end consumers to retrofit equipment and aligning incentives across various stakeholders (such as building owners who invest capital and tenants who may see the benefits of reduced operating costs).[43]

Agriculture and food. In the net-zero scenario analyzed here, agricultural emissions would be reduced as a result of producers deploying GHG-efficient farming practices, and some consumers shifting their diets away from ruminant animals that generate significant quantities of methane.[44] The scenario would also entail an increase in production of

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[39] Our definition of stranded assets represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years.

[40] For more on the power sector, see Jason Finkelstein, David Frankel, and Jesse Noffsinger, "How to decarbonize global power systems," McKinsey & Company, May 2020; and Rory Clune, Ksenia Kaladiouk, Jesse Noffsinger, and Humayun Tai, "A 2040 vision for the US power industry: Evaluating two decarbonization scenarios," McKinsey & Company, February 2020.

[41] EMIT database, McKinsey Sustainability Insights, September 2021; data for 2019. For more on the mobility sector, see "Why the automotive future is electric," McKinsey & Company, September 2021; Timo Moller, Asutosh Padhi, Dickon Pinner, and Andreas Tschiesner, "The future of mobility is at our doorstep," McKinsey Center for Future Mobility, December 2019; and Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yuksel, "The zero-carbon car: Abating material emissions is next on the agenda," McKinsey & Company, September 2020.

[42] EMIT database, McKinsey Sustainability Insights, September 2021; data for 2019. For more details on decarbonization of the steel sector, see Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey & Company, June 2020. For cement, see Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020; and Thomas Hundertmark, Sebastian Reiter, and Patrick Schulze, "Green growth avenues in the cement ecosystem," McKinsey & Company, December 2021.

[43] For more on the building sector, see Paolo D'Aprile, Hauke Engel, Godart van Gend, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020.

[44] Agricultural practices are also tied to forestry emissions, as much of deforestation is driven by expansion of agricultural land. See discussion on forestry elsewhere in the report.

energy crops to produce biofuels. As a result of these shifts, the net-zero transition would result in about 34 million direct jobs lost (predominately due to diminished production of ruminant meat) and 61 million gained (related in large part to increased production of energy crops and poultry) by 2050. This net gain of about 27 million direct jobs due to the transition is about 4 percent of the 720 million or so direct agriculture jobs today. These job shifts need to be considered against a long-standing trend in the agricultural sector of workers shifting to nonfarm work in addition to productivity, population, and income growth. Through 2050, more than $60 billion of annual capital spending would be needed to enable more emissions-efficient farming. Such investment need not all be new funds; repurposing existing subsidies and spending could cover a substantial amount of this cost.[45]

Forestry and other land use. This system contributes to an increase in CO_2 emissions today from land clearing and deforestation. Reaching net zero in this scenario would involve halting deforestation and accelerating efforts to restore forests and other natural environments to serve as a net sink of emissions. Making these changes would require capital spending of $40 billion per year between 2021 and 2050 in the scenario analyzed here, about 75 percent of which would be spent in the next decade, primarily on acquiring and protecting land. Reducing deforestation would also require managing adjustments to both commercial and subsistence-level farming activity (a substantial portion of deforestation is driven by expansion of agricultural land).[46] Opportunities for economic gain might come from voluntary carbon markets and industries based on ecosystem services.[47]

New energy sectors (hydrogen and biofuels). The expansion of low-emissions energy technologies will create opportunities. Expanding capacity and infrastructure for other low-carbon fuels would require additional capital spending of about $230 billion per year between 2021 and 2050, in the scenario analyzed here. We estimate that the hydrogen and biofuel sectors would create approximately two million direct jobs by 2050.

The transition would unevenly affect lower-income and fossil fuel resource–producing countries—and low-income consumers everywhere

Our in-depth analysis of 69 countries focuses on four areas that can collectively help define a climate agenda: decarbonization actions and investment; managing transition exposures; capturing transition opportunities; and addressing physical risks. As discussed previously, low-income households across countries and regions would be most affected by a net-zero transition. Moreover, our analysis suggests that while all countries face some exposure to the transition, its effects would be unevenly distributed. Regions with lower GDP per capita and those with greater fossil fuel resources would need to invest more, relative to GDP, to reduce their emissions, build a low-emissions economy, and support economic development.

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[45] For more information, see *Incentivizing food systems transformation,* World Economic Forum and McKinsey & Company, January 2020. For more on the agriculture and food sector, see Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, “Agriculture and climate change: Reducing emissions through improved farming practices,” McKinsey & Company, April 2020.

[46] *The state of the world’s forests 2020: Forests, biodiversity, and people,* FAO, 2020.

[47] See “Valuing nature conservation,” McKinsey & Company, September 2020.

These countries also have relatively greater shares of their jobs, GDP, and capital stock in sectors that would be most exposed to the transition. And some of them will face a double burden—being exposed both to the transition adjustments and to rising physical risks.[48] This could challenge progress on economic development goals in these regions, bolstering the case for global cooperation. At the same time, the transition could create potential for economic growth in many geographies.

To better understand exposure and opportunities, we take a closer look at the 69 countries in our sample by dividing them into six archetypes based on the distribution of their most significant exposure across sectors and households.

To manage exposure, each country can consider taking actions of its own, such as investing in assets, funding worker-retraining programs, and supporting the growth of low-emissions sectors. Some countries are likely to face more difficult economic and societal adjustments than others. Collective action and solidarity would therefore help countries meet challenges and ensure that the economic and societal adjustments needed for the net-zero transition are addressed. Enabling institutions would likely play an essential role in coordinating any such efforts.

Developing countries and those with large fossil fuel sectors would likely spend more on physical assets, relative to GDP, on decarbonization and low-carbon growth

In the NGFS Net Zero 2050 scenario, every country and region would spend to reduce emissions and develop low-emissions energy sources to power their economic growth.[49] The need for capital expenditures varies considerably across geographies given differences in their economies, and their decarbonization trajectories vary in the NGFS Net Zero 2050 scenario.

The world's largest economies—the United States, China, the European Union, Japan, and the United Kingdom—would account for about half of global spend on physical assets and would spend about 6 percent of their combined GDP from 2021 to 2050. In developing regions, spend on energy and land would form a substantially larger share of national GDP: about 10 percent in sub-Saharan Africa, India and some other Asian countries, and Latin America (Exhibit E10).

For developing countries, higher projected rates of economic growth naturally create higher investment needs relative to GDP than in developed countries.[50] In our analysis of the NGFS Current Policies scenario, spending in India, sub-Saharan Africa, and Latin America would total more than 9 percent of GDP. Spending would increase to some extent from these levels in the net-zero scenario analyzed here. For example, in the Net Zero 2050 scenario, India's capital requirements would be 11 percent of GDP, compared to the global average of about 7.5 percent of GDP. It would moreover be spent differently than in the Current Policies case. Some 60 percent of annual average investments in India would be on low-emissions assets under current policies compared to 80 percent in the NGFS Net Zero 2050 scenario. Much of that capital would be used to reduce the use of existing coal power and expand low-emissions electricity capacity.

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[48] For example, India faces the double burden of transition exposure and elevated physical risks. Our previous research suggests that by 2030 in India, 160 million to 200 million people could be living in urban areas with a nonzero annual probability of experiencing a lethal heat wave, in a scenario where no adaptation or mitigation measures are implemented. *Will India get too hot to work?* McKinsey Global Institute, November 2020.

[49] Our analysis looks at both individual countries and multicountry regions because the NGFS scenarios provide some decarbonization trajectories at the regional level and others at the national level.

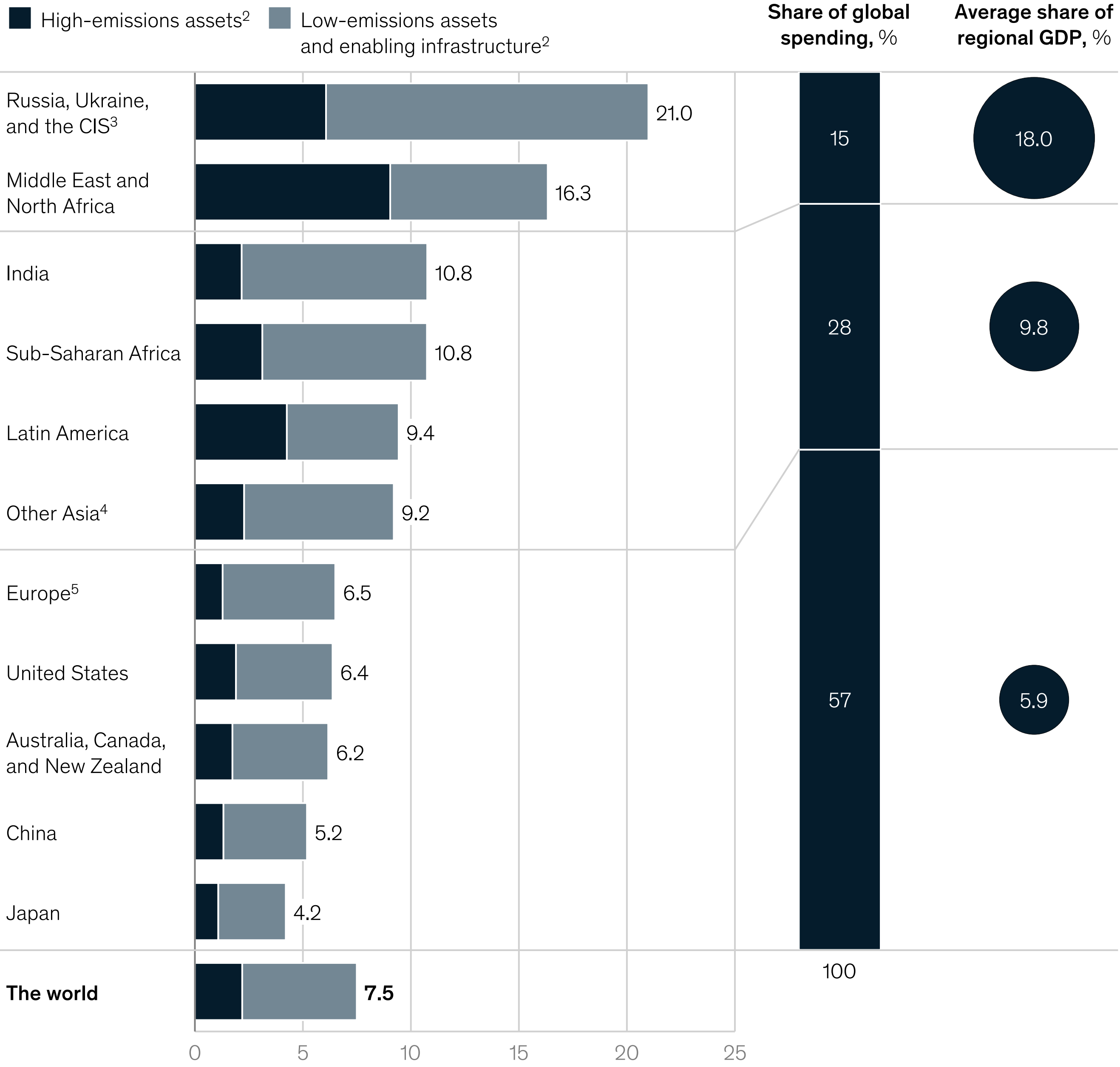
[50] Sub-Saharan Africa and India, for example, are expected to see real GDP growth of about 4–5 percent per year on average over the next 30 years, compared with 3 percent growth for China and 1–2 percent growth for developed regions in the NGFS scenario examined here.

Exhibit E10

As a percentage of GDP, fossil fuel–producing regions and developing countries would spend more than others on physical assets for energy and land-use systems.

Spending on physical assets for energy and land-use systems under NGFS Net Zero 2050 scenario,[1]

% of 2021–50 GDP



1. Estimation includes spend for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (eg, for vehicles), and land use. This includes both what are typically considered "investments" in national accounts and spend, in some cases, on consumer durables such as personal cars. Scenario based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall carbon dioxide equivalent (CO_2e) emissions today. Our analysis includes a more comprehensive view of spending by households and businesses on assets that use energy, capital expenditures in agriculture and forestry, and some continued spend in high-emissions physical assets like fossil fuel–based vehicles and power assets. For further details, see technical appendix.
2. Our analysis divides high-emissions assets from low-emissions assets. High-emissions assets include assets for fossil fuel extraction and refining, as well as fossil fuel power production assets without CCS; fossil fuel heat production, gray-hydrogen production; steel BOF; cement fossil fuel kilns; ICE vehicles; fossil fuel heating and cooking equipment; dairy, monogastric, and ruminant meat production. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, geothermal, biomass, gas with CCS, and nuclear power along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using EAF, DRI with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or fossil fuel kilns with CCS; low-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass, including heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; and land restoration. See technical appendix.
3. CIS refers to the Commonwealth of Independent States.
4. Includes, among others, South Korea and Southeast Asia.
5. Includes, among others, the 27 European Union countries, Norway, Switzerland, Turkey, and the United Kingdom.

Note: Figures may not sum to 100% because of rounding.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

Fossil fuel–based economies would also have substantial spend on physical assets as a share of their GDP: above 15 percent in the Middle East and North Africa, Russia, Ukraine, and Commonwealth of Independent States such as Kazakhstan. Much of this spending would be continued spending on fossil fuel assets in the near term. However, even these economies would allocate half or more of their spending to low-emissions assets under a net-zero transition.

While the relative scale of the spending on physical assets is substantially higher for developing and fossil fuel–based economies, this alone is not an indicator of how difficult it will be for these regions to reach a low-emissions economy. Indeed, as mentioned previously, much of this spend is to be expected as they grow their economies and increase energy access. However, specific aspects of their net-zero transition could make deploying capital challenging for these regions.

First, developing regions might face challenges in accessing capital markets. This may be particularly acute as they look to invest in low-emissions technologies, which may be harder to finance and come with different risk-return expectations. Second, as mentioned above, existing high-emissions assets in these economies are still relatively young; thus there may be less incentive to undertake low-carbon capital spending amid concerns about stranded assets. Third, there may not always be sufficient know-how and capacity on the ground to implement projects. Fourth, concerns of other socioeconomic consequences from a net-zero transition, for example, job dislocations, could exist. Finally, because the economies of these countries rely on emissions-intensive sectors, government tax revenues and public spending may be more constrained under a net-zero transition.[51]

Developing countries and fossil fuel–producing regions have relatively large exposure to the transition, raising concerns about growth and inequality

Beyond spending on decarbonizing their existing assets and building low-emissions assets, economies will also need to transform under a net-zero transition. We assessed each country's exposure to the transition by measuring the proportion of employment, economic production, and physical capital stock in exposed sectors today. It is important to note that current efforts undertaken by countries could reduce this exposure going forward.[52] According to our analysis, all countries now have some exposure to the transition—and, as discussed earlier, low-income households everywhere would be most exposed to any cost increases that feed through to consumers.

The highest levels of exposure are in countries with relatively lower GDP per capita, such as Bangladesh, India, and Kenya. These tend to be countries with relatively higher shares of jobs, GDP, and capital stock in sectors that are more exposed to the transition—which is to say, sectors with emissions-intensive operations, products, and supply chains (Exhibit E11). Significant fossil fuel resource production also creates high exposure for some countries, such as Qatar, Russia, and Saudi Arabia. Secondary effects from direct exposure could also extend to government tax revenues and exports, which are often linked with exposed sectors like fossil fuel extraction or steel (see Box E6, "Potential implications of the net-zero transition for trade flows"). By contrast, countries with higher GDP per capita tend to be less exposed because a majority of their economies are in service sectors, which have relatively lower exposure.

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[51] Similar conclusions were also reached by the IEA. See for example *Financing clean energy transitions in emerging and developing economies,* International Energy Agency, June 2021.

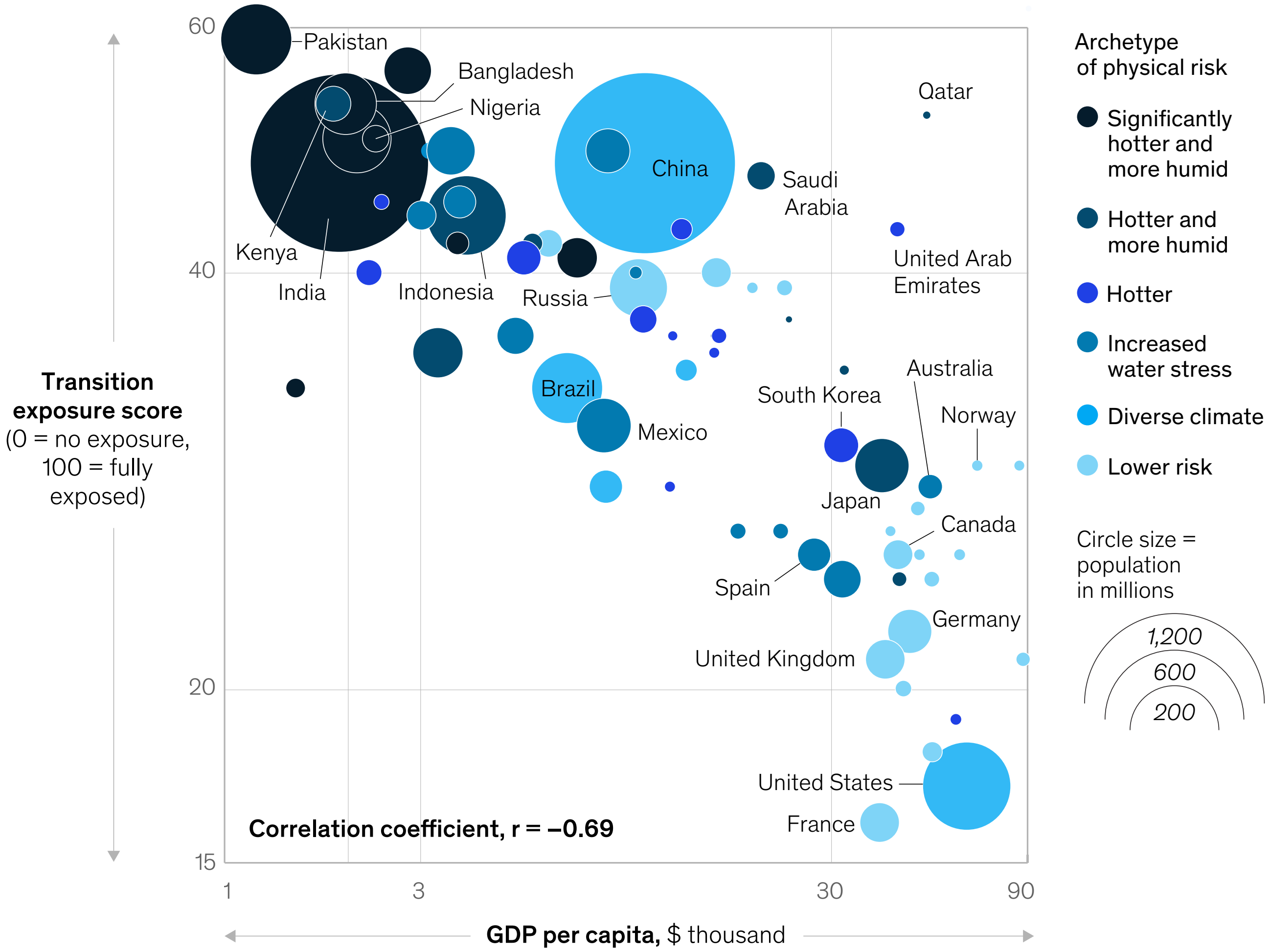
[52] To gauge each national economy's exposure to the transition, we calculated a score ranging from 0 (no exposure) to 100 (full exposure). The score reflects the share of each economy's employment (jobs), production activity (GDP), and capital stock in sectors that are most exposed to the effects of the transition—for example, sectors with high emissions in their operations, in the use of their products, or in their supply chains. For details, see chapter 4 and the technical appendix.

Thus, for many lower-income and fossil fuel–producing countries, challenges associated with climate change could compound. These countries would need to balance multiple imperatives: decarbonizing their economies and funding associated capital expenditures, managing exposure of large parts of their economies to a net-zero transition, and enabling economic development and growth, particularly by expanding access to affordable, secure energy. And, as noted earlier, these challenges will be aggravated for some lower-income countries by heightened physical climate risk, such as the growing probability of lethal heat waves in parts of India.[53] Inequity concerns would grow as an issue, particularly as developing economies argue that they have contributed less than others to emissions and yet are being asked to shoulder a large burden in the net-zero transition.

Exhibit E11

Countries with lower GDP per capita and fossil-fuel resource producers have higher transition exposures.

Archetype of physical risk[1] through transition exposure vs GDP per capita by country[2] (logarithmic scale)



1. For further details, see *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.
2. Based on average share of jobs, GDP, and capital stock in exposed sectors. These sectors are identified based on their scope 1, 2, and 3 emissions intensity. For further details, see technical appendix.

Source: Oxford Economics; OECD; ILO; World Input-Output Database; IHS Connect; World Bank; International Energy Agency; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; UN; International Renewable Energy Agency (IRENA); MINSTAT; INDSTAT; Global Solar Atlas; Global Wind Atlas; US Geological Survey; WEF; McKinsey Nature Analytics; McKinsey Global Institute analysis

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[53] *Will India get too hot to work?* McKinsey Global Institute, November 2020.

Box E6

Potential implications of the net-zero transition for trade flows

Value chains have grown in length and complexity in recent decades, and global trade has increased. Since 2000, the value of intermediate goods traded globally has tripled to more than $10 trillion annually.[1] Increasing production of goods for export tends to increase a country's own carbon emissions since most manufacturing still involves carbon-emitting processes or energy use. For example, other researchers have estimated that in some manufacturing sectors, such as chemicals, textiles, leather, and apparel, 30 to 65 percent of the emissions in China and India are induced by foreign final demand.[2] Another way to think about this phenomenon is to regard exported goods as having their production emissions embedded or embodied in them. A look at the emissions that are embodied in goods traded across borders reveals that considerable quantities of CO_2 are, in effect, moved internationally every year (Exhibit E12).

As demand for high-emissions goods falls and demand for low-emissions goods increases, trade flows might shift as countries' comparative advantages change. For example, shifts in consumer preferences or the presence of carbon taxes or other regulatory measures could produce advantages for countries that make products with low emissions intensity. Countries could also pursue opportunities to meet growing overseas demand for new kinds of low-emissions goods or emerging decarbonization technologies. In some cases, decarbonization could raise production costs, which could make exports from countries that take decarbonization action less competitive. All of these factors could result in shifting trade patterns in sectors such as electric vehicles, solar panels, and minerals, and they would need to be systematically addressed.

The outlook for global trade flows thus remains uncertain, and outcomes could depend on many factors, including how consumer preferences and regulation evolve and what opportunities different regions decide to pursue. In making strategic decisions, businesses may want to account for the ongoing discussion among countries of whether to implement border-adjustment taxes that price carbon emissions into the value of traded goods and account for developments in broader regulation, consumer preferences, and evolving markets. In some cases, markets may well go from global to local; for example, global energy markets for oil and gas could transform to more local or regional markets for power or hydrogen. For some countries, the net-zero transition could also provide opportunities to grow domestic industries and reduce imports of commodities like fossil fuels.

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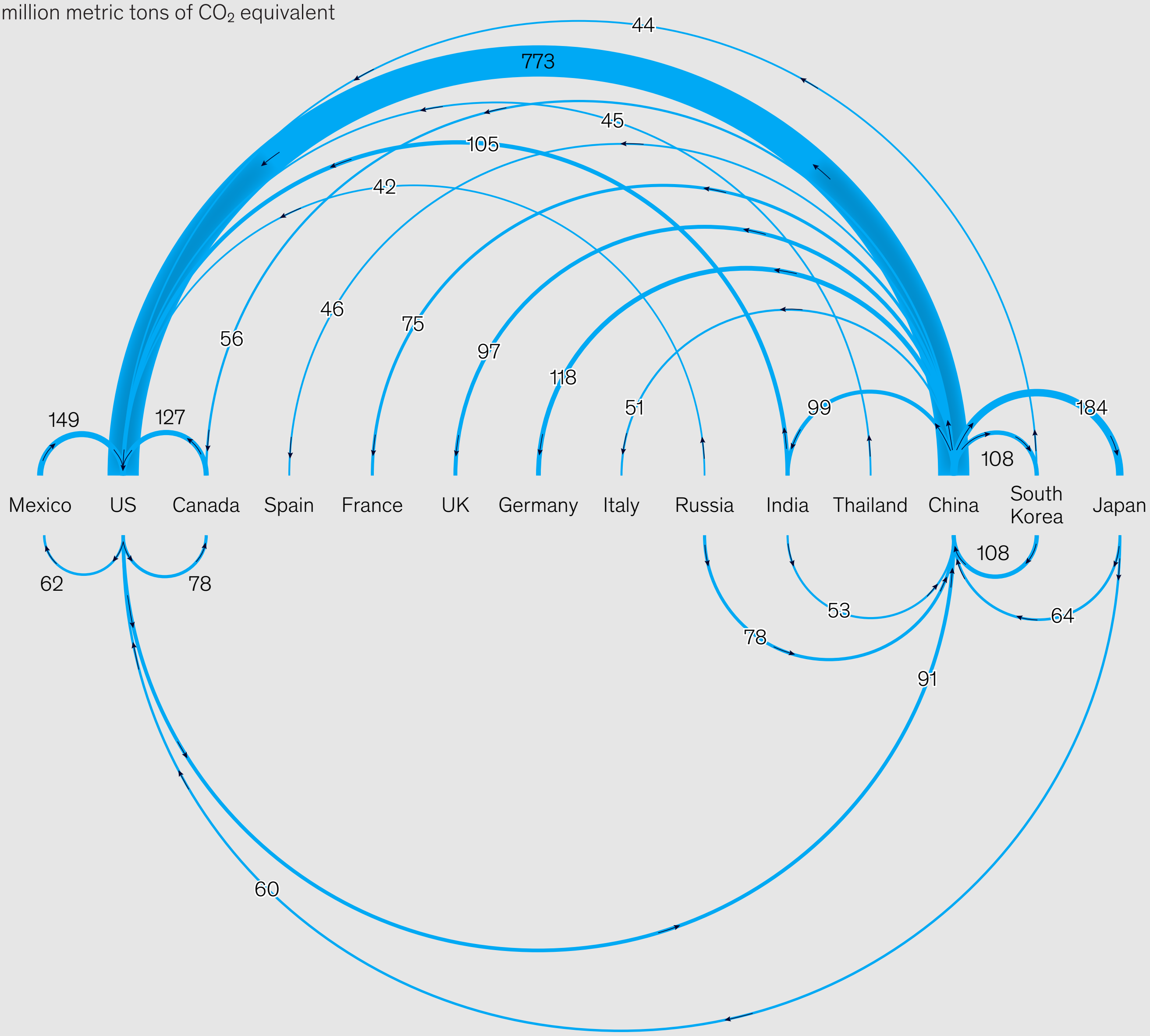
[1] See *Risk, resilience, and rebalancing in global value chains,* McKinsey Global Institute, August 2020.

[2] Daniel Moran et al., *The carbon loophole in climate policy: Quantifying the embodied carbon in traded products,* ClimateWorks Foundation, August 2018.

Exhibit E12

Goods traded internationally represent significant cross-border flows of embedded CO_2 emissions.

Largest interregional flows of carbon embodied in trade, 2021,
million metric tons of CO_2 equivalent



Note: Calculations are based on consumption-based accounting of emissions (also called carbon footprints). Consumption-based accounting accounts for emissions associated with imported and exported goods and reports the total emissions associated with final demand in each country. Exhibit above shows flows of embodied CO_2 from each origin/emitter country to each destination/consumer country.
Source: Eora global supply chain database; McKinsey Global Institute analysis

Countries can use natural endowments or technological, human, and physical resources to harness the transition's growth potential

All countries have opportunities to tap into the transition's potential for growth and secure advantages, through their endowments of natural capital such as sunshine and wind and through the availability of technological, human, and physical capital.[54]

Countries could benefit from the transition if they possess rich stocks of natural capital such as ample sunlight and wind, forestland, mineral resources, and CO_2 sequestration potential (see Exhibit E13 for one example for solar and wind power potential, and chapter 4 for other examples). Generally speaking, many developing countries have the natural resources to accommodate solar power production and forestry protection or restoration efforts, which could be supported by flows of capital through mechanisms such as voluntary carbon markets. And most countries, developing or otherwise, have at least some of the natural-capital endowments that would likely be in demand during the transition. For example, Australia and Saudi Arabia have extensive solar resources, Argentina and the United Kingdom have high wind power potential, and Chile and China have large reserves of minerals.

Some countries have already gained strong positions in the markets for sophisticated low-carbon goods, such as solar panels and EVs. Even so, these markets offer considerable growth potential, which should be accessible to countries with adequate technological capital. For example, South Korea has approximately 6,600 patents on technologies related to climate-change mitigation and human capital. Countries like China and Singapore have a high share of STEM graduates in the population, which provides an indication of the workforce's technical skill. This in turn might be applied to developing solutions for the climate transition.

A country's physical capital, in the form of low-emissions infrastructure and industrial systems, could also create growth potential in a net-zero transition, for example, if consumers shift their preferences or carbon border taxes are applied. Even currently high-emissions infrastructure could be a benefit if it can readily be retrofitted, for example, with alternate low-emissions fuel sources.

All countries have opportunities to tap into the transition's potential for growth and secure advantages, through their endowments of natural capital such as sunshine and wind and through the availability of technological, human, and physical capital.

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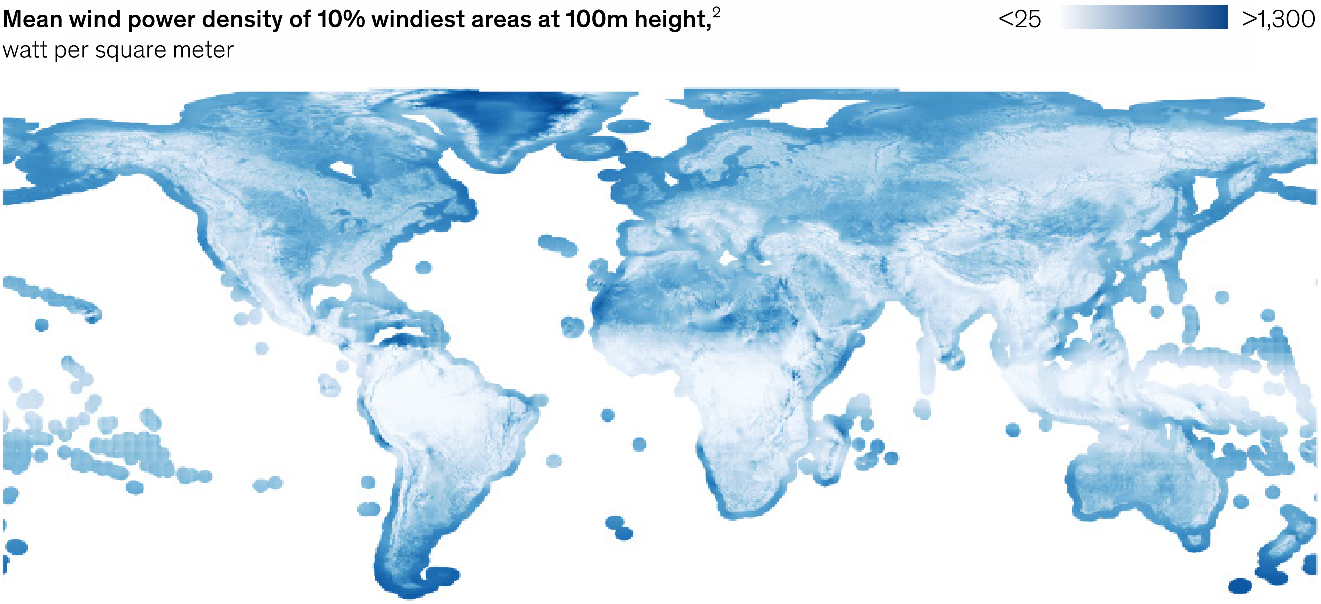
[54] For a more detailed list of potential endowments countries can tap into and data on the same, see chapter 4.

Exhibit E13

Countries could capture potential growth opportunities from the transition to net-zero emissions: Renewable power example.

Average theoretical solar potential,[1]
kilowatt-hour per square meter per day

Mean wind power density of 10% windiest areas at 100m height,[2]
watt per square meter



1. Calculated as the power output achievable by a typical configuration of the utility scale PV system, taking into account GHI (global horizontal irradiation, or the total solar radiation that reaches a horizontal surface), the air temperature affecting the system performance, the system configuration, shading and soiling, and topographic and land-use constraints.
2. Calculated by downscaling large-scale forecasting data from the European Centre for Medium-Range Weather Forecasts. These data are then entered into the DTU Wind Energy modeling system to model local wind climates for a 250m grid across the globe.

Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.
Source: Global Solar Atlas; Global Wind Atlas; McKinsey Global Institute analysis

We identify six main archetypes of countries, based on the common nature of their transition exposure

To help illustrate how the net-zero transition might play out differentially across the globe, we have defined six archetypes of countries according to the nature and magnitude of their exposure across sectors and households. We use sector exposure to define country archetypes as a way to highlight the distinct economic and societal adjustments that countries may need to make under a net-zero transition, while noting that countries will face myriad specific issues that are not reducible to a single archetype. In each case, we also describe endowments that countries possess to help them capture transition opportunities, as well as their exposure to physical risks, where relevant. (See Exhibit E14 for the archetypes based on transition exposure and chapter 4 for further detail related to opportunities for countries to benefit from the transition and their physical risk exposure.)[55]

The following are the six archetypes:

Fossil fuel resource producers. Countries in this category include Australia, Bahrain, Canada, Egypt, Kuwait, Nigeria, Norway, Oman, Qatar, Russia, Saudi Arabia, the United Arab Emirates, and Venezuela. Fossil fuel resource–producing sectors account for a significant portion of GDP in these countries, ranging from 3 percent in Australia to 39 percent in Kuwait, and a large share of physical capital—an average of about 15 percent compared to 2 percent in the rest of the countries. The magnitude of exposure varies among countries in this grouping. For example, Saudi Arabia has about 25 percent of its GDP in fossil fuel–producing sectors, and Qatar has about one-third of its GDP and its capital stock in those sectors. That compares with about 3 percent of GDP and 13 percent of capital stock in Australia.

For the countries with higher shares in particular, various challenges could exist: the potential loss of government revenues from exposed sectors, the reallocation of capital spending from high- to low-emissions assets, and the potential need to diversify their economies. Many countries could also experience rising physical risks; countries in this grouping that are near the equator will become hotter and more humid as warming increases. At the same time, a net-zero transition offers opportunities that these countries can tap into, though capturing them and sufficiently compensating for loss in revenues and exports could also come with challenges. They generally have high solar power or wind power potential, which they could use to develop capacity for renewable-energy generation and make green hydrogen. Some fossil fuel producers, for example those in the Middle East, also have relatively low levels of carbon intensity associated with their oil and gas extraction and have relatively lower costs; thus, they could be the last standing providers of the remaining fossil fuels needed in a net-zero economy, in the scenario modeled here.

Emissions-intensive producers. Countries in this category include Bangladesh, China, India, Indonesia, Pakistan, South Africa, Thailand, Turkey, Ukraine, and Vietnam. These countries derive sizable portions of their GDP, about 18 percent on average, from highly exposed sectors such as high-emissions manufacturing, fossil fuel–based power, and agriculture. Jobs tend to be concentrated in agriculture (more than 20 percent), while much of their capital stock is in manufacturing and fossil fuel–based power. These countries would likely adjust to the transition mainly by decarbonizing industrial processes, expanding renewable-power capacity, and helping farmers adopt low-carbon practices or transition away from agriculture. As discussed above, many of these countries will need to make substantial investment to decarbonize their economies and secure low-carbon growth. Our analysis suggests that these countries face a particular risk of asset stranding. Capital stock in these countries (coal-fired power plants, for example) is often newer than in advanced economies. The average age of coal power plants in China and India is less than 15 years, compared with more than 30 in the United States.[56] Lower-income countries may also find that some low-carbon technologies (for example, electric-arc furnaces for steel production and CCS equipment for steel or cement factories) remain too expensive to deploy or, in some cases, unready for large-scale deployment.

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[55] *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[56] See *World Energy Outlook 2021,* International Energy Agency, December 2021.

Without careful planning, however, they run the risk that continued spending on lower-cost, high-emissions assets could result in the need to prematurely retire or reduce utilization of these assets after only a few years as the world transitions to a net-zero path. At the same time, these countries will have potential to serve the growing markets for low-emissions goods. Asian countries—many of which are included in this archetype—more broadly possess resources that could be conducive to low-emissions innovation.[57] Capital spending for the transition would need to be complemented by investment in adaptation measures, since many countries in this archetype would become hotter, more humid, and more prone to flooding as warming increases.

Agriculture-based economies. Countries in this group include Ghana, Kenya, Morocco, the Philippines, Senegal, and Sri Lanka. Agriculture is the primary source of employment and income for a large share of the population in these countries, accounting for up to about 55 percent of jobs and up to about 30 percent of GDP. An important adjustment for these countries will be adopting low-emissions farming practices, which would require mobilizing millions of stakeholders. As discussed above, many of these countries are expected to invest substantially in new assets as they grow their economies, particularly related to the power sector; securing financing would thus be a key priority under a net-zero transition. These countries also have significant potential to produce solar power and use forestland to generate carbon credits.[58] Almost all of these countries are exposed to physical climate risk because rising heat and humidity affect their agricultural workforces, and also increase volatility of agricultural yields.

Land-use-intensive countries. This group includes Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, Peru, and Uruguay.[59] In these countries, which have generally reached the early or middle stages of industrialization, the agriculture and forestry sectors together represent significant shares of GDP (more than 5 percent), jobs (more than 10 percent), and capital stock (more than 5 percent). They would have to balance land-use needs with protection of forests and would have to support communities whose livelihoods depend on them. The contribution of other sectors such as fossil fuel production, power, and industry to GDP, jobs, and capital stock is also sizable for some countries in the archetype, like Brazil, which could also therefore be exposed to issues described for other archetypes. With their stocks of natural capital, these countries would have growth potential in sectors such as renewable energy, minerals needed for the transition, and forest management; reforestation and afforestation projects could generate valuable carbon credits and ecosystem services.

Downstream-emissions manufacturers. Countries in this group include Austria, Bulgaria, Czech Republic, Germany, Hungary, Italy, Japan, Mexico, Poland, Romania, Slovakia, South Korea, and Sweden. The main exposure for these middle-to-high-income countries relates to the manufacturing of goods, such as automobiles and industrial machinery, that could experience falling demand in their current form because they use fossil fuel–based energy. Countries in this category could manage their exposure to shifts in demand for these products by reinventing products and supply chains. Many make large investments in R&D, which position them well to develop and commercialize low-emissions technologies.

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[57] *See Climate risk and response in Asia,* McKinsey Global Institute, November 2020.

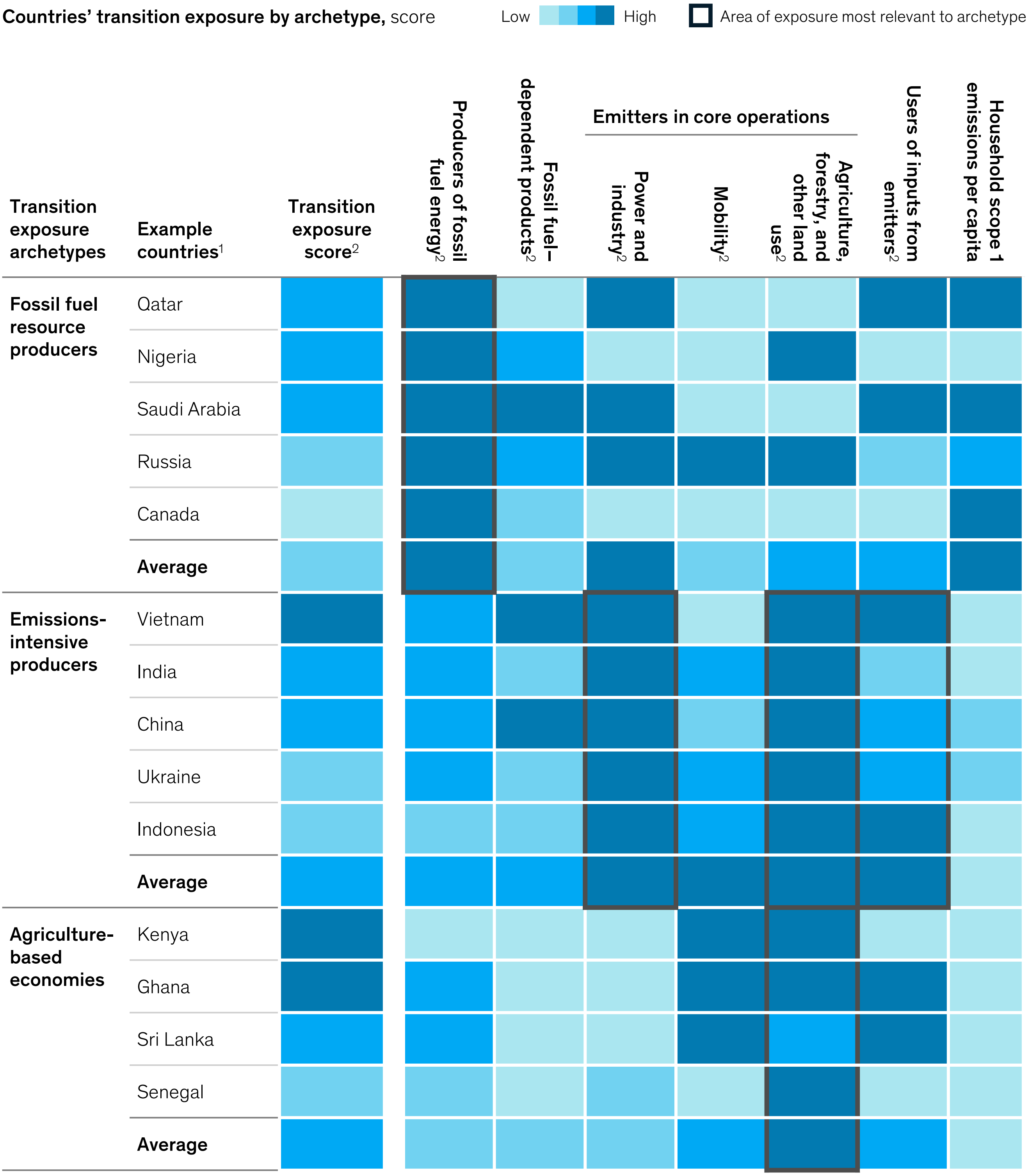
[58] For additional opportunities for African countries, see also Lynn Bouchene, Ziyad Cassim, Hauke Engel, Kartik Jayaran, and Adam Kendall, “Green Africa: A growth and resilience agenda for the continent,” McKinsey & Company, October 28, 2021.

[59] As described above, countries could fall into multiple archetypes. A large share of the economy of Brazil, for example, is related to fossil fuels, and would also be exposed to the types of issues described for that archetype.

Exhibit E14

Based on the nature of their exposure to the net-zero transition, countries can be grouped into six archetypes. (1 of 2)

Countries' transition exposure by archetype, score



1. Averages rows within each archetype are based on a simple average of every country within that archetype, both those shown in rows and other countries in the archetype. For fossil-fuel producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, and Uruguay; for downstream emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland.
2. Simple average of the share of GDP, jobs, and capital stock in the sectors with highest exposure to the net-zero transition.

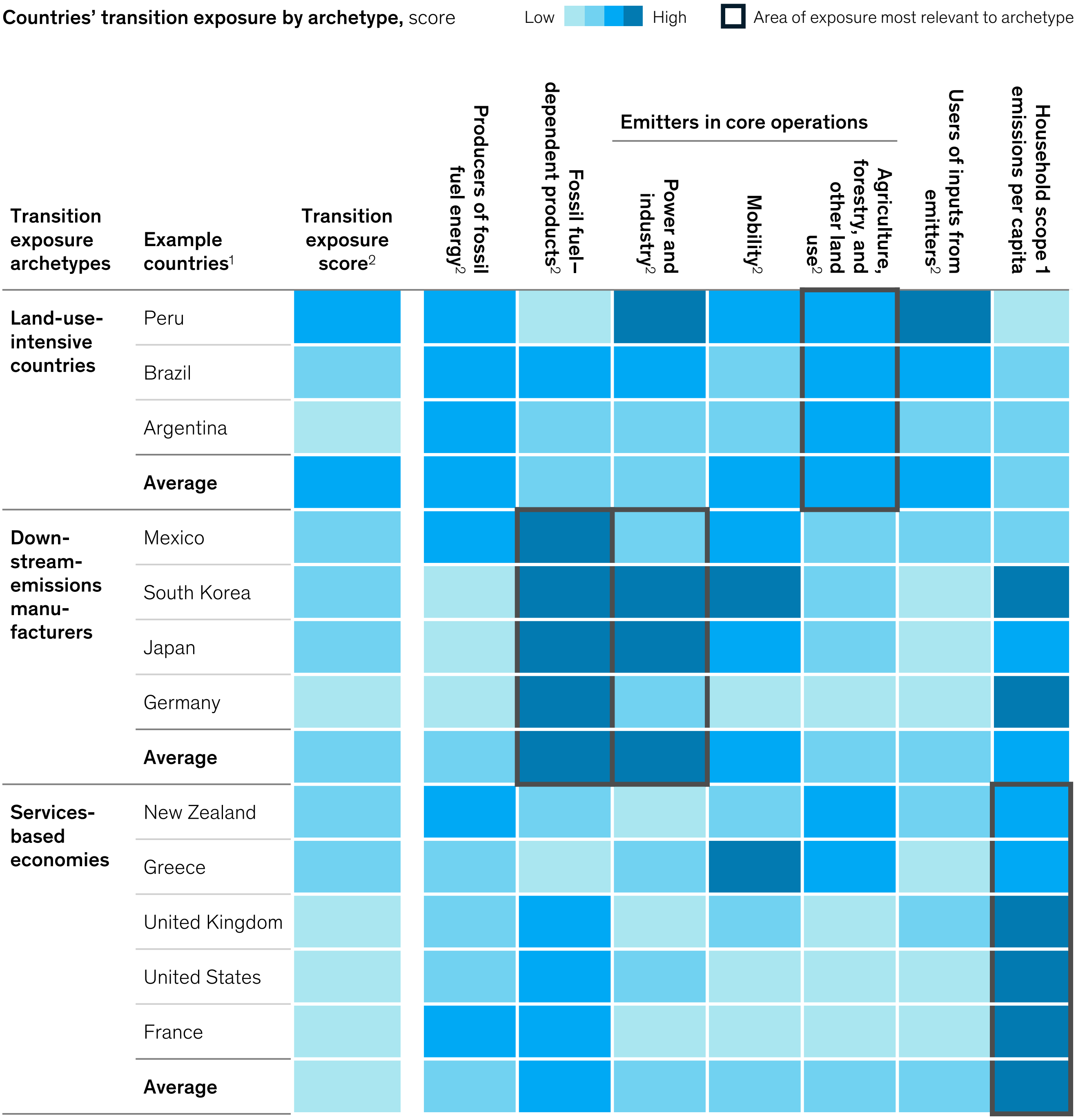
Note: Colors in each column based on relative quartiles within each column rather than across columns. Countries are allocated to an archetype to illustrate specific transition exposures they may experience. However, any given country—especially those with large diversified economies—could face some of the exposures highlighted for other archetypes. Low = below 1st quartile; high = above 3rd quartile. For exposed sectors included, see technical appendix.

Source: Oxford Economics; OECD; ILO; World Input-Output Database; IHS Connect; World Bank; International Energy Agency; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; MINSTAT; INDSTAT; McKinsey Global Institute analysis

Exhibit E14 (continued)

Based on the nature of their exposure to the net-zero transition, countries can be grouped into six archetypes. (2 of 2)

Countries' transition exposure by archetype, score



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1. Averages rows within each archetype are based on a simple average of every country within that archetype, both those shown in rows and other countries in the archetype. For fossil-fuel producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, and Uruguay; for downstream emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland.
2. Simple average of the share of GDP, jobs, and capital stock in the sectors with highest exposure to the net-zero transition.

Note: Colors in each column based on relative quartiles within each column rather than across columns. Countries are allocated to an archetype to illustrate specific transition exposures they may experience. However, any given country—especially those with large diversified economies—could face some of the exposures highlighted for other archetypes. Low = below 1st quartile; high = above 3rd quartile. For exposed sectors included, see technical appendix.

Source: Oxford Economics; OECD; ILO; World Input-Output Database; IHS Connect; World Bank; International Energy Agency; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; MINSTAT; INDSTAT; McKinsey Global Institute analysis

Services-based economies. Countries in this group include Belgium, Denmark, Finland, France, Greece, Ireland, Israel, the Netherlands, New Zealand, Portugal, Singapore, Spain, Switzerland, the United Kingdom, and the United States. These countries have high GDP per capita and derive most of their economic output from service sectors, so their overall exposure to net-zero transition adjustments is low. However, in certain regions and sectors, exposure could be high. These countries also tend to have high consumer emissions—1.6 tons per capita on average, compared to 0.9 tons per capita on average for other countries—and will therefore need to induce behavioral changes in their populations and incur up-front capital costs in order to decarbonize (although, as discussed previously, this could come with long-term benefits, such as lower total cost of ownership). These countries could use their ample natural, technological, and human capital to develop new low-emissions industries or provide services, such as financial or information services, in support of the transition.

Challenges could compound for many lower-income and fossil fuel–producing countries, which would need to balance multiple imperatives.

Stakeholders will need to act with singular unity, resolve, and ingenuity, and toward equitable, long-term outcomes to support the economic transformation a net-zero transition entails

The transition to net zero we have outlined in this report will require economies and societies to make significant adjustments. Many of these adjustments can be best supported through coordinated action involving governments, businesses, and enabling institutions, and by extending planning and investment horizons. This action would need to be taken in a spirit of unity for two key reasons: first, the universal nature of the transition means that all stakeholders will need to play a role. Every country and sector contributes to emissions, either directly or indirectly, through its role in global production and consumption systems. Second, the burdens of the transition will not be evenly felt, and, for some stakeholders, the costs will be much more difficult to bear than for others. This is all the more challenging because contributions to emissions have not been even across stakeholder groups. Thus, without a real effort to address these effects in a spirit of fairness, it appears unlikely that the most affected stakeholders would be either able or willing to do their share to advance the transition.

The following three categories of action stand out:[60]

- Catalyzing effective capital reallocation and new financing structures, including through scaling up climate finance, developing new financial instruments and markets, including voluntary carbon markets, deploying collaborations across the public and private sectors, and managing risk to stranded assets
- Managing demand shifts and near-term unit cost increases for sectors through building awareness and transparency around climate risks and opportunities, lowering technology costs with R&D, nurturing industrial ecosystems, collaboration across value chains to reduce or pass through cost increases from the transition, and sending the right demand signals and creating incentives for the transition
- Establishing compensating mechanisms to address socioeconomic impacts, through economic diversification programs, reskilling and redeployment programs for affected workers, and social support schemes

As these actions are undertaken, individual leaders will need to both consider risks and opportunities to their organizations and to their stakeholders, and determine the role they can play in supporting the necessary adjustments for all. We consider more detailed actions and the role of stakeholders below.

Companies can consider integrating climate considerations into their strategies and their decision-making frameworks. Companies have begun to develop comprehensive plans for achieving net-zero emissions and to integrate those plans into their strategies, combining elements of what might be called “offense” (such as entering new markets, funding R&D, and participating in innovation ecosystems) and “defense” (divesting businesses and retrofitting high-emissions assets to lower their emissions).[61] As they embark on this journey, they can consider the following steps:

- Articulate and communicate a coherent case for change and upskill employees to help drive their organizations toward net-zero goals while also supporting broader economic and societal adjustments. As they initiate action, most CEOs will want to communicate a coherent case for change and take visible ownership of the sustainability agenda.
- Develop ongoing capabilities to make granular, holistic, and dynamic assessments of transition-related risks and opportunities in order to capture shifts in regulations, investor preferences, consumer behaviors, and competition. To stay abreast of new developments and emerging possibilities, organizations are likely to need new capabilities, data, infrastructure, and talent. A key part of this will also be better tracking of scope 1, 2, and 3 emissions, including through the use of digital tools to increase transparency of emissions in companies’ own operations and in their supply chains.

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[60] The actions described in this section specifically relate to the economic and societal adjustments needed for the transition, given the scope of this research. An effective response to climate change, we believe, will involve not only making economic and societal adjustments to deal with the effects of the net-zero transition, but also meeting the other fundamental requirements described previously. We identify seven categories of actions. Leaders can understand and commit to the transition, including understanding the fundamentals of climate science and the transition and making personal and professional commitments; assess and plan their actions, including through building risk assessment capabilities and establishing decarbonization plans; reduce and remove emissions in accordance with these plans; conserve and regenerate natural capital to support decarbonization; adapt and build resilience to manage the physical risk that is already locked in; and reconfigure and grow, for example by reallocating capital and ramping down high-carbon businesses while scaling low-carbon ones; and seek to engage and influence their communities, across their investors, customers, suppliers, peers, and regulators. While the actions described in this section are specific to the economic and societal adjustments needed for the transition, they fall into the various categories listed above. See Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai. “Solving the net-zero equation: Nine requirements for a more orderly transition,” McKinsey & Company, October 2021.

[61] Daniel Pacthod and Dickon Pinner, “Time is running out for business leaders who don’t have a ‘net zero’ strategy,” *Fortune,* April 22, 2021.

- Define decarbonization and offsetting plans and update them as competitive, financial, and regulatory conditions change. This would include scope 1 and 2 emissions (with priority given to “no regret” actions such as improving energy efficiency and making decarbonization investment with positive returns). Where feasible, needed, and material, and depending on the nature of their operations, businesses can expand these plans to include scope 3 emissions.[62]

- Create a portfolio of agile business strategies consistent with these decarbonization plans and with the risks and opportunities emerging in a net-zero economy. They can then put these plans in place as conditions change and opportunities arise. For companies, repositioning themselves could involve investing in new physical assets and reallocating capital, redesigning products, or building new low-emissions businesses.

- Integrate climate-related factors into key business decisions for strategy, risk management, finance and capital planning, R&D, operations (including supplier management and procurement), organizational structure and talent management, pricing, marketing, and investor and government relations.

- Consider if and where to take a leadership position in the company’s industry and its ecosystem of investors, supply chains, customers, and regulators.

Financial institutions can support large-scale capital reallocation, even as they manage their individual risks and opportunities. In the near term, they will need to consider assessing and disclosing their risks and measuring and committing to reduce their financed emissions. Over time, they will need to translate these commitments into actions that lower emissions. Relevant practices for financial institutions to consider include the following:

- Rethinking conventions for risks and returns. Some decarbonization projects are likely to have longer-than-normal payback periods. This possibility may compel financial institutions to adjust their criteria for which projects they finance.

- Assessing and disclosing climate risks. For example, various regulators and supervisors already require banks to conduct climate-risk assessments, and more are planning to start these assessments.

- Measuring and reducing financed emissions. Financial institutions are increasingly making pledges to align their portfolios with 1.5°C or 2.0°C warming targets or to achieve net-zero financed emissions by a certain date. They have started translating these commitments into targets for sectors and geographies. Given that emissions ultimately are from counterparties, financial institutions may find it helpful to support the transition plans of those counterparties—for instance, by offering new financial solutions, advising them on emissions-abatement methods, and introducing partnership opportunities.

- Over time, translating these commitments into actions that lower emissions, including expanding the range of climate-finance products and services (for example, funding for low-emissions power projects, new financial instruments to support negative emissions or nature-based solutions, and well-governed voluntary carbon markets).[63]

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[62] For purposes of this report, “scope 1” emissions are direct greenhouse emissions that occur from sources that are controlled or owned by an organization; “scope 2” emissions are associated with the purchase of electricity, steam, heat, or cooling. “Scope 3” emissions are the result of activities from assets not owned or controlled by the reporting organization but that the organization indirectly impacts in its value chain; thus “scope 3” emissions result from emissions across an organization’s value chain that are not within the organization’s scope 1 and 2 boundary. See *Greenhouse gases at EPA,* United States Environmental Protection Agency.

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

Governments and multilateral institutions could consider the use of existing and new policy, fiscal, and regulatory tools to establish incentives, support vulnerable stakeholders, and foster collective action. Public-sector organizations have a unique role in managing uneven effects on sectors and communities. Among other options, they could consider the following:

- Assess exposure to risks and opportunities, develop decarbonization plans, and create net-zero strategies (similar to businesses). This would include governments bringing climate considerations into decisions about such matters as urban planning, infrastructure development, and tax and subsidy regimes in an effort to anticipate future dynamics, as well as efforts to increase awareness of and transparency about climate risks and opportunities. One major adjustment that governments may need to make is developing new low-emissions industries as demand wanes for fossil fuels and emissions-intensive industries.
- Use policy measures and regulation to encourage decarbonization investment across sectors (for example, consider where and how to best use subsidies, grants, demand signals, and carbon taxes, to name a few). They can also play a role in accelerating research and development that would lower technology costs.
- Governments could establish multilateral and government funds to support low-carbon investment, and manage stranded-asset risk.
- Institute reskilling, redeployment, and social-support programs for workers and manage negative effects on lower-income households.
- Collaborate with other stakeholders to drive collective action. For example, governments can catalyze private-sector action to build new low-emissions industries in various ways; strategies might include setting road maps and convening stakeholders.

Enabling institutions such as standard setters, industry groups, and civil-society coalitions will be critical in coordinating action across sectors and geographies. Although individual actions by companies and governments can support a wide range of stakeholders during the transition, these actions may not be enough to meet all stakeholder needs. The pace and scale of the transition mean that many of today's institutions may need to be revamped, and new institutions created to disseminate knowledge, support capital deployment, manage uneven effects, and organize collective action. Enabling institutions could play valuable roles in developing and enforcing governing standards, tracking and market mechanisms (for example, related to the measurement of emissions or climate finance), convening stakeholders and facilitating collaboration (for example, to arrange collective investment or organize the build-out of infrastructure), and giving a voice to vulnerable workers and communities.

As they initiate action, most CEOs will want to communicate a coherent case for change and take visible ownership of the sustainability agenda.

Individuals will need to manage their own exposure to the transition and can play powerful roles as consumers and citizens. They can begin by continuing to learn about the effects of both ongoing climate change and the net-zero transition that they may experience as consumers or workers. The goal of net-zero emissions can only be reached if people adopt new behaviors and consumption patterns, such as switching to electric vehicles, and renovating or retrofitting homes for energy efficiency. Civic discourse has an important role to play: an informed, engaged public that recognizes the imperative for a net-zero transition could spur decisive and transformative action on the part of government and business leaders.

The economic transformation required to achieve net-zero emissions by 2050 will be massive in scale and complex in execution. The transition would bring substantial shifts in demand, capital allocation, costs, and jobs, which will be challenging to a wide range of stakeholders, not least because they will be distributed unevenly. Yet the costs and dislocations that would result from a more disorderly transition to net-zero emissions would likely be far greater, and the transition would prevent the further buildup of physical risks. The findings of this research serve as a clear call for more thoughtful and decisive action, taken with the utmost urgency, to secure a more orderly transition to net zero by 2050. It is important not to view the transition as only onerous; the required economic transformation will not only create immediate economic opportunities but also open up the prospect of a fundamentally transformed global economy with lower energy costs, and numerous other benefits—for example, improved health outcomes and enhanced conservation of natural capital. Actions by individual companies and governments, along with coordinated action to support more vulnerable sectors, geographies, and communities, could help support the needed economic and societal adjustments. Moreover, the level of global cooperation that such a transition will ultimately require could serve as both a model and a basis for solving a broader array of global challenges. Daunting as the task may seem, it is fair to assume that human ingenuity would ultimately rise to the challenge of achieving net zero, just as it has solved other seemingly intractable problems over the past 10,000 years. The key issue is whether the world can muster the requisite boldness and resolve to broaden its response during the upcoming decade, which will, in all likelihood, decide the nature of the transition.

It is important not to view the transition as only onerous; the required economic transformation will not only create immediate economic opportunities but also open up the prospect of a fundamentally transformed global economy with lower energy costs, and numerous other benefits.

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1. The net-zero challenge

Governments, companies, and other institutions increasingly recognize that the physical risks associated with a changing climate will continue to build up until the world reduces greenhouse gas (GHG) emissions and counterbalances any remaining emissions with equivalent removals of GHGs from the atmosphere.[64] To do so will require decarbonizing six energy and land-use systems—power, industry, mobility, buildings, agriculture, and waste—and restoring a seventh, forestry and other land use, that acts as both a source of and a natural sink for CO_2 and other greenhouse gases.

Yet today, the net-zero equation is not solved and we are not on track to reach net zero and implement these changes in time to limit global warming to 1.5°C, in line with the highest objective of the 2015 Paris Agreement. As of December 2021, more than 70 countries accounting for more than 80 percent of global CO_2 emissions and about 90 percent of global GDP had put net-zero commitments in place, as had more than 5,000 companies as part of the United Nations' Race to Zero campaign.[65] Yet even if all the existing commitments were fulfilled, greenhouse gas emissions between now and 2050 would still likely exceed the potential budget of what scientists consider necessary to keep warming below 1.5°C.[66] Moreover, these commitments have yet to be translated into implementation plans. Execution would not be easy: it would require a careful balancing of the shorter-term risks of poorly prepared or uncoordinated action with the longer-term risks of insufficient or delayed action.

Decarbonizing the energy and land-use systems will be possible only if nine system-level requirements are met, encompassing physical building blocks, economic and societal adjustments, and governance, institutions, and commitment.[67] These requirements would need to be fulfilled against the backdrop of many economic (for example, inflation) and political challenges (for example, polarization within and among countries). This report focuses on the economic and societal adjustments needed for a net-zero transition. Specifically, we analyze the nature and magnitude of the transition's likely socioeconomic consequences in four domains: demand, capital allocation, costs, and jobs. In this chapter, we outline the context for the net-zero challenge and the shifts that will be needed across energy and land-use systems.

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[64] "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

[65] Includes countries that have achieved their net-zero targets, or have put them in law, in policy documents, or made a declaration or a pledge. Net Zero Tracker, Energy and Climate Intelligence Unit, Data-Driven EnviroLab, New Climate Institute, and Oxford Net Zero, 2021. GDP data for 2019 from World Development Indicators Data Bank, World Bank. Emissions data for 2018 from Emissions Database for Global Atmospheric Research (EDGAR), v6.0, May 2021. "Race to Zero campaign," United Nations Framework Convention on Climate Change.

[66] *Emissions gap report 2021: The heat is on,* UNEP, 2021. See also *World energy outlook 2021,* IEA, 2021; and *Warming projections global update,* Climate Action Tracker, November 2021.

[67] Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.

Physical risks will continue to intensify until net-zero emissions are reached

The average combined global land-and-sea surface temperature of this past decade was about 1.1°C warmer than preindustrial temperatures, defined as the period between 1850 and 1900.[68] Earth is now warming at a rate of about 0.2°C per decade and losing Arctic sea ice at roughly 3,000 cubic kilometers per decade.[69] Climate science tells us the main driver of this temperature increase is the human-caused rise in atmospheric levels of CO_2 and other GHGs, including methane (CH_4) and nitrous oxide (N_2O).[70]

As average temperatures rise, acute hazards such as heat waves and floods increase in frequency and severity, and chronic hazards, such as drought and rising sea levels, intensify. Most recently, the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR6) reaffirmed that continued emissions of GHGs will cause acute and chronic climate events to increase in frequency, severity, or both.[71]

The physical manifestations of a changing climate are increasingly visible across the globe, as are their socioeconomic impacts. Both will continue to grow, most likely in a nonlinear way, until the world transitions to a net-zero economy. Our 2020 report on climate risk explored physical climate risks and their socioeconomic impacts in detail.[72] It found that physical climate risk is rising and could lead to nonlinear and systemic impacts on human livability and workability, food systems, physical capital, infrastructure, and natural capital.

As physical climate risk spreads, it could trigger broader economic, financial, and social disruptions.[73] Estimates suggest that failing to limit the rise of GHG emissions could affect between 2 and 20 percent of global GDP by 2050 under a high-emissions (RCP 8.5) scenario.[74] The wide range reflects the intrinsic difficulty in making these estimates.

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[68] "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

[69] National Aeronautics and Space Administration Goddard Institute for Space Studies, 2019.

[70] "Approximately 98 percent of observed warming since 1850 is attributable to the rise in atmospheric GHG concentrations, and approximately 55 percent is attributable to CO_2 directly. Most of the remaining warming is caused by short-lived GHGs such as methane, which, because they decay in the atmosphere, warm the planet as a function of rate (or flow) of emissions, not cumulative stock of emissions." See "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

[71] Ibid.

[72] *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020. For a detailed global assessment of the number of people exposed to four key physical climate hazards, see Harry Bowcott, Lori Fomenko, Alastair Hamilton, Mekala Krishnan, Mihir Mysore, Alexis Trittipo, and Oliver Walker, "Protecting people from a changing climate: The case for resilience," McKinsey & Company, November 2021.

[73] See Box 1 in *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[74] We have not attempted to make estimates of this kind in our research. The ranges here come from a review of the literature focused on quantifying the various impacts of physical climate effects on real GDP or GDP growth. Most of the literature reviewed takes a global focus, either through assembling and modeling a large group of countries or by aggregating total economic activity into a simplified global model of standardization across results. Reported results were generated under RCP 8.5 or a specific and consistent global average temperature increase. See Rob Dellink et al., "The sectoral and regional consequences of climate change to 2060," *Environmental and Resource Economics,* volume 72, 2017; Matthew E. Khan et al., *Long-term macroeconomic effects of climate change: A cross-country analysis,* Federal Reserve Bank of San Francisco, October 2019; Tom Kompas et al., "The effects on climate change on GDP by country and the global economic gains from complying with the Paris Climate Accord," *Earth's Future,* volume 6, issue 8, July 2019; Sebastian Acevedo Mejia et al., *The effects of weather shocks on economic activity: What are the channels of impact?* IMF Working Papers, issue 144, June 2018; Matthias Kalkuhl and Leonie Wenz, *The impact of climate conditions on economic production: Evidence from a global panel of regions,* Leibniz Center for Economics, 2018; Nicole Glanemann et al., "Paris Climate Agreement passes the cost-benefit test," *Nature Communications,* volume 11, 2020; Falko Ueckerdt et al., "The economically optimal warming limit of the planet," *Earth System Dynamics,* volume 10, issue 4, November 2019; *The economics of climate change: No action is not an option,* Swiss Re Institute, April 2021; and Frances Moore and Delavane Diaz, "Temperature impacts on economic growth warrant stringent mitigation policy," *Nature Climate Change,* volume 5, February 2015.

The effect of hard-to-predict biotic feedback loops (for example, the thawing of permafrost) or knock-on economic effects (for example, from impacts on financial valuations) could push losses well beyond the high-end estimate.[75] It is also likely that some physical impacts (for example, sea-level rise caused by melting glaciers) will be irreversible over millennia if critical thresholds are reached. Prudent risk management thus calls for limiting GHG emissions.

To stabilize the climate and limit physical climate risks, climate science tells us that it is necessary to reduce the addition of GHGs to the atmosphere to net zero.[76] And the less GHG that is emitted before the world reaches net zero, the less warming will take place. As a result of this relationship between cumulative emissions and global temperatures, Earth has a so-called carbon budget, a specific amount of CO_2 that can be emitted before it becomes probable that warming will exceed a certain level. The IPCC AR6 report estimated that restricting net emissions to 400–500 gigatons of carbon dioxide ($GtCO_2$), combined with substantial decreases in emissions of short-lived GHGs like methane, would result in a 50 to 67 percent probability of limiting warming to 1.5°C above preindustrial levels. Climate scientists have identified 1.5°C warming as a possible threshold above which feedback loops such as the melting of permafrost or collapse of ocean currents may be activated, causing abrupt changes to the planet and exacerbating or accelerating the effects of a changing climate. Restricting emissions to 1,150–1,350 $GtCO_2$ would result in a 50 to 66 percent probability of limiting warming to 2.0°C.[77]

However, time is running out to reach net-zero emissions in time to limit warming to these levels. Global CO_2 emissions are about 40 $GtCO_2$ today.[78] Emissions of CO_2 have risen significantly since 1970, though the rate of growth has slowed in recent years, including a temporary reduction caused by the COVID-19 pandemic (Exhibit 1).[79] Similarly, emissions of other greenhouse gases like methane and nitrous oxide have also been rising. Indeed, the importance of reducing emissions of these latter greenhouse gases in order to restrict warming to 1.5°C is increasingly being emphasized.[80] At current emissions rates, the carbon budget for 1.5°C of warming would likely be exceeded within about the next decade, and the 2.0°C budget would be exceeded in about three decades.

Given the cumulative nature of the problem and the relatively short window until carbon budgets are spent, action today is critical. Every year without significant progress makes the task more arduous and raises the risk that warming limits are reached.[81] The decisions of the next decade are therefore crucial to preventing the worst effects of climate change. Climate science tells us that the Earth system will continue to change along the journey to net zero and that some changes will continue even after we have stopped the planet from warming. Given the thermal inertia of the Earth system, some physical impacts like sea level rise and ocean acidification will continue to intensify even once net zero is reached and warming has stopped. This suggests that societies will continue to need to take action to adapt (see Box 1, "The adaptation agenda").[82]

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[75] See, for example, Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences,* volume 115, number 33, August 2018; M. Previdi et al., "Climate sensitivity in the Anthropocene," *Quarterly Journal of the Royal Meteorological Society,* volume 139, number 674, June 2013; James Hansen et al., "Climate sensitivity, sea level, and atmospheric carbon dioxide," *Philosophical Transactions of the Royal Society,* volume 371, number 2001, October 2013. See also Ruth DeFries et al., *The missing economic risks in assessments of climate change impacts,* London School of Economics, September 2019.

[76] "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

[77] This assumes associated methane reductions of about 50% by 2050. "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

[78] Numbers may be slightly higher or slightly lower than this, depending on the specific data source used, given the uncertainty with global emissions measurement.

[79] Emission data for other greenhouse gases are less frequently reported. In 2019 annual emissions were 364 megatons of methane (CH_4), and 10 megatons of nitrous oxide (N_2O). See EMIT database by McKinsey Sustainability Insights, September 2021; and Global Carbon Budget 2021. For impact of the pandemic, see Zhu Liu et al., "Carbon Monitor, a near-real-time daily dataset of global CO_2 emission from fossil fuel and cement production," *Scientific Data,* volume 7, article 392, October 2020.

[80] "Curbing methane emissions: How five industries can counter a major climate threat," McKinsey & Company, September 2021.

[81] See, for example, Felix Preston and Puja Jain, *The time value of carbon,* Generation Investment Management, May 2021.

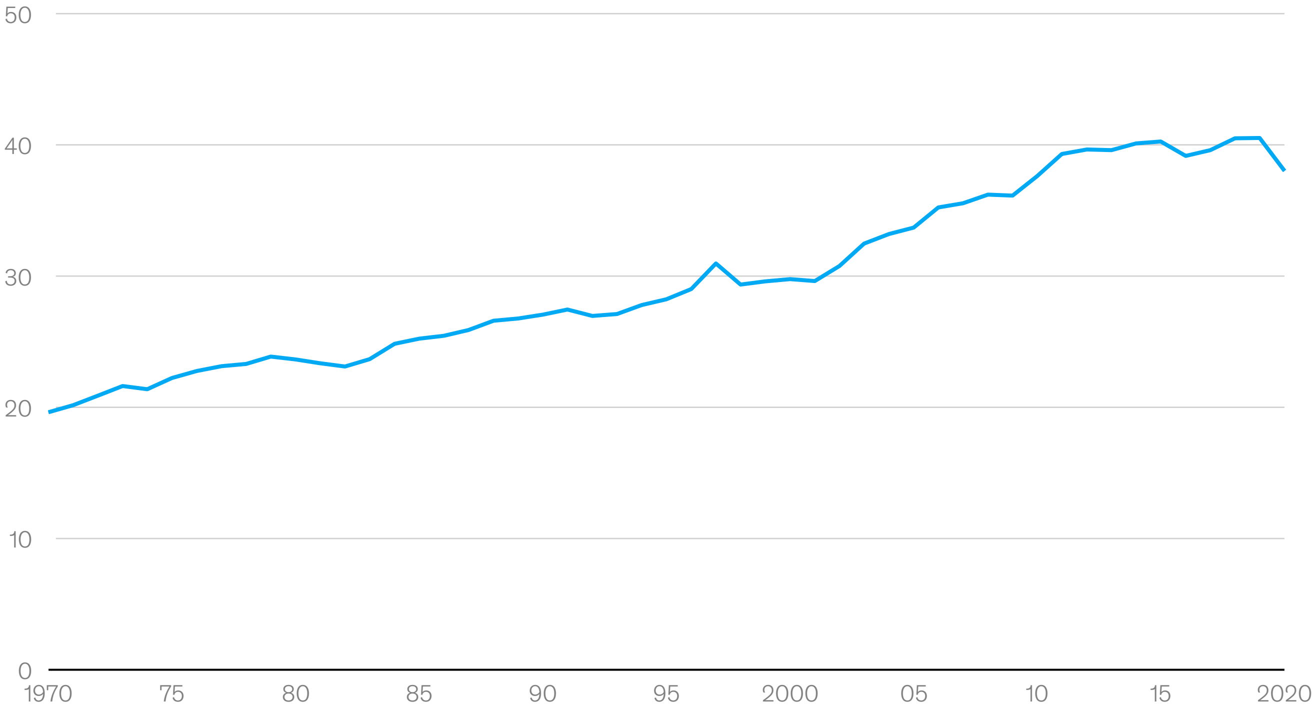
[82] "Summary for policymakers," in *Climate change 2021: The physical science basis: Contribution of Working Group I to the Sixth Assessment Report,* IPCC, 2021.

Exhibit 1

Emissions of carbon dioxide and other greenhouse gases have increased since 1970.

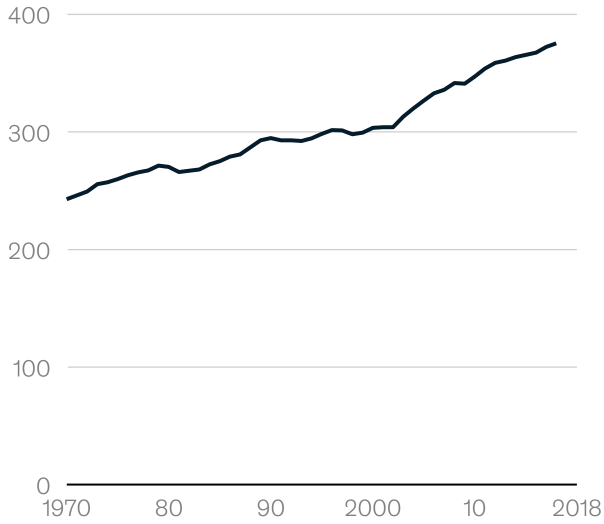
In the past ~50 years, CO_2 emissions have continued to rise, though growth has slowed in recent years including during the COVID-19 pandemic

Annual global CO_2 emissions
Billion metric tons per year

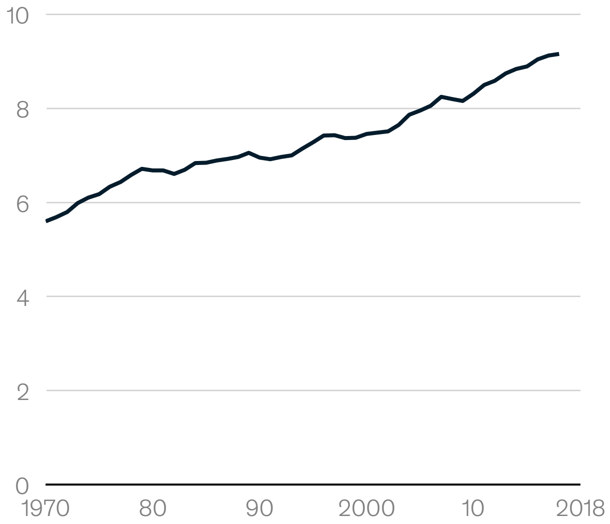


In the past ~50 years, methane and nitrous oxide emissions have also been steadily increasing

Annual global methane emissions[1]
Million metric tons per year



Annual global nitrous oxide emissions[1,2]
Million metric tons per year



1. 2018 is latest year for which emissions data are available.
2. Nitrous oxide emissions include direct and indirect emissions (eg, from managed soils, manure management, atmospheric deposition).

Source: Friedlingstein et al.; *Global Carbon Budget 2021;* Earth System Science Data, 2021; Emissions Database for Global Atmospheric Research v6.0, May 2021; Crippa et al., 2021; Liu et al., 2020; McKinsey Global Institute analysis

Box 1

The adaptation agenda

Adaptation action is needed to manage a continually increasing level of physical risk, irrespective of the decarbonization measures required to achieve net-zero emissions.

Key adaptation measures that stakeholders can consider include the following:

- protecting people and assets through measures that include installing “gray” infrastructure such as elevation for buildings or sea walls, protecting or restoring “green” infrastructure such as coral reefs, or adjusting working hours to reduce exposure to extreme heat[1]
- building resilience and backups in systems with actions like increasing global inventories and diversifying supply chains
- reducing exposure where necessary, for example by relocating assets from regions that are too difficult to protect, or thoughtful planning of where to build new assets
- ensuring appropriate financing and insurance to enhance resilience and manage risk

In 2016, the UN Environment Programme identified adaptation costs of $140 billion to $300 billion per year for developing countries by 2030, rising to $280 billion to $500 billion annually by 2050. The Global Commission on Adaptation calculated necessary adaptation investment of $1.8 trillion between 2020 and 2030, equivalent to less than 1 percent of projected total gross fixed capital formation in that period, for a specific set of adaptation actions.[2] The calculated investment includes strengthening early warning systems, hardening new infrastructure, improving dryland agriculture crop production, protecting mangroves, and making management of water resources more resilient.

There are many reasons why adaptation is challenging and will need to be carefully managed. The intensity of physical hazards is likely to grow, and so the cost of adaptation could increase over time, and there may eventually be technical or other limits to effective adaptation. Additionally, societies would have to assess trade-offs, including who and what to protect or relocate. Finally, adaptation costs are ultimately incurred at the local level, by individual countries, communities, or companies, and financing adaptation may be challenging for these stakeholders depending on specific economic conditions.

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[1] Holly P. Jones et al., “Global hotspots for coastal ecosystem-based adaptation,” *PLOS ONE,* volume 15, number 5, May 2020; Filippo Ferrario et al., “The effectiveness of coral reefs for coastal hazard risk reduction and adaptation,” *Nature Communications,* volume 5, number 3794, May 2014; *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[2] Anne Olhoff et al., *The adaptation finance gap report,* UNEP DTU Partnership, 2016; and Manish Bapna et al., *Adapt now: A global call for leadership on climate resilience,* Global Commission on Adaptation, September 2019.

Net-zero emissions can be achieved only through a universal transformation of energy and land-use systems

Today, seven energy and land-use systems account for all GHG emissions, while one, forestry and other land use, also acts as a natural sink for carbon, which absorbs CO_2 from the atmosphere and is being depleted by deforestation. The vast majority of carbon dioxide emissions, as much as 83 percent, is energy related (Exhibit 2).[83]

Carbon dioxide emissions in each case result from the combustion of fossil fuels to produce energy (oil, gas, and coal) as well as non-energy emissions—for example, emissions associated with industrial processes, like the reduction of iron ore to produce steel, and with deforestation. Combustion of coal makes up about 35 percent, oil an additional 31 percent, and gas 17 percent of all carbon dioxide emissions.[84]

Actions to reach net-zero emissions include shifting the energy mix away from fossil fuels and toward zero-emissions electricity and other low-emissions energy carriers such as hydrogen; adapting industrial and agricultural processes; increasing energy efficiency and managing demand for energy; utilizing the circular economy; consuming fewer emissions-intensive goods; deploying carbon capture, utilization, and storage (CCS) technology; and enhancing sinks of both long-lived and short-lived greenhouse gases.[85] Managing fugitive emissions is important for this last action, as are avoiding deforestation and enabling forest restoration. Recent McKinsey research on what it would take to achieve a 1.5°C pathway examined a range of scenarios and found that the above actions would need to be deployed across all sectors in the economy and would require emission-reduction efforts, beginning today.[86]

A key feature of any transition to net-zero emissions is its universality, across energy and land-use systems and throughout the global economy. This is for two reasons. First, each of these energy and land-use systems contributes substantially to emissions and will need to undergo transformation if the net-zero goal is to be achieved. Second, these systems are highly interdependent; actions to reduce emissions must therefore take place in concert and at scale across systems, economic sectors, and geographies. For instance, electric vehicles are valuable only to the extent that low-emissions electricity production has been achieved. All sectors of the economy participate in these energy and land-use systems across global value chains. Similarly, all countries contribute to emissions, either directly or through their role in value chains. Reaching net-zero emissions will thus require a transformation of the global economy.

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[83] Notably, this is based on the current system of emissions measurement, in which forestry emissions in particular are considered as net emissions, considering their role as both sources and sinks of greenhouse gases. Considering just their role as gross sources of emissions, and accounting for second-order effects of deforestation, would substantially increase the contribution of forestry as sources of emissions. For further details, see chapter 3.

[84] EMIT database by McKinsey Sustainability Insights, September 2021.

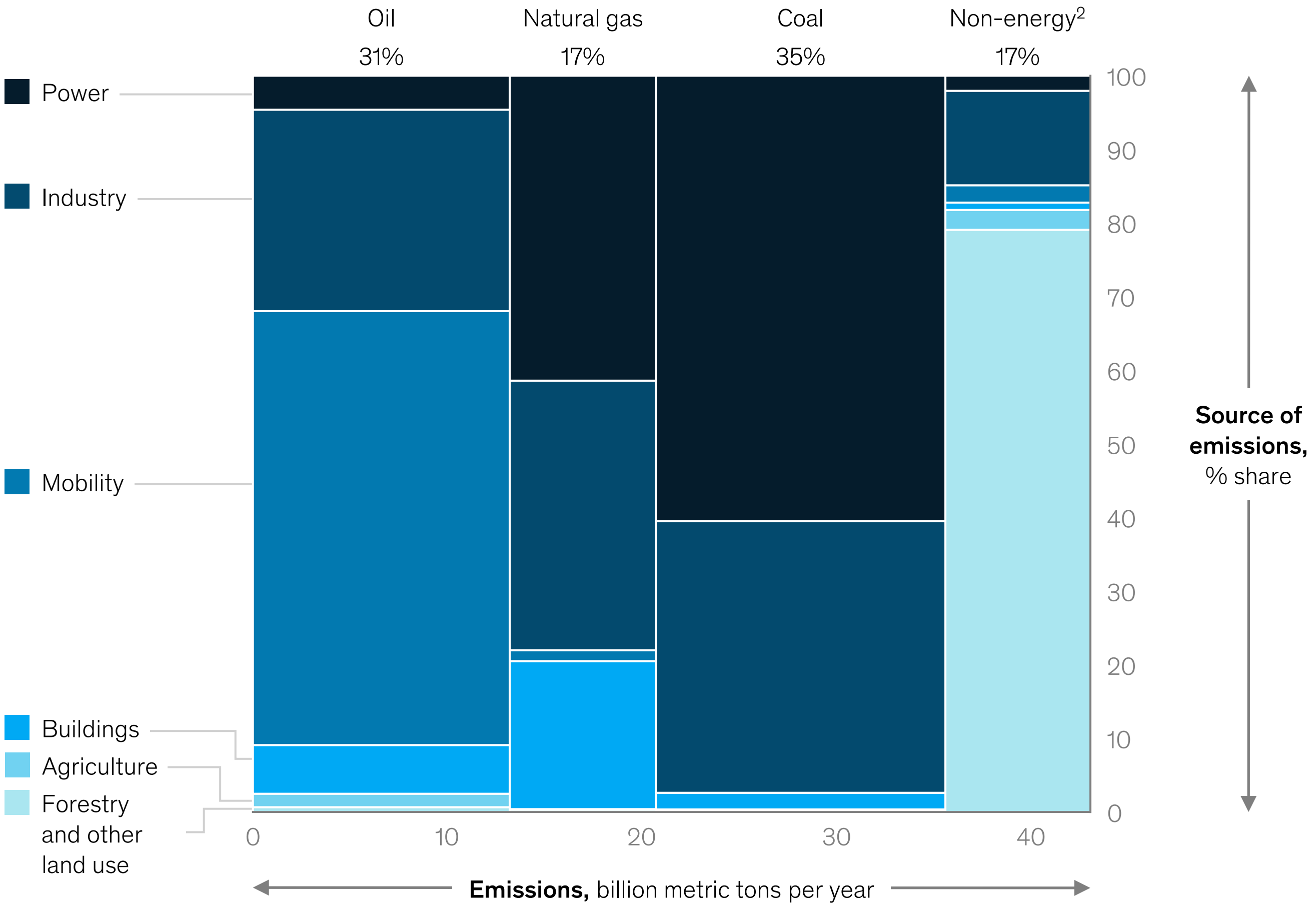
[85] In this report we refer to carbon capture, utilization, and storage in abbreviated form as CCS, as we have not modeled utilization.

[86] Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," McKinsey & Company, April 2020.

Exhibit 2

Energy use accounts for 83 percent of the CO_2 emitted across energy and land-use systems.

CO_2 emissions per fuel and energy and land-use system, 2019, share[1]



1. Includes all fossil fuel CO_2 sources as well as short-cycle emissions (eg, large-scale biomass burning, forest fires). Power includes emissions from electricity and heat generation (i.e., from combined heat and power plants); Industry includes various industrial processes, including production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal; Mobility includes emissions from road, aviation, rail, maritime, and other forms of transportation; Buildings includes emissions from heating, cooking, and lighting of commercial and residential buildings; Agriculture includes emissions from direct on-farm energy use and fishing; Forestry includes net flux of CO_2 from land use and land cover change but not the opportunity cost of lost carbon capture. The global CO_2 emissions in this exhibit represent the total emissions of the full sectors, not of the subsectors considered in this report. Based on 2019 emissions.
2. In addition to energy-related CO_2 emissions, anthropogenic emissions include industry process emissions and deforestation.

Note: This is based on the McKinsey EMIT database that draws on a variety of bottom-up sources. Depending on the emissions database used, data per sector and the economy as a whole may vary. Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021, data for 2019); International Energy Agency; McKinsey Global Energy Perspectives; McKinsey Global Institute analysis

For each of the seven systems, sources of emissions and decarbonization actions are as follows (Exhibit 3, see also chapter 3 for further details):

— **Power.** Generating electricity and heat through burning coal, natural gas, and—to a lesser extent—oil accounts for 30 percent of global CO_2 emissions (of which China and the United States produce nearly half) and 3 percent of N_2O emissions.[87] Achieving zero-emissions electricity requires accelerating the replacement of fossil fuels in power generation with low-emissions sources, such as wind, solar, and nuclear. The growth of renewables like solar and wind raises the question of how to deal with their daily and seasonal intermittency and ensure reliability. Various options are typically considered for this. For example, some fossil fuel plants would likely remain in use to ensure flexibility of the grid, and their use would need to go hand-in-hand with storage technologies, the use of carbon capture, utilization, and storage and power-to-gas-to-power conversions, as well as demand management and long-distance interconnections to pool renewable assets across a larger geographic area[88] (see Box 2, "The role of carbon capture and negative emissions"). Another consideration would be managing the physical footprint of renewable technologies, which is much higher than that of traditional fossil fuels.[89] Scaling the power sector and producing zero-emissions electricity can also be a key part of helping other sectors reduce emissions.

— **Industry.** Industry accounts for about 30 percent of global CO_2 emissions, 33 percent of methane emissions, and 8 percent of N_2O emissions, from various industrial processes such as the production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal.[90] Emissions result from burning fossil fuels for energy, from the production process itself, and from fugitive emissions from extraction, refining, and transportation of fossil fuels. Decarbonizing industry emissions would require a shift to processes and plants that are more energy efficient, using alternate fuels and inputs such as green hydrogen, and scaling carbon capture, utilization, and storage for hard-to-abate emissions, to name a few decarbonization actions.[91] Some of these technologies are in relatively early stages and further efforts will be needed to scale them and drive down costs.

— **Mobility.** Road, aviation, rail, maritime, and other forms of transportation contribute approximately 19 percent of global CO_2 emissions annually, with the United States producing nearly one-quarter of that total, and 2 percent of N_2O emissions.[92] The primary decarbonization lever is replacing internal combustion engine (ICE) vehicles with battery-electric vehicles (BEVs) and vehicles powered by hydrogen fuel cells (fuel cell electric vehicles, or FCEVs), supported by the expansion of corresponding infrastructure: electric charging stations for BEVs and hydrogen fueling stations for FCEVs, plus upstream production of low-emissions electricity and hydrogen. These low-emissions technologies could be used for passenger vehicles such as cars, buses, and two- and three-wheelers, as well as road freight. Aviation could reduce emissions through a mixture of shifting short-haul trips from air to rail, retiring older aircraft, retrofitting existing fleets with energy-efficient features, and increasing the use of sustainable aviation fuel (SAF), to name a few decarbonization routes. Reducing emissions in marine shipping could involve slower growth in tanker demand as oil usage decreases, improvements in fuel

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[87] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019. Heat generation includes heat from combined heat and power plants.

[88] For more on the power sector, see Jason Finkelstein, David Frankel, and Jesse Noffsinger, "How to decarbonize global power systems," McKinsey & Company, May 2020; and Rory Clune, Ksenia Kaladiouk, Jesse Noffsinger, and Humayun Tai, "A 2040 vision for the US power industry: Evaluating two decarbonization scenarios," McKinsey & Company, February 2020.

[89] Current power technologies such as coal and gas require about 12 acres per megawatt of power generation. In contrast, solar and wind power require approximately 43 and 71 acres of land per megawatt, respectively. Thus, switching to wind and solar power would likely increase land use by a factor of three to six. See *The footprint of energy and land use of US electricity production,* Strata, 2017.

[90] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[91] For more details on decarbonization of the steel sector, see Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey & Company, June 2020. For cement, see Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020; and Thomas Hundertmark, Sebastian Reiter, and Patrick Schulze, "Green growth avenues in the cement ecosystem," McKinsey & Company, December 2021.

[92] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

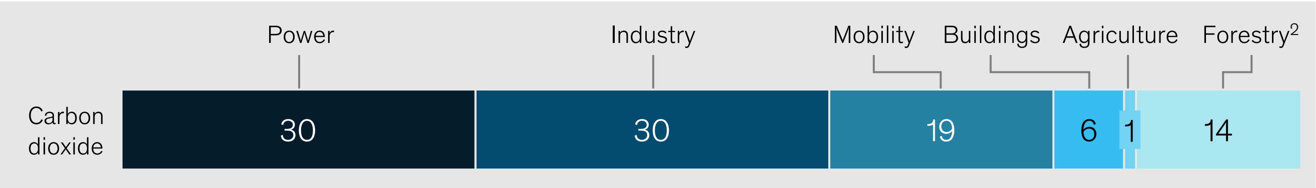
efficiency, and the use of alternate fuels, for example green hydrogen–based synthetic fuels, such as ammonia.[93] Additional effort for aviation and shipping is needed to lower costs, improve the supply chain, and ensure availability of reliable feedstock.

— **Buildings.** Heating and cooking in buildings contribute about 6 percent of global CO_2 emissions, of which residential buildings account for the majority.[94] The key decarbonization levers here are enhancing the energy efficiency of buildings and appliances (for example, via making appliances more efficient and upgrading buildings' insulation and airflow) and replacing appliances and heating systems that run on fossil fuels with models that run on low- or zero-emissions energy sources (for example, replacing gas or oil boilers with electric heat pumps, replacing gas stoves and ovens with electric models, and building out infrastructure such as district heating systems that can run on renewable sources and municipal hydrogen networks).

Exhibit 3

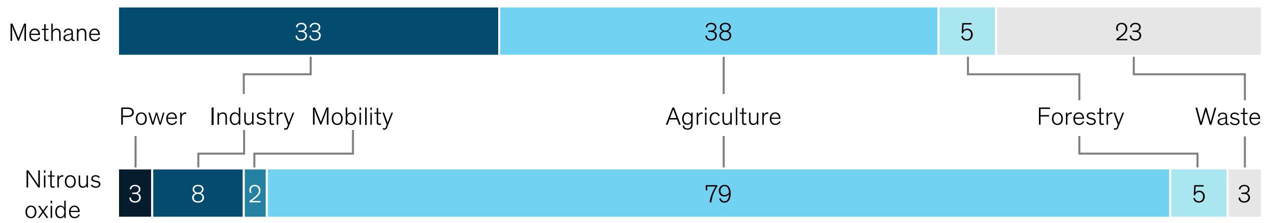
Power and industry are major energy consumers and together generate about 60 percent of CO_2 emissions.

Share of emissions[1] per energy and land-use system, 2019, %



Subsectors' share of system emissions, %

Power		Industry		Mobility		Buildings		Agriculture		Forestry[2]	
Electricity	97	Steel	26	Road	75	Residential	70	Farming	96	Forestry	100
Heat	3	Cement	20	Aviation	13	Commercial	30	Fishing	4		
		Oil and gas extraction	15	Maritime	11						
		Chemicals	12	Rail	1						
		Coal mining	6	Other	<1						
		Other	20								



1. Includes all fossil fuel CO_2 sources as well as short-cycle emissions (eg, large-scale biomass burning, forest fires). Power includes emissions from electricity and heat generation (i.e., from combined heat and power plants); Industry includes various industrial processes, including production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal; Mobility includes emissions from road, aviation, rail, maritime, and other forms of transportation; Buildings includes emissions from heating, cooking, and lighting of commercial and residential buildings; Agriculture includes emissions from direct on-farm energy use and fishing; Forestry includes net flux of CO_2 from land use and land cover change but not the opportunity cost of lost carbon capture; Waste includes emissions from solid waste disposal and treatment, incineration, and wastewater treatment. The global CO_2 emissions in this exhibit represent the total emissions of the full sectors, not of the subsectors considered in this report. Based on 2019 emissions.
2. Forestry and other land use.

Note: This is based on the McKinsey EMIT database that draws on a variety of bottom-up sources. Depending on the emissions database used, data per system and the economy as a whole may vary. Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021, data for 2019); McKinsey Global Institute analysis

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[93] For more on the mobility sector, see "Why the automotive future is electric," McKinsey & Company, September 2021; Timo Möller, Asutosh Padhi, Dickon Pinner, and Andreas Tschiesner, "The future of mobility is at our doorstep," McKinsey Center for Future Mobility, December 2019; and Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel, "The zero-carbon car: Abating material emissions is next on the agenda," McKinsey & Company, September 2020.

[94] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

- **Agriculture.** Direct on-farm energy use and emissions from agricultural practices and fishing are responsible for approximately 1 percent of global CO_2 emissions, 38 percent of global methane emissions, and 79 percent of global N_2O emissions.[95] Decarbonizing agriculture would occur through shifting farming practices toward lower-emissions practices and technologies, such as making changes in animal feeding and breeding practices, improving fertilization practices, and adopting zero-emissions machinery, and through shifting diets that are currently high in protein from ruminant animals toward more plant-based foods or lower-emissions animal protein sources such as poultry, as well as reducing food waste by improving supply chains and changing consumer behavior.[96] Any such diet shifts would need to be balanced with nutritional imperatives: in some parts of the world, raising protein consumption—including through the use of ruminant-based protein sources—is vital to improving health outcomes for the population.[97]

- **Forestry and other land use.** Forestry and other land use accounts for nearly 14 percent of annual CO_2 emissions, 5 percent of global methane emissions, and 5 percent of global N_2O emissions.[98] Forestry contributes to emissions through CO_2 released into the atmosphere from land cover change (for instance, from slash-and-burn deforestation, the decomposition of felled trees, soil disturbance, and forest degradation, as well as the loss of carbon-sequestration capacity), and the release of carbon stored in soil from land cover change. Currently, ten million hectares of land are deforested every year.[99] Forests play a crucial role in decarbonization as natural carbon sinks, absorbing carbon dioxide and releasing oxygen to contribute to negative emissions. Although measuring the effects of deforestation is challenging, and trees absorb CO_2 at widely varying rates (depending on species, location, and the concentration of CO_2 in the atmosphere), estimates suggest that over a 30-year period, a tree can store an additional 60 to 85 percent as much carbon as is released when the tree is cut down or burned, and that overall emissions could be even higher considering uncertainties around secondary emissions and forgone carbon sequestration resulting from deforestation.[100] The only ways to lessen these effects are to reduce rates of deforestation, replant destroyed forests, and afforest new areas.[101]

- **Waste.** Solid waste disposal and treatment, incineration, and wastewater treatment contribute to 23 percent of methane emissions and 3 percent of N_2O emissions.[102] Actions to reduce waste emissions include diverting more recyclable materials and organic waste from landfills, investing in anerobic digestors and composters, and implementing on-site methane capture.

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[95] Ibid.

[96] For more on the agriculture and food sector, see Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, "Agriculture and climate change: Reducing emissions through improved farming practices," McKinsey & Company, April 2020.

[97] Walter Willett et al., "Food in the Anthropocene: The EAT–*Lancet* Commission on healthy diets from sustainable food systems," *The Lancet,* volume 393, number 10170, February 2019.

[98] Nitrous oxide emissions come from the oxidation of nitrogen fixated in soil that can be exposed and released by land-use change. Methane emissions come from incomplete combustion of organic matter caused by slash-and-burn practices and from the decomposition of organic material. EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[99] Forests here are defined as land spanning more than 0.5 hectare with trees higher than five meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. See *The state of the world's forests 2020: Forests, biodiversity, and people,* FAO, 2020.

[100] Research indicates that forgone carbon sequestration and forest degradation are highly underestimated in current evaluations of deforestation emissions. Estimates are associated with large uncertainties including lack of data (especially on secondary effects) and variations in carbon sequestration due to tree species, location, and concentration of CO_2 in the atmosphere. Overall, secondary emissions and forgone carbon sequestration resulting from deforestation could be up to three to nine times higher than direct emissions alone. See Sean Maxwell et al., "Degradation and forgone removals increase the carbon impact of intact forest loss by 626%," *Science Advances,* volume 5, issue 10, October 2019. For further details, see chapters 1 and 3. See also Richard Houghton and Alexander Nassikas, "Global and regional fluxes of carbon from land use and land cover change 1850–2015," *Global Biogeochemical Cycles,* volume 31, issue 3, February 2017; Nancy L. Harris et al., "Baseline map of carbon emissions from deforestation in tropical regions," *Science,* volume 336, June 2012; and Richard Houghton and Alexander Nassikas, "Negative emissions from stopping deforestation and forest degradation, globally," *Global Change Biology,* volume 24, number 1, August 2017.

[101] See "Why investing in nature is key to climate mitigation," McKinsey & Company, January 2021.

[102] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

All countries contribute to global emissions, but in general, the emissions of individual nations tend to vary in correlation with GDP and population. Overall, the top 10 emitters account for about 60 percent of global CO_2 emissions (Exhibit 4). The top three are China (approximately 26 percent), the United States (approximately 12 percent), and India (approximately 6 percent).[103]

These large emitters have very different profiles due to the structures of their economies. China's emissions derive principally from industry (approximately 12 percent of global CO_2 emissions) and power (approximately 11 percent), reflecting its emergence as a key global manufacturing hub in the past two decades. Similarly, India ranks third largely because of emissions from power generation (approximately 3 percent of global CO_2 emissions) and heavy-emitting industry processes (approximately 2 percent). By contrast, US emissions come to a greater extent from power (approximately 4 percent) and consumption of fossil fuels in road transportation (approximately 3 percent). Among other top emitters, Russia's position reflects the key role of oil and gas in the country's economy, and Japan's profile indicates the role of power generation and industry.

This profile looks somewhat different when considering cumulative historical emissions. In that respect, the United States is the largest emitter: it accounted for 417 $GtCO_2$ between 1800 and 2020, or 25 percent of global cumulative historical CO_2 emissions. China is next, with 14 percent of global cumulative historical CO_2 emissions, but the gap is closing. Russia ranks third with 7 percent of global cumulative historical CO_2 emissions, followed by Germany (5 percent), the United Kingdom (5 percent), and Japan (4 percent). India, the third-largest contributor today, ranks seventh historically because its emissions are mostly recent (45 percent of India's cumulative historical emissions have happened since 2010). The top ten largest historical emitters account for 68 percent of global cumulative historical CO_2 emissions.[104]

Achieving net-zero emissions will require addressing nine interrelated, system-level requirements

Achieving net zero is, in its essence, solving an equation that balances sources and sinks of emissions by reducing GHG emissions as much as possible while increasing GHG stores to remove any remaining emissions from the atmosphere.[105] This is what we refer to as the net-zero equation. In reality, it is not a single equation but a system of equations. The emissions equation is coupled with a capital and a labor equation; demand for capital and labor in a net-zero economy must match supply, over time and across regions. And these equations must be solved simultaneously while pursuing economic development and inclusive growth.

At present, though, the net-zero equation cannot be solved: emissions remain high and are not counterbalanced by removals. What's more, the world is not on pace to complete the net-zero transition and limit warming to 1.5°C. Based on policies currently enacted into law, UNEP, Climate Action Tracker, and the IEA project that warming will be 2.6–2.7°C by 2100. In alternate scenarios, in which current long-term net-zero targets and interim 2030 pledges are fully implemented, these organizations project that warming would be restricted between 2.1 and 2.2°C. IEA lowers this estimate to 1.8°C if net-zero targets still under discussion were also fully implemented.[106]

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[103] EMIT database, McKinsey Sustainability Insights, September 2021.
[104] Robbie Andrew and Glen Peters, "The Global Carbon Project's fossil CO_2 emissions dataset," October 2021.
[105] Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.
[106] *Emissions gap report 2021: The heat is on,* UNEP, 2021; *Warming projections global update,* Climate Action Tracker, November 2021; *World energy outlook 2021,* International Energy Agency, October 2021.

Box 2

The role of carbon capture and negative emissions

Keeping warming to 1.5°C will likely require pursuing steep reductions in gross emissions at the same time as investing in carbon capture and negative-emission technologies that remove carbon from the atmosphere and store it over the long term.[1] Promising technologies to capture and remove CO_2 from the atmosphere exist, though more effort will be needed to scale them and reduce their costs.

Emissions abatement via carbon capture, utilization, and storage.[2] Carbon capture, utilization, and storage often refers to the engineered removal of CO_2, commonly via amine scrubbing, a chemical process that absorbs CO_2 from exhaust gases. This can be done to abate CO_2 directly at the source in the case of fossil-based power plants and industrial point sources such as steel, cement, and blue-hydrogen production. Alternatively, it can be used to create negative emissions, either by removing CO_2 from the stack of a bioenergy with carbon capture and storage (BECCS) facility, or by removing CO_2 from ambient air via direct air capture (DAC) (see further detail below on negative emissions).[3] Captured CO_2 is either sequestered in sealed formations or utilized as an input for materials and goods that use recycled CO_2 such as plastics, building materials, and fuel. Approximately 40 commercial-scale CCS facilities exist globally today, which collectively abate about 40 million to 50 million tons of CO_2 per year (Mtpa).[4] Estimates for the annual abatement level required to achieve 1.5°C goals range from 5,000 to upwards of 10,000 Mtpa, more than 100 times current abatement capacity.[5] Some promising but nascent markets such as CO_2-cured concrete, plastics, and synthetic fuels could potentially expand and contribute to abatement efforts if market economics improve. Most typical transition scenarios involve other types of abatement, for example increased use of renewables, for much of the mitigation need, but they project that CCS could play a role in reducing emissions in the hardest to abate sectors.[6] It could also contribute to the gigatons of negative emissions required to stay on a 1.5°C pathway. Currently, per-tonne CO_2 capture costs can be as low as \$10–40 for high-purity industrial point sources, \$50–\$100 for low-purity point sources like coal or cement, and more than \$300 for direct air capture.[7] Capturing CO_2 often represents the largest cost in the CCS value chain which also includes compression, transportation, storage, and utilization. Manufacturer willingness to pay for CO_2 as a material input varies widely across industries and may change over time as the CCS market matures.[8] By 2030, smaller high-margin industries (for example, carbon fiber) may be willing to pay close to \$250 per ton while larger industries comprising the majority of the CO_2 market (for example, cement and enhanced oil recovery) may require prices under \$50 per ton, potentially below average future capture costs.

However, it is possible that CCS could be used more extensively to extend the lifespan of current fossil fuel–based infrastructure while minimizing additional emissions, particularly if capture costs fall. Additionally, if the scale-up of renewables proves more disorderly than forecast, CCS may play an increasingly important role in decarbonizing the backup fossil-based energy generation needed to bridge any energy gaps.

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[1] For further information, see *The case for negative emissions,* Coalition for Negative Emissions, June 2021; and Peter Cooper, Emma Gibbs, Peter Mannion, Dickon Pinner, and Gregory Santoni, "How negative emissions can help organizations meet their climate goals," McKinsey & Company, June 30, 2021. See also *Global warming of 1.5°C: IPCC special report,* Intergovernmental Panel on Climate Change, 2018.

[2] For further information, see *The case for negative emissions,* Coalition for Negative Emissions, June 2021; and *Global warming of 1.5°C: IPCC special report,* Intergovernmental Panel on Climate Change, 2018.

[3] See also Peter Cooper, Emma Gibbs, Peter Mannion, Dickon Pinner, and Gregory Santoni, "How negative emissions can help organizations meet their climate goals," McKinsey & Company, June 30, 2021.

[4] See also Krysta Biniek, Kimberly Henderson, Matt Rogers, and Gregory Santoni, "Driving CO_2 emissions to zero (and beyond) with carbon capture, use, and storage," McKinsey & Company, June 30, 2020.

[5] *Global status of CCS 2021,* Global CCS Institute, 2021.

[6] See for example, Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020.

[7] *Is carbon capture too expensive?* International Energy Agency, February 17, 2021. For conversion purposes, 1 tonne (metric ton) = 1.102 tons (US tons).

[8] CCS costs and carbon prices are a subset of the many factors that could affect overall decarbonization economics across industries. Additional transition-related and macroeconomic factors could affect not only the CCS market but overall industry economics across sectors with potential knock-on effects in the markets for CO_2 and other material inputs.

Box 2 (continued)

Negative emissions. A wide range of negative-emission solutions is available today at varying stages of deployment readiness. For example, natural climate solutions (NCSs) such as reforestation and coastal ecosystem restoration use biological mechanisms to remove CO_2 from the air and water. NCSs require minimal technological advancement and can be readily implemented today (though with potential land use constraints in some geographies). As described above, various engineered atmospheric carbon capture technologies that can be used to create negative emissions, specifically removing CO_2 from the stack of a BECCS facility, or from ambient air via DAC, are technologically feasible today but would require significant investment to drive sufficient economies of scale. BECCS creates negative emissions by capturing the CO_2 already sequestered in biomass-based fuels that would otherwise have been re-released into the atmosphere upon heating, while DAC removes CO_2 directly from the air and therefore does not require a specific point emissions source for implementation. More nascent technologies like direct ocean capture (DOC) involve either chemically or electrically capturing CO_2 directly from ocean water, in some instances producing both captured CO_2 and hydrogen as byproducts.[9] DOC, while promising due to higher concentrations of CO_2 in water than in ambient air, is still under development.

Enabling significant mobilization of negative emissions and expanding the market for CO_2 will require collaborative efforts to define what constitutes a high-quality negative emission and to shape a market for trading negative-emission credits, as well as possible regulatory intervention to encourage their purchase and the use of CO_2 more broadly as a material feedstock. If these criteria are met, some estimates suggest NCS, BECCS, and DAC could collectively deliver eight to 12 gigatons of negative emissions per year by 2050.[10]

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[9] Katie Lebling and Eliza Northrop, "Leveraging the ocean's carbon removal potential," World Resources Institute, October 2020.

[10] Peter Cooper, Emma Gibbs, Peter Mannion, Dickon Pinner, and Gregory Santoni, "How negative emissions can help organizations meet their climate goals," McKinsey & Company, June 30, 2021.

Exhibit 4

The top ten emitters account for 62 percent of global CO_2 emissions and 49 percent of global methane emissions.

% of global emissions: 0–0.2 | 0.2–0.5 | 0.5–1 | 1–2 | 2–4 | 4–8 | >8

% of global CO_2 emissions for top 10 emitting countries, 2019[1]

	Overall	Power	Industry	Mobility	Buildings	Agriculture
China	26	>8	>8	2–4	1–2	0.2–0.5
United States	12	2–4	2–4	4–8	1–2	0–0.2
India	6	2–4	2–4	0.5–1	0.2–0.5	0–0.2
Russia	4	1–2	1–2	0.5–1	0.5–1	0–0.2
Indonesia	3	0.5–1	0.5–1	0.2–0.5	0–0.2	0–0.2
Japan	3	1–2	0.5–1	0.5–1	0.2–0.5	0–0.2
Brazil	3	0–0.2	0.2–0.5	0.5–1	0–0.2	0–0.2
Germany	2	0.5–1	0.5–1	0.2–0.5	0.2–0.5	0–0.2
South Korea	2	0.5–1	0.5–1	0.2–0.5	0–0.2	0–0.2
Iran	2	0.2–0.5	0.5–1	0.2–0.5	0.2–0.5	0–0.2
Total, top 10 countries	62	22	21	10	4	1

% of global methane emissions for top 10 emitting countries, 2019[1]

	Overall	Industry	Agriculture	Waste
China	15	4–8	2–4	4–8
United States	7	2–4	2–4	1–2
India	8	0.5–1	4–8	1–2
Indonesia	5	1–2	0.5–1	0.5–1
Brazil	6	0.2–0.5	0–0.2	1–2
Russia	4	0–0.2	0.5–1	1–2
Japan	0	2–4	0–0.2	0–0.2
Iran	2	0–0.2	0–0.2	0.2–0.5
Germany	1	2–4	0.2–0.5	0–0.2
Canada	1	0.5–1	0.2–0.5	0.2–0.5
Total, top 10 countries	49	18	17	12

1. Power includes emissions from electricity and heat generation; industry includes various industrial processes, including production of steel, cement, and chemicals, and extraction and refining of oil, gas, and coal; mobility includes emissions from road, aviation, rail, maritime, and other forms of transportation; buildings includes emissions from heating, cooking, and lighting of commercial and residential buildings; agriculture includes emissions from direct on-farm energy use and fishing; forestry includes net flux of CO_2 from land use and land cover change but not the opportunity cost of lost carbon capture; waste includes emissions from solid waste disposal and treatment, incineration, and wastewater treatment. The global emissions in this exhibit represent the total emissions of all energy and land-use systems, not only those considered in this report. Based on proprietary estimation conducted by McKinsey Sustainability Insights, which leveraged data from McKinsey Global Energy Perspectives, EDGAR, IEA, FAO, Global Carbon Project. Based on 2019 emissions.

Note: Forestry and other land use, as well as waste for CO_2 and power, mobility, and buildings for CH_4, are included in the total country percentages but are not shown separately. Figures may not sum to 100% due to this and because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); McKinsey Global Institute analysis

To address the challenges inherent in solving the net-zero equation would require coordinated action by companies and countries to fulfill nine fundamental, interrelated system-level requirements—none of which has been fully met so far.[107] These can be grouped into three categories, as follows:

- *Physical building blocks,* encompassing (1) technological innovation; (2) ability to create at-scale supply chains and support infrastructure; and (3) availability of necessary natural resources. Past McKinsey research suggests that there is a line of sight to the technologies needed to limit warming to 1.5°C above preindustrial levels, although continued innovation is still needed. McKinsey research on decarbonization in Europe, for example, suggests that more than 85 percent of the emissions abatement needed to achieve net-zero emissions by 2050 could come from technologies already demonstrated, including 28 percent that are now mature and 32 percent that are in an early phase of adoption.[108] Further innovation, both to develop new technologies that can be deployed at scale and to reduce their costs, is still needed, particularly related to various hard-to-abate sectors. Nor should the deployment challenges be underestimated; effective deployment would require addressing many other requirements. For example, under a 1.5°C pathway, McKinsey analysis finds that the number of solar panels installed globally per week would be approximately eight times higher than the number today. The rate of wind-turbine installations would need to increase fivefold.[109] And natural resources, including raw materials such as copper, nickel, rare-earth metals, land, and water, would also need to be carefully managed to ensure sufficient availability, and minimize bottlenecks, and prevent price spikes and inflation. Building out supply chains to support the kind of step change in deployment needed requires not only significant capital and the right capabilities but also extensive coordination.

- *Economic and societal adjustments,* comprising (4) effective capital reallocation and financing structures; (5) management of demand shifts and near-term unit cost increases; and (6) compensating mechanisms to address socioeconomic impacts. As we discuss in this research, an orderly transition to net zero would require significant changes to capital allocation. Companies and countries would need to manage the demand shift and cost changes from a wholesale revamping of energy and land-use systems, even as the implications for individuals and communities in livelihoods and expenditures could be substantial.

- *Governance, institutions, and commitment,* consisting of (7) governing standards, tracking and market mechanisms, and effective institutions; (8) commitment by, and collaboration among, public-, private-, and social-sector leaders globally; and (9) support from citizens and consumers. The pace, scale, and systemic nature of the required transition mean that all stakeholders will need to play a role, working together in new ways. Securing an orderly transition will require leaders who have the commitment and capabilities to develop coherent, reliable, and workable policies and help their organizations navigate the changes that lie ahead. The transition is also unlikely to occur without the support of citizens and consumers, and in some cases, consumers may need to fundamentally shift behaviors to reduce their own emissions.

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[107] Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.

[108] See Paolo d'Aprile, Hauke Engel, Godart van Gendt, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, December 2020.

[109] Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad, and Daniela Vargas, "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly,* April 2020.

As stakeholders have increased their commitments to net zero, moving from commitments to action has not proven easy or straightforward. This is for five reasons: the scale and pace of the step-up in spending needed on physical assets, given that entire energy and land-use systems that evolved over a century or two would have to be transformed over the next 30 years; the collective and global action required, particularly as the burdens of the transition would not be evenly felt; the near-term shifts needed for longer-term benefits; the shifts needed in business practices and lifestyles that have evolved over decades; and the central role of energy in all economic activity, which means that transformation would need to be carefully managed. Indeed, the transition will transform the very systems that support our lives and well-being. Even small disturbances to these systems could affect daily lives, from raising producer and consumer costs to impairing energy access. This in turn could lead to delays and a public backlash. Together, these factors highlight why the prevailing notion of enlightened self-interest alone is unlikely to be sufficient to help achieve net zero.

Challenging as the problem may be, not solving it is not an option. A key first step is better understanding what it takes to meet the requirements described above. In this report, we focus on the second of these groupings of requirements, the economic and societal adjustments, to better understand these requirements and how stakeholders can respond. There is a real risk that transition burdens could be unbearable to many in the absence of compensating measures; for example, if companies and countries do not manage the shifts in demand or cost impacts to their existing products and services, or if communities are left behind as the world transitions to a net-zero economy. By recognizing the nature and magnitude of the changes the net-zero transition would entail, decision makers can better prioritize and coordinate actions facilitating a prompt, relatively orderly, and inclusive net-zero transition. They can also navigate their organizations toward a prosperous future.[110]

We illustrate the significant adjustments that would need to be made through an analysis of the nature and the magnitude of the transition on demand, capital allocation, costs, and jobs. Various other knock-on effects could also ensue and potentially affect, among others, value pools, financial valuations, GDP, and global trade flows. While we do not quantify these, we discuss some of them qualitatively throughout the report.[111]

Large-scale decarbonization of the world's energy and land-use systems will be essential to slow and halt the buildup of physical climate risk. But what will the shifts in a transition to net-zero emissions actually mean for the global economy and individual countries, sectors, and consumers? In the following chapters, we provide the findings of our analysis, highlighting the extent of the potential shifts, the key challenges, and the opportunities that the transition to net zero will bring.

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[110] The concept of a just transition is sometimes used in the context of the climate transition, with a focus on so-called climate justice. This concept implies that the impact of physical and transition risks, as well as the ability to deal with these risks, will differ significantly across generations, regions, socioeconomic status, and gender. It also implies that these differential risks need to be managed for the transition to be effective and sustainable for the global community as a whole. See Mary Robinson, *Climate justice: Hope, resilience, and the fight for a sustainable future,* Bloomsbury Publishing, 2018.

[111] We have focused on quantifying the direct shifts, given the vast uncertainties involved in modeling these higher-order effects, and because their outcome could vary based on specific actions taken to manage them. For further details on our methodology, see the technical appendix.

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2. The economic transformation

In this chapter, we examine the economic transformation that would need to take place over the next three decades to achieve a successful transition to net-zero emissions by 2050. We look at the shifts in the economy in aggregate, on energy and land-use systems and the sectors that make them up, and on individuals, both consumers and workers. Our focus is on four areas—demand, capital allocation, costs, and jobs.[112]

Our analysis, focused on scenarios from the Network for Greening the Financial System (NGFS), is neither a projection nor a prediction.[113] We consider a scenario with a pathway for emissions reductions that would give an even chance of limiting warming to 1.5°C, with a focus on areas that produce about 85 percent of overall emissions. However, it is not clear whether the world will be able to keep the temperature increase to that level, or which of numerous pathways it may take in an effort to do so. This research does not take a position on such questions. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable.

Even under the relatively orderly net-zero transition scenario considered here, the economic transformation will be universal, significant, and often front-loaded, with uneven exposure across sectors, geographies and communities, and individuals. Among the challenges is the risk of short-term disruptions in energy markets, and in the economy more broadly, if the ramp-down of high-emissions activities is not carefully managed in parallel with the ramp-up of low-emissions ones. A disorderly transition could affect the economy as a whole and come with a backlash that delays the transition.

For all its short-term risks, the transition will also create rich new opportunities across sectors and geographies, for example in the form of new markets for low-emissions products and support services. More broadly in considering the economic and societal adjustments necessary for achieving net-zero emissions, it is important not to lose sight of the bigger context: the substantial longer-term risks from increased warming and the further buildup of physical risks. The findings of this research thus highlight the need for more thoughtful and decisive action towards an orderly transition to net-zero emissions.

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[112] Multiple higher-order effects beyond these four areas could also occur as the economy transitions; for example on GDP, inflation, valuations, trade flows, and profit pools. We do not directly analyze these, given the complexities of modeling these effects, but we discuss some of them qualitatively here and in chapter 4. For further details on our methodology, see Box E1 and the technical appendix.

[113] Our analysis in this chapter and the full report is focused on a hypothetical path based on the NGFS Net Zero 2050 scenario, which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." Net zero is reached on a global basis in the scenario. Some high-emissions activities in hard to abate sectors such as industry, road freight, and agriculture, do not fall to zero by the middle of the century. Residual CO_2 emissions from these activities are counterbalanced by removals such as through land restoration and the use of bioenergy with CCS in the scenario. If investment in removals proves insufficient, these high-emissions activities would need to fall by an even greater extent to give an even chance of limiting warming to 1.5°C. In some instances, variables were downscaled by Vivid Economics to provide more sector granularity, in a manner consistent with the overall NGFS Net Zero 2050 scenario. More broadly, this analysis does not consider the question of how the transition is financed, and the impacts that would have on the results shown here. In this chapter, we sometimes compare the NGFS Net Zero 2050 scenario with the NGFS Current Policies scenario, which projects the greenhouse gas emissions that would occur if today's policies remain in place. To estimate the potential shift in jobs, we conduct a third analysis that separates out the transition-related effects from other potential labor-market shifts resulting from GDP growth, population growth, productivity gains, and automation adoption. For a detailed discussion of our methodology, see the technical appendix.

Six features characterize the net-zero transition

Six features characterize the shifts in energy and land-use systems, economic sectors, and countries in the net-zero transition, according to our analysis. They are the following:

Universal. All seven major energy and land-use systems contributes substantially to emissions individually, and each will thus need to undergo transformation if the net-zero goal is to be achieved. Moreover, these systems are highly interdependent. Actions to reduce emissions must therefore take place in concert across the systems. For instance, electric vehicles lead to overall emissions reductions only to the extent that low-emissions electricity production has been achieved. More broadly, all sectors and geographies must play a role. All sectors of the economy participate in these energy and land-use systems across global value chains. Similarly, all countries contribute to emissions, either directly or through their role in value chains (although with significant differences, as we note below).

Significant. The economic transformation needed to achieve the transition to net zero will be substantial. Our analysis focuses on demand, capital allocation, costs, and jobs. Looking just at capital allocation, we find that annual spending on physical assets for the energy and land-use systems through 2050 would need to be about 60 percent greater than it is today, rising by $3.5 trillion annually on average and $0.9 trillion relative to a Current Policies scenario. In all, our analysis suggests that the Net Zero 2050 scenario would require spending on physical assets of about $275 trillion between 2021 and 2050 (about 7.5 percent of GDP over the period) in the areas we analyzed. We also see significant shifts in demand for various goods and services in the scenario analyzed here, including steep declines in demand for coal, oil, and gas production and an eventual virtual end to manufacturing of cars with internal combustion engines, as sales of zero-emissions alternatives (battery-electric and fuel cell-electric vehicles) increase from 5 percent of new-vehicle sales in 2020 to virtually 100 percent by 2050.

Front-loaded. Several aspects of the transition to net zero would be more significant in the early stages of the shift. For example, the capital spending increase noted above would rise from 6.8 percent of GDP today to about 9 percent of GDP between 2026 and 2030 before falling. Delivered cost of electricity could increase in the near term relative to 2020 levels. In our scenario, delivered cost of electricity could rise about 25 percent from 2020 levels until 2040 and still be about 20 percent higher in 2050 to build out renewable power assets and grid infrastructure. In the long run, it is conceivable that the delivered cost of electricity could be on par with or potentially even less than today, because renewables have a lower operating cost—provided that the power system can find ways to overcome the intermittency of renewable power and build flexible, reliable, low-cost grids. The up-front capital spending for the net-zero transition could also lower other operating costs over time for consumers. A key example of that is mobility. More broadly, action is needed over the next decade to reduce the buildup of emissions and prevent rising physical risks that might occur in future decades.

Uneven. While universal, the economic exposure to the transition will not be uniform across sectors, geographies, and communities and individuals. First, sectors that account for approximately 20 percent of GDP are most directly exposed to the transition; they have high levels of emissions in their operations (for example, steel and cement) and in the use of their products (for example, automobiles and fossil fuels). Sectors accounting for about another 10 percent of GDP are also exposed because of emissions in their supply chains (for example, construction).[114] Many could see a decline in demand for products in their current form. Many of these sectors would also incur cost increases as they decarbonize. For example, steel and cement production costs would rise by about 30 percent and 45 percent, respectively, by 2050, compared with today, in the scenario analyzed here. Second, lower-income countries or those with economies that depend heavily on fossil fuel

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[114] See chapter 3 for details.

resource–producing sectors would also be more exposed; for example, sub-Saharan Africa, Latin America, India, and some other Asian countries would require capital spending of about 10 percent or more of GDP, approximately one and a half times more than the capital spending in other regions such as Europe, the United States, and Japan, and deploying this capital may be more challenging for these regions; a greater share of their economic activity, employment, and capital stock would also be exposed and may need to transform (see chapter 4 for further details). Finally, within countries, certain communities could be more affected than others if their economies rely heavily on industries that have high levels of emissions or whose products are heavy emitters; in the United States, for example, more than 10 percent of employment in 44 counties is in coal, oil, and gas, fossil fuel–based power, and automotive. Workers in such exposed sectors are especially vulnerable; for example, by 2050 in the Net Zero 2050 scenario, demand for fossil fuel–based power jobs could be about 60 percent lower compared to today's direct jobs related to operational activities due to the net-zero transition, while millions of new jobs could be created in the renewables sector.[115] Finally, any increase in prices would affect lower-income households the most.

Exposed to risks. Management of the transition to net zero will substantially influence outcomes, and any net-zero transition scenario including the Net Zero 2050 one we use in this research will be exposed to risks. These risks range from the potential for increased physical climate risks, if any transition is abrupt or delayed, to heightened labor market disruption in the event that the nature of any change is so abrupt that workers have insufficient time to adapt. Large-scale asset-stranding is also a significant risk, if an abrupt transition means that even relatively new high-emissions assets are retired or replaced with low-emissions ones before their normal replacement cycles. Our analysis for stranded assets in the power sector suggests that about $2.1 trillion of assets could be prematurely retired or underutilized in the net-zero scenario analyzed here between now and 2050.[116] One of the most immediate risks is that of a disorderly energy transition, if the ramp-up of low-emissions activities does not take place fast enough to fill gaps left by the ramping down of high-emissions activities. That mismatch could potentially affect energy markets and the economy more broadly if energy supply and prices become volatile. This in turn could potentially create a backlash that delays the transition. Higher-order effects could include declines in market prices including for financial assets.

Rich in opportunity. The opportunities for countries, sectors, and companies could be considerable if they are able to tap into growing markets as the world transforms to a net-zero economy. Nations that have abundant natural capital, such as more hours of sunshine, or that invest in technological, human, and physical capital could be well positioned to prosper in the net-zero economy. Companies could also gain from three categories of opportunity: first, through decarbonizing processes and products, which can make them more cost-effective in some cases or tap into new markets for relatively lower-emissions products; second, from entirely new low-carbon products and processes that replace established high-carbon options, for example carmakers meeting new demand for electric rather than ICE vehicles; and third, through new offerings to support production in the first two categories. These could take the form of inputs such as lithium and cobalt for battery manufacturing, physical capital such as solar panels, and an array of technical services from forest management to financing to emissions measurement. And the most significant benefit of the net-zero transition and limiting warming to 1.5°C is preventing the buildup of physical risks and reducing the odds of initiating the most catastrophic impacts of a changing climate.

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[115] By "direct" jobs we mean jobs in the specified sector, as opposed to "indirect" jobs, which refers to the upstream jobs that produce inputs for production in the specified sector, as discussed in detail below.

[116] Our definition of stranded assets represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years. Other research has found similar effects on the power sector. See, for example, *Stranded assets and renewables: How the energy transition affects the value of energy reserves, buildings and capital stock,* International Renewable Energy Agency, 2017; and David Nelson et al., *Moving to a low-carbon economy: The impact of policy pathways on fossil fuel asset values,* Climate Policy Initiative, October 2014. Studies in the academic literature for fossil fuel stranded value have estimated forgone revenues of between $7 trillion and $11 trillion, discounted over the next 15 years relative to a current policies scenario. See Jean-Francois Mercure et al., "Reframing incentives for climate policy action," *Nature Energy,* November 2021.

Demand: In the scenario analyzed here, high-emissions products would see shrinking demand, while the uptake of low-emissions products would create opportunities

For most companies today, GHG emissions build up along their value chains as they use energy and materials to produce and sell their offerings. In some cases, such as for vehicles with internal combustion engines, the use of their products also generates emissions. Under the NGFS Net Zero 2050 scenario, our analysis suggests, changes in policies, technologies, and consumer and investor preferences would drive demand away from goods and services whose production or use results in high emissions and toward low- or zero-emissions goods and services (Exhibit 5). While the transition to a net-zero economy could result in the need for transformation in some parts of the economy, it would also provide opportunities, as we discuss later in this chapter.

A key demand shift from the Net Zero 2050 scenario relates to energy. Demand for carbon-intensive fossil fuel energy would fall sharply, while demand for emissions-free electricity, as well as hydrogen and biofuels, would rise. By 2050, in this scenario, oil and gas production volumes would be 55 percent and 70 percent lower, respectively, than they are today. Coal production for energy use would all but disappear.

This shift in energy mix would have cascading effects on sectors that sell products whose use relies on fossil fuels. These sectors include makers of internal combustion engine–based cars, other transportation equipment, and industrial equipment such as motors and furnaces. The mix of products in certain sectors would change as a result; for example, the automotive sector would transition from selling ICE cars to electric vehicles. In the Net Zero 2050 scenario, sales of low-emissions cars would increase from 5 percent of new-vehicle sales in 2020 to virtually all sales by 2050.

Demand could also fall or shift for products with high scope 1 emissions as the result of emissions-intensive operations. End users of products from those sectors may switch to substitutes or reduce their consumption to lower their upstream emissions or minimize their exposure to upstream cost increases. In the scenario analyzed here, steel production would increase by about 10 percent relative to today, with low-emissions steel rising from one-quarter of all production to almost all production by 2050. Agriculture and food sectors could potentially face the effect of dietary shifts away from emissions-intensive beef and lamb toward lower-emissions sources of protein.[117]

In other areas, demand could grow.[118] Power demand in 2050 in this scenario would more than double from today. New industries based on hydrogen, biofuels, and CCS could expand. Our analysis suggests that the production of both hydrogen and biofuels would increase more than tenfold from now to 2050 in the Net Zero 2050 scenario.[119] Carbon management could also offer substantial opportunity; for example, in the Net Zero 2050 scenario, forestland cover would rise by 160 million hectares by 2050, an increase of 4 percent relative to today, sequestering approximately nine metric gigatons of CO_2 by the middle of the century.

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[117] Over the past two decades, there has been a trend toward greater consumption of meat protein, particularly as many developing countries have become wealthier. In the NGFS Current Policies scenario, this trend continues to manifest over time between 2020 and 2050, raising the share of livestock within overall food production. See *OECD-FAO agricultural outlook 2020-2029,* OECD, July 2020. In the net-zero scenario analyzed in this report, the share of livestock in agricultural production increases at the same rate as in the Current Policies scenario, but consumers allocate more of their meat consumption to lower-emission poultry rather than ruminants like beef or lamb.

[118] Increased energy access relative to today and growing population globally would also drive some of the increase described here.

[119] For hydrogen, this excludes captive production for industrial end uses such as refineries and chemicals.

While the discussion above focuses on sectors and products, the Net Zero 2050 transition could also affect companies, potentially changing the basis of competition among companies within the same sector as they internalize the cost of carbon by paying for abatement solutions or by transforming their business models to move out of shrinking markets and into growing ones. For example, in sectors such as auto manufacturing, companies such as Tesla are offering low-emissions alternatives and incumbents are rapidly adapting to shifts in demand, reshaping the sector.

Capital allocation: About $275 trillion of spending on physical assets would be needed over the next three decades under the NGFS Net Zero 2050 scenario

Shifts in demand during the net-zero transition would trigger the retirement or transformation of some existing physical assets and the acquisition of new ones.[120] Our analysis suggests that these moves would influence spending on physical assets in two ways. First, spending would increase significantly relative to today. Second, a portion of the capital that is now being spent on high-emissions assets would be spent instead on low-emissions assets, including those with CCS installed.[121]

Our analysis of the NGFS Net Zero 2050 scenario suggests that about $275 trillion in cumulative spending on physical assets, or approximately $9.2 trillion per year, would be needed between 2021 and 2050 in the sectors we studied. This is equivalent to about 7.5 percent of GDP over the period (Exhibit 6).[122]

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[120] Based on analysis of systems that account for about 85 percent of overall GHG emissions today. This estimation includes spending for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (for example, for vehicles and alternate methods of steel and cement production), and various forms of land use (for example, GHG-efficient farming practices). This includes both what is typically considered investment in national accounts and, in some cases, spending on consumer durables such as personal cars. We typically consider spending to replace physical assets at the point of emissions (for example, cars for mobility); additional spending would also occur through the value chain. We have not sized this to minimize double counting.

[121] Our analysis divides high-emissions assets from low-emissions assets and enabling infrastructure. Low-emissions assets have a relatively low emissions footprint; the term does not always mean carbon neutral. This segmentation was done to allow us to size the scale of capital reallocation needed for the net-zero transition. In doing so, we recognize that the demarcation between high and low emissions is not always clear. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, geothermal, biomass, gas with CCS, and nuclear power along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using EAF, DRI with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or coal and gas kilns with CCS; zero-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass, including heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; land restoration.

[122] For details of the methodology used to arrive at these figures, see the technical appendix.

Exhibit 5

The NGFS Net Zero 2050 scenario entails a transformation of energy and land-use systems. (1 of 2)

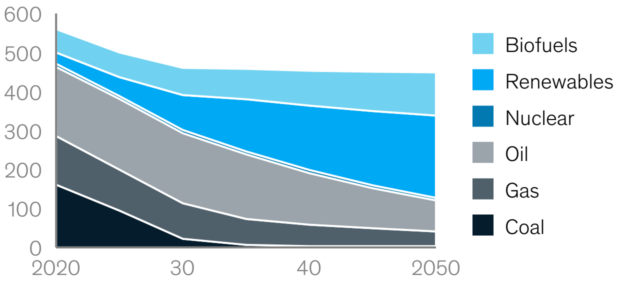
Not exhaustive

Activity level trajectory, 2020–50[1]

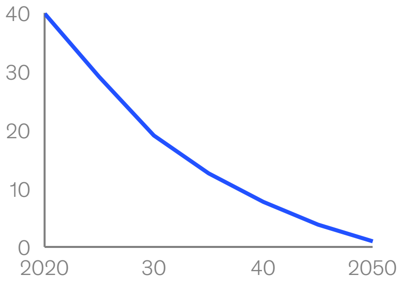
Emissions trajectory, 2020–50[1]

Overall

Primary energy, Exajoule

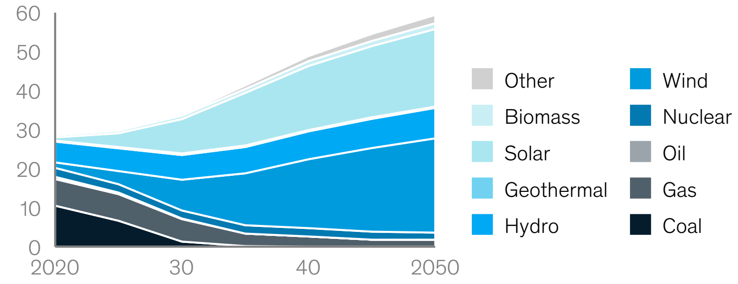


Global CO_2 emissions, billion metric tons[2]

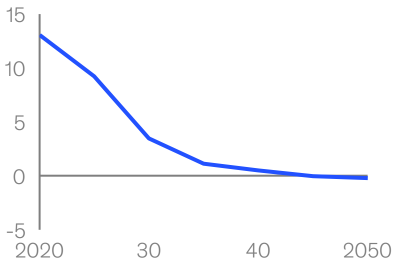


Power

Electricity generation by source, Peta-Watt hours

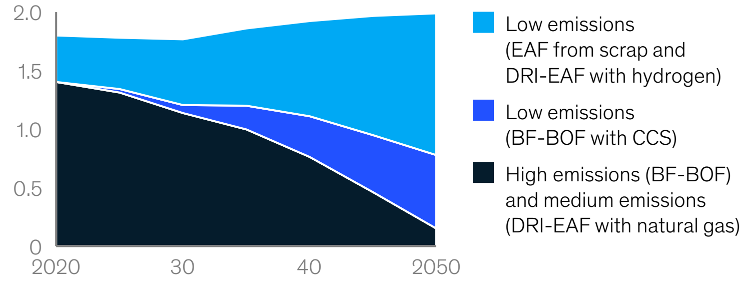


Electricity generation CO_2 emissions, billion metric tons

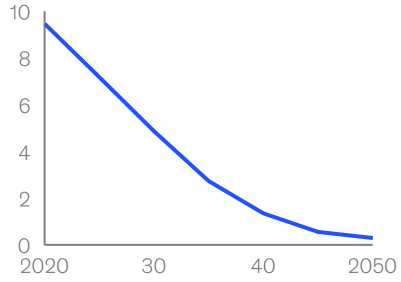


Industry: **Steel**

Steel production, billion metric tons

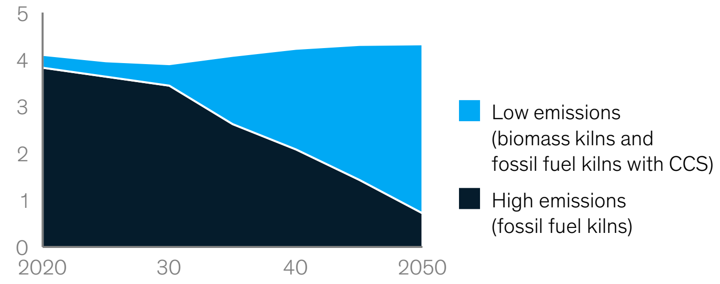


Industrial process and energy demand, CO_2 emissions, billion metric tons[3]



Industry: **Cement**

Cement production, billion metric tons



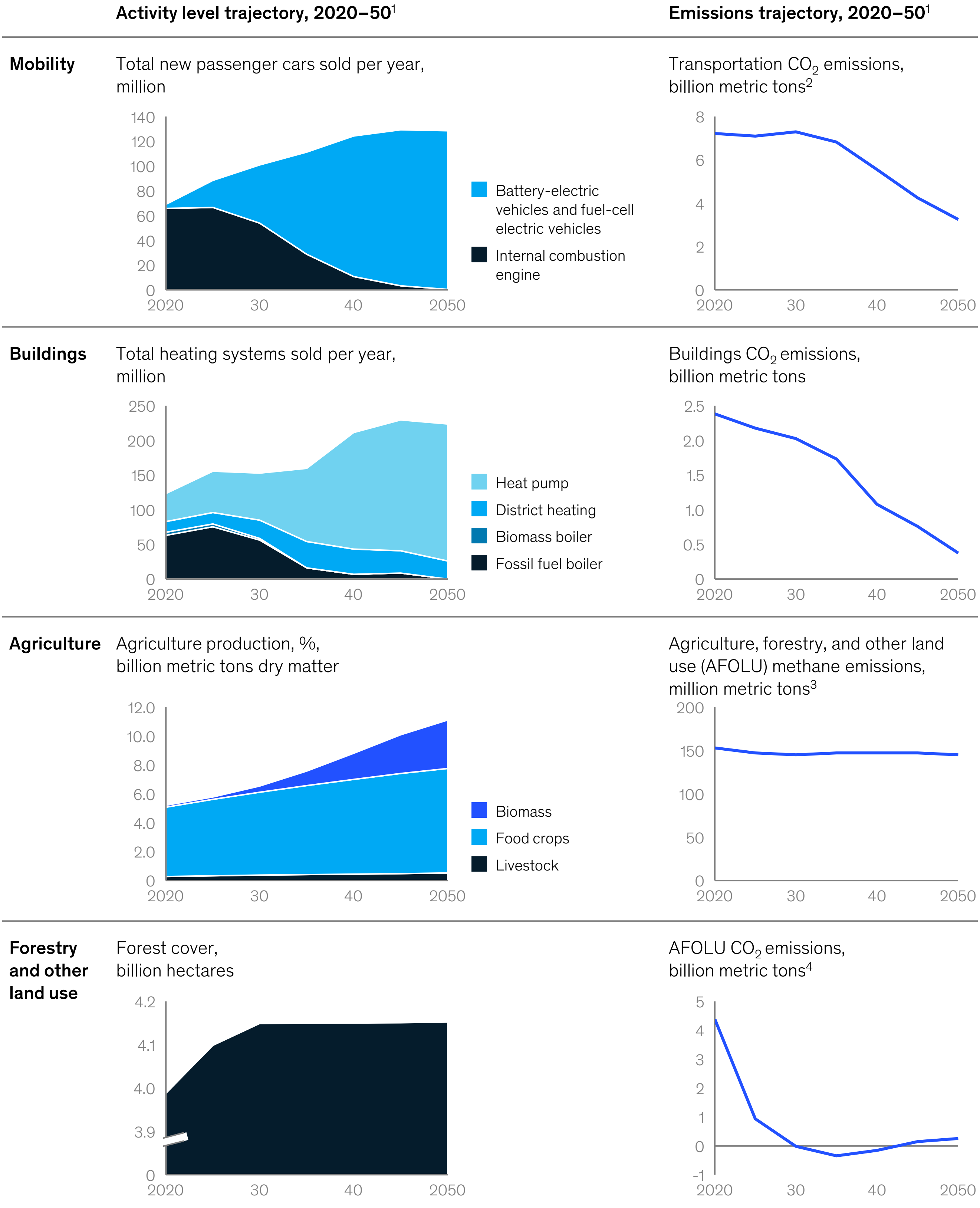
1. Based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE. In some instances, variables were downscaled by Vivid Economics. This represents global activity levels and emissions. In the Net Zero 2050 scenario, different systems reach zero emissions at different times.
2. The overall trajectory of CO_2 emissions will be influenced in large part by the trajectory and mix of primary energy use. However, other factors, for example rates of afforestation and deforestation as well as industrial processes, will also play a role.
3. Emissions for the entire industry system, not only for cement and steel.

Source: NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2); Vivid Economics; McKinsey Sustainability Insights; McKinsey Global Institute analysis

Exhibit 5 (continued)

The NGFS Net Zero 2050 scenario entails a transformation of energy and land-use systems. (2 of 2)

Not exhaustive



Activity level trajectory, 2020–50[1]

Emissions trajectory, 2020–50[1]

Mobility

Total new passenger cars sold per year, million

Transportation CO_2 emissions, billion metric tons[2]

Buildings

Total heating systems sold per year, million

Buildings CO_2 emissions, billion metric tons

Agriculture

Agriculture production, %, billion metric tons dry matter

Agriculture, forestry, and other land use (AFOLU) methane emissions, million metric tons[3]

Forestry and other land use

Forest cover, billion hectares

AFOLU CO_2 emissions, billion metric tons[4]

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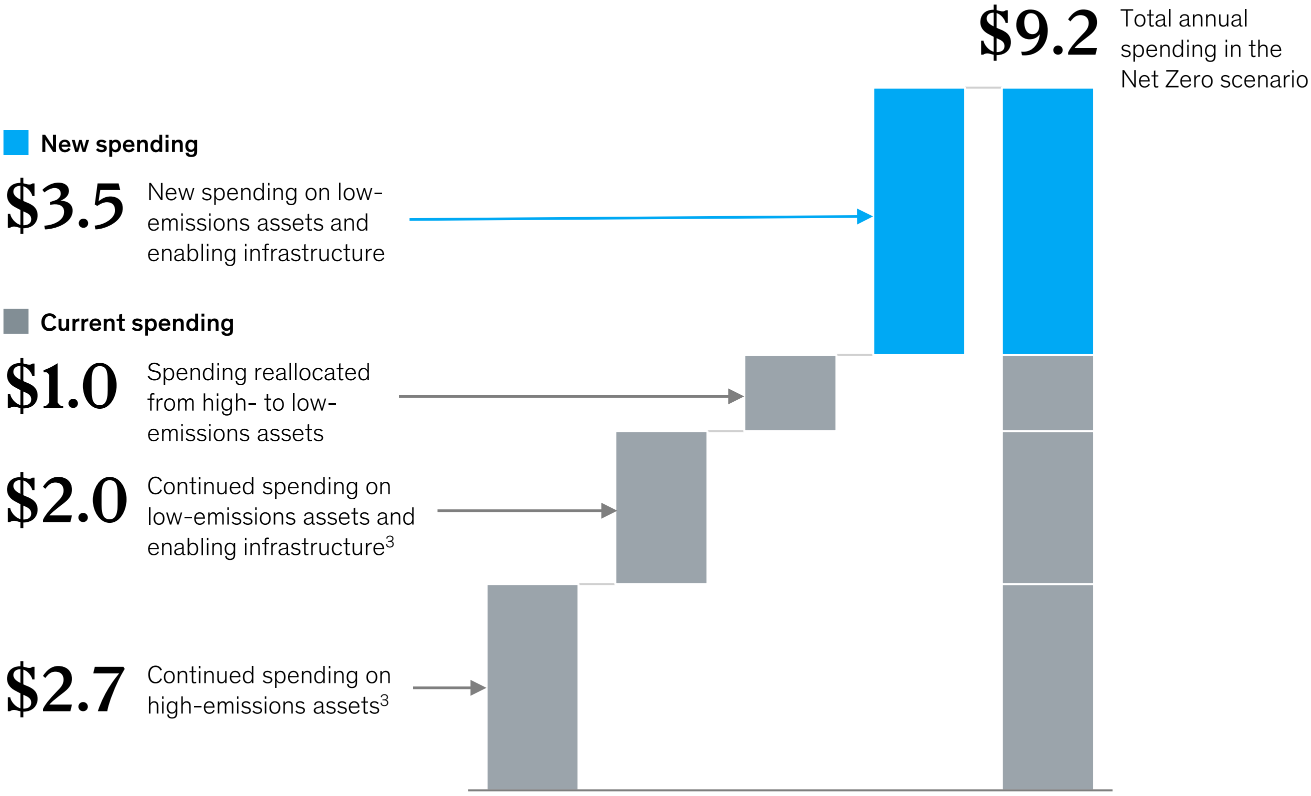
1. Based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE. In some instances, variables were downscaled by Vivid Economics. This represents global activity levels and emissions. In the Net Zero 2050 scenario, different systems reach zero emissions at different times.
2. Includes road transportation, aviation, freight, and rail.
3. Methane emissions from agriculture, forestry, and other land use are mostly influenced by agriculture, but they also include a small amount of emissions from forestry and other land use.
4. Carbon dioxide emissions are mostly influenced by forestry and other land use, but they also include a small amount of emissions from agriculture. Afforestation contributes to cumulatively sequestering approximately nine metric gigatons of carbon dioxide by 2050 in the NGFS Net Zero scenario.

Source: NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2); Vivid Economics; McKinsey Sustainability Insights; McKinsey Global Institute analysis

Exhibit 6

Spending on physical assets for energy and land-use systems in the NGFS Net Zero 2050 scenario would rise to about $9.2 trillion annually, or about $3.5 trillion more than today.

Annual spending on physical assets for energy and land-use systems[1] in the Net Zero 2050 scenario,[2] average 2021–50, $ trillion



1. We have sized the total spending on physical assets in power, mobility, fossil fuels, biofuels, hydrogen, heat, CCS (not including storage), buildings, industry (steel and cement), agriculture, and forestry. Estimation includes spend for physical assets across various forms of energy supply (eg, power systems, hydrogen, and biofuel supply), energy demand (eg, for vehicles, alternate methods of steel and cement production), and various forms of land use (eg, GHG-efficient farming practices).
2. Based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall CO_2 emissions today. Spend estimates are higher than others in the literature because we have included spend on high-carbon technologies, agriculture, and other land use, and taken a more expansive view of the spending required in end-use sectors.
3. Our analysis divides high-emissions assets from low-emissions assets. High-emissions assets include assets for fossil fuel extraction and refining, as well as fossil fuel power production assets without CCS; fossil fuel heat production, gray-hydrogen production; steel BOF; cement fossil fuel kilns; ICE vehicles; fossil fuel heating and cooking equipment; dairy, monogastric, and ruminant meat production. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, geothermal, biomass, gas with CCS, and nuclear power along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using EAF, DRI with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or fossil fuel kilns with CCS; low-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass, including heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; and land restoration.

Source: McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

This represents spending related specifically to the deployment of new physical assets and to the decarbonization of existing assets. It does not include spending to support other adjustments—for example, to reskill and redeploy workers, compensate for stranded assets, or account for the loss of value pools in specific parts of the economy. Other research to date that has sized investment needs for the transition has largely focused on estimating required energy investment. Here we expand this to include additional spending categories.[123] As a result, our estimates exceed to a meaningful degree the $3 trillion to $4.5 trillion of annual spending for the net-zero transition that others have estimated.[124]

The required spending would be front-loaded and would rise from about 6.8 percent of GDP today to about 9 percent of GDP between 2026 and 2030 before falling. In dollar terms, the increase in spending is about $3.5 trillion per year, or 60 percent, more than is being spent today, all of which would be spent in the future on low-emissions assets. This incremental spending of $3.5 trillion per year would be worth about 2.8 percent of global GDP on average between 2020 and 2050. To put this in comparable terms, the increase is approximately equivalent, in 2020, to half of global corporate profits, one-quarter of total tax revenue, 15 percent of gross fixed capital formation, and 7 percent of household spending.

The second aspect, the reallocation of spending, would also be significant. At present, $3.7 trillion—or 65 percent of total spending—goes annually toward high-emissions assets, such as coal-fired power plants and vehicles with internal combustion engines. In this net-zero scenario, about $1 trillion of today's spending on high-emissions assets would need to be reallocated to low-emissions assets. Of the overall $9.2 trillion needed annually for a net-zero transition over the next 30 years, $6.5 trillion—or 70 percent of total spending—would go toward low-emissions assets, reversing today's trend. The economic transformation that this large-scale reallocation of spending implies could lead to some physical assets becoming redundant or stranded (see Box 3, "A portion of today's productive capital stock could be stranded under a net-zero transition, with knock-on consequences").

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[123] We broadened the analysis here to include a more comprehensive view of spending by households and businesses on assets that use energy (for example, the full cost of passenger cars and heat pumps); capital expenditures in agriculture and forestry; and some continued spend in high-emissions physical assets like fossil fuel–based vehicles and power assets. This spending will be particularly needed in the early years of the transition. Our estimates may thus be higher than others in the literature because we have accounted for these categories, including incumbent spending on high-carbon technologies, spending on agriculture, and land use, and taken a more expansive view of the spending required in end-use sectors. For further details, see the technical appendix.

[124] See *Net Zero by 2050: A roadmap for the global energy sector,* IEA, 2021; *NGFS climate scenarios for central banks and supervisors,* NGFS, 2021; Christoph Bertram et al., "Energy system developments and investments in the decisive decade for the Paris Agreement goals," *Environmental Research Letters,* volume 16, number 7, June 2021; David McCollum et al., "Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals," *Nature Energy,* volume 3, June 2018. The Energy Transitions Commission found incremental spending needs are $1.5 trillion–$1.8 trillion per annum, which is also within the $3 trillion–$4.5 trillion range cited for total spending needs. See *Making Mission Possible: Delivering a Net-Zero Economy,* Energy Transitions Commission, September 2020. Back in 2014, the Global Commission on the Economy and Climate with an expanded scope more similar to this report found investment needs of around $6 trillion between 2015 and 2030, but much smaller incremental spending needs. See *Better Growth, Better Climate: The New Climate Economy Report,* The Global Commission on the Economy and Climate, 2014.

While the above comparisons were relative to spending today, if we consider the likely evolution of spending across the economy given population growth, GDP growth, and current momentum toward the net-zero transition, the capital outlay would be smaller but remain significant. If we take as a basis the NGFS Current Policies scenario—which accounts for expected income and population growth, as well as currently legislated policies and expected cost reductions in key low-emissions technologies—the incremental annual spending in a net-zero scenario would be about $0.9 trillion rather than the $3.5 trillion increase noted above (Exhibit 7).[125] Approximately 50 percent of the $8.3 trillion in annual spending in the NGFS Current Policies scenario would be on low-emissions assets, which highlights that already some shift to low-emissions spending is anticipated in this scenario from existing technological trends and policies today.

Three groups of systems—mobility, power, and buildings—would account for approximately 75 percent of the total spending on physical assets in the Net Zero 2050 scenario. The mobility system will need the most spending by far between 2021 and 2050—a cumulative total of about $105 trillion. The annual average spending of $3.5 trillion over this period for road mobility is 1.5 times greater than it is today. This increase is primarily driven by the increase in new vehicle sales with population growth and the build-out of BEV charging and FCEV refueling infrastructure. With the decline of battery prices, the premium of EV car prices to ICE cars is expected to narrow over time (see chapter 3 for details).

The power sector accounts for the second-highest component of spending globally, after mobility. This amounts to a cumulative total of $60 trillion between 2021 and 2050, split approximately evenly between expanding power production capacity and building out enabling infrastructure such as transmission, distribution, and storage. Annual average spending over the period is more than twice today's spending. This is due to increased electrification needs of the economy to support growth as well as the net-zero transition, and from investment in a system which is moving from high fuel-driven variable costs to one which is dominated by capital deployment with relatively low operating expenses. Buildings would need cumulative spending of almost $50 trillion between 2021 to 2050 to install heating and cooking systems with electric and other alternatives and to improve insulation.

Although electrification combined with decarbonizing the power supply is a common theme in the NGFS Net Zero 2050 scenario, it is by no means the only energy shift. Electricity is not a suitable energy carrier for many end-user applications, requiring the development of alternative low-emissions-fuel options. About $50 billion per year would be needed to expand the supply of commercial heat to district heating networks, particularly in regions that have a high density of apartment buildings where other low-emissions technologies like heat pumps may not be suitable. In addition, about $230 billion per year, or $6.9 trillion in total over the next three decades, would be spent in this scenario on increasing production capacity of hydrogen and liquid biofuels. This represents a step change in spending relative to today.

Much of these alternative fuels would be used in industry. That would require capital spending in sectors such as steel and cement to build alternative production capacity (for example, using hydrogen and biomass as fuel sources). Spending would also be needed to retrofit machinery (for example, by installing carbon capture and sequestration technology) to lower overall emissions intensity. Within industry, some spending on fossil fuels would continue as the economy transitions to alternatives. Spending on the extraction, processing, and distribution of coal, oil, and gas would amount to close to $20 trillion in total between 2021 and 2050 in the NGFS Net Zero 2050 scenario; the annual average would be one-third less than the annual spend today despite significant population growth over the period as the world transitions away from such fuels.

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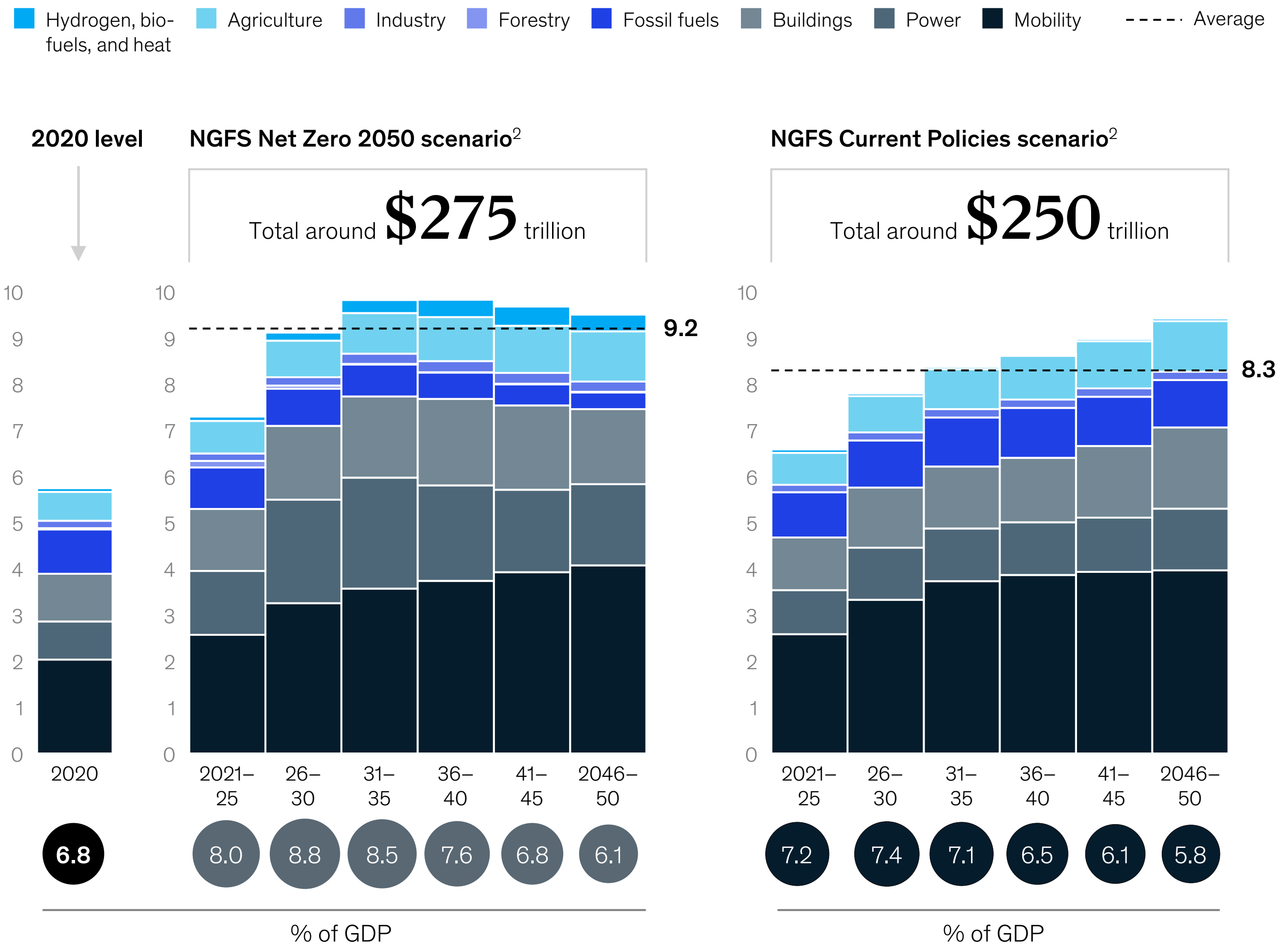
[125] The NGFS Current Policies scenario projects the greenhouse gas emissions that would occur if only today's policies remained in place, and it anticipates about 3°C of warming by 2100. See Box E1 and the technical appendix.

Exhibit 7

The NGFS Net Zero 2050 scenario would entail $275 trillion in cumulative investments over 30 years—almost $25 trillion more than the Current Policies scenario.

Annual spend on physical assets for energy and land-use systems,[1] $ trillion per year



1. We have sized the total spending on physical assets in power, mobility, fossil fuels, biofuels, hydrogen, heat, CCS (not including storage), buildings, industry (steel and cement), agriculture, and forestry. Estimation includes spend for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (for example, for vehicles, alternate methods of steel and cement production), and various forms of land use (for example, GHG-efficient farming practices). This includes both what are typically considered "investments" in national accounts and spend, in some cases, on consumer durables such as personal cars. Annual average over 5-year periods.
2. Scenario based on the Network for Greening the Financial System Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Current policies is based on the NGFS Current Policies scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall CO_2e emissions today. Our analysis includes a more comprehensive view of spending by households and businesses on assets that use energy, capital expenditures in agriculture and forestry, and some continued spend in high-emissions physical assets. See technical appendix.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

Box 3

A portion of today's productive capital stock could be stranded under a net-zero transition, with knock-on consequences

Under a net-zero transition, a proportion of today's physical capital stock could become redundant in its current form, either because it emits large volumes of greenhouse gases or because it would no longer be needed as a result of falling demand for emissions-intensive products—for example, manufacturing equipment for internal combustion engines. The physical capital stock that is vulnerable would need to be retrofitted to decarbonize operations or face being underutilized or retired before the end of its useful life or stranded and lose value, and possibly replaced with new low-carbon assets.[1] The stranding of natural capital, such as fossil fuel reserves and resources that cannot be used, is also expected to be significant.

In the context of the net-zero transition, stranded physical assets should be taken into account when preparing for the transition for a number of reasons. First, the capital stock associated with fossil fuels and emissions is worth many trillions of dollars, a significant share of the total global capital stock, and even more capital stock depends indirectly on these assets (for example, ICE vehicle plants whose value relies on the continued use of ICE vehicles). Stranding large portions of this capital stock in a disorderly or abrupt way could impede value generation in many industrial sectors and, indeed, the global economy. Second, many such assets are capitalized on the balance sheets of listed companies. Prematurely retiring these assets would potentially lead to the destruction of currently perceived value and to bankruptcies and credit defaults, with knock-on effects on the global financial system. Third, stakeholders linked with these assets—from owners of capital to employees, suppliers, and the wider economy in locations reliant on high-carbon assets—could see substantial negative effects on their wealth, revenues, and livelihoods.

Certain sectors face the most acute risks. In the fossil fuel sector, external research suggests that producers would forgo $7 trillion to $11 trillion of cumulative discounted oil, gas and coal revenues over the next 15 years under a net-zero scenario. This prospect has led to concerns about the valuations of companies that own these reserves and about the potential second-order risks to the financial sector.[2]

In power, our analysis of the NGFS Net Zero 2050 scenario suggests that about $2.1 trillion worth of assets could be stranded by 2050. About 80 percent of these stranded assets would pertain to fossil fuel–based power plants in operation today, primarily coal-fired plants in countries such as China and India (Exhibit 8) which are prematurely retired or underutilized.[3] The remaining 20 percent would relate to assets that are built in the future, particularly future gas plants, that are eventually succeeded by alternative technologies. Most coal plants in China and India were built relatively recently and have an average capacity-weighted age of less than 15 years. This compares to an average age of more than 30 years in the United States.[4] Their owners face a difficult choice: it is unclear whether early retirement (and replacement) or brown-to-green installations of CCS will be more economical. CCS is still expensive and difficult to scale. And while the falling costs of solar and wind power are making it harder to justify large outlays to keep coal plants online, installing new renewable-power assets also requires substantial capital spending.

Industrial assets and those used in buildings for heating and cooking may also see some stranding, given relatively long asset lifetimes. Aviation and shipping assets could also see stranded asset risk if regulation tightens, and the pace of decarbonization increases, particularly if retrofits to substitute fossil fuel use are expensive or difficult because of alternative fuel supply constraints.

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[1] A physical asset is considered stranded when a decarbonization action causes it to lose value because of early retirement or lower utilization. Stranded value can be measured based on loss of book value (the remaining book value of early retired or underutilized assets) or market value (based on forgone future cash flows due to price and volume changes from early retirement of assets or lower utilization). Stranding can also be used to describe the effect of the transition on corporate valuations, which are typically measured based on the market value approach described previously. The ways in which stranding can take place vary; regulation (for example, a carbon price or levy) can strand assets by altering the economics of production, investor or consumer preferences can change, and competing lower-cost and lower-carbon technologies can also strand assets. For instance, a coal-fired power plant can strand because the regulator imposes a levy; consumers switch to renewable energy sources; investors withdraw capital, which leads to higher cost of capital; or lower-cost renewables put pressure on the wholesale price of electricity, thereby making the continued operation of the plant unprofitable.

[2] These estimates represent the difference in cumulative revenues over the next 15 years for fossil fuel producers in a net-zero scenario relative to current policies discounted by 6 percent. See Jean-Francois Mercure et al., “Reframing incentives for climate policy action,” *Nature Energy,* November 2021. See also David Nelson et al., *Moving to a low-carbon economy: The impacts of policy pathways on fossil fuel asset values,* Climate Policy Initiative, 2014.

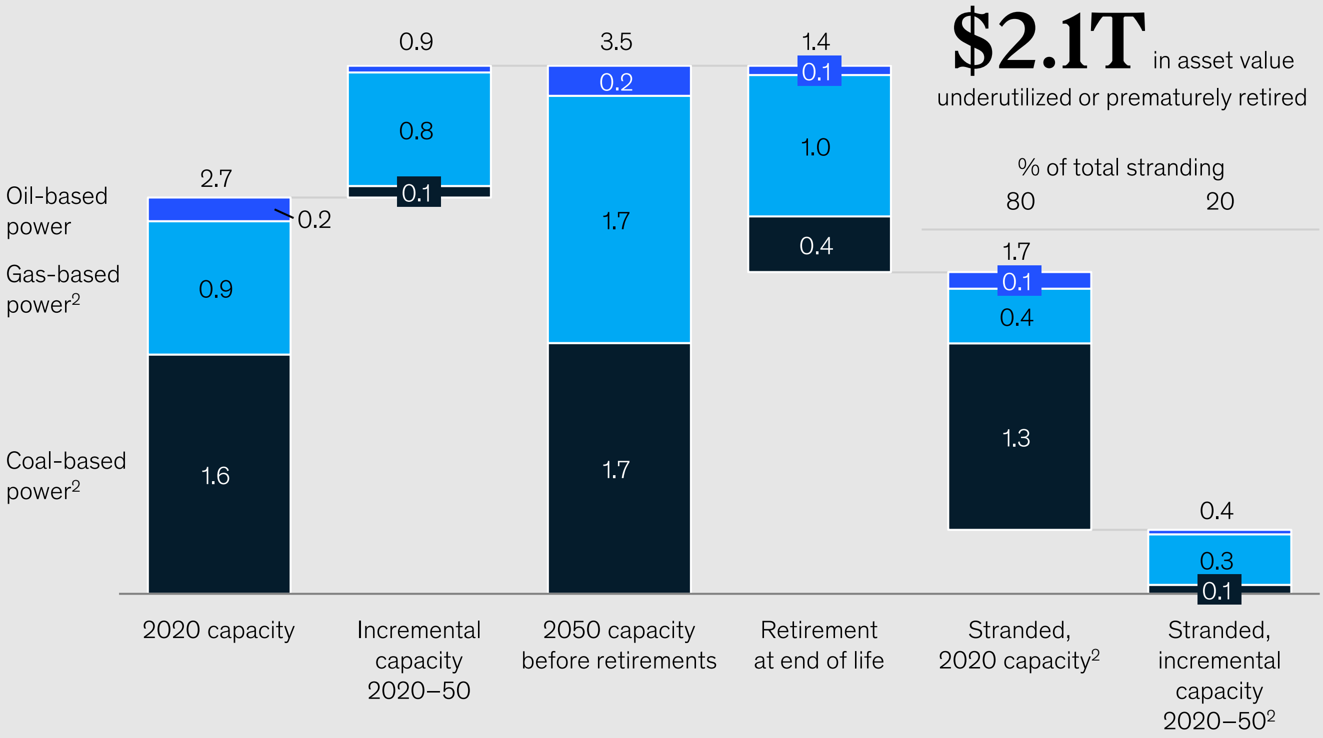
[3] Our definition of stranded assets represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years.

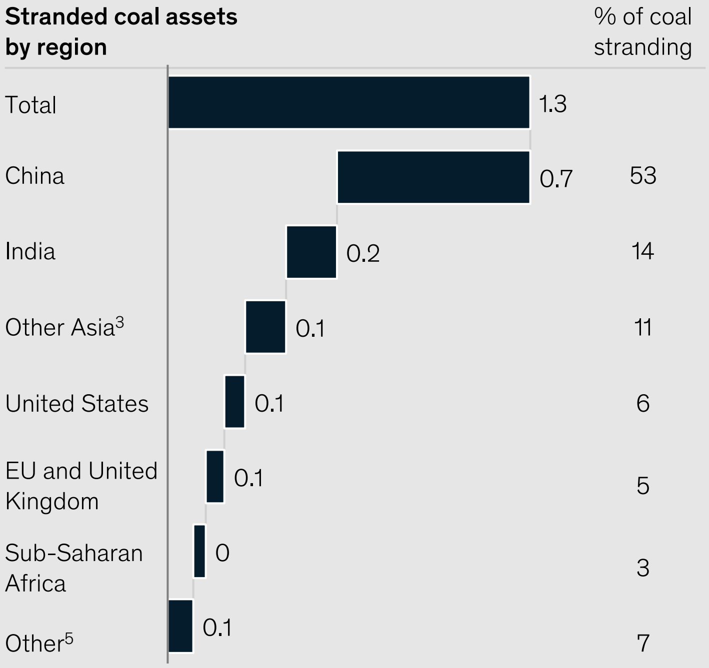
[4] See, *World Energy Outlook 2021,* International Energy Agency, December 2021.

Exhibit 8

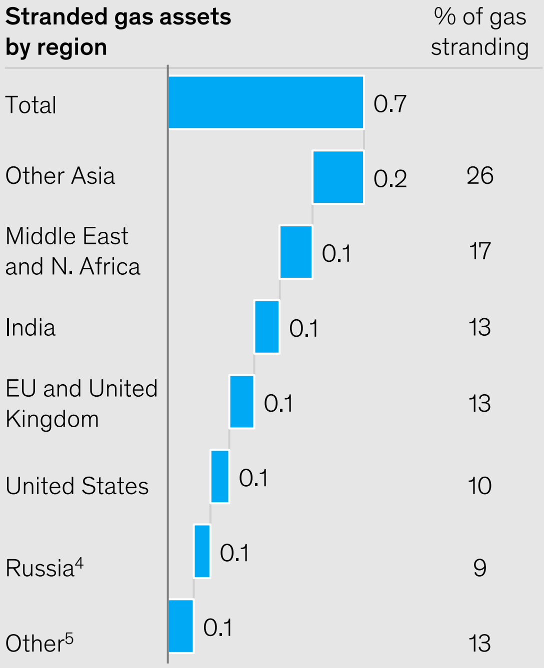
In the NGFS Net Zero 2050 scenario, about $2.1 trillion of power assets would be underutilized or prematurely retired by 2050.

$ trillion[1]





Stranded coal assets by region



Stranded gas assets by region

1. Not counting any additional capacity added after 2050. Our definition of stranded assets represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years.
2. Stranded capacity refers to capacity underutilized or prematurely retired before the end of its useful life.
3. Includes, among others, South Korea and Southeast Asia.
4. Russia, Ukraine, and Commonwealth of Independent States (CIS).
5. "Other" for coal includes Latin America and the Caribbean, Canada, Australia, New Zealand, Middle East and North Africa, Russia, Ukraine, and Commonwealth of Independent States (CIS), other Europe, and Japan. "Other" for gas includes China, Latin America and the Caribbean, sub-Saharan Africa, Canada, Australia, New Zealand, other Europe, and Japan.

Note: Scenario based on NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). For further details, see technical appendix. Figures may not sum to 100% because of rounding.

Source: World Resources Institute; Network for Greening the Financial System; McKinsey Power Solutions; McKinsey Global Institute analysis

Finally, close to $30 trillion would cumulatively be spent on expanding agricultural production to feed a growing population, shifting some investment towards lower-emissions proteins, implementing lower-emissions farming practices such as more efficient use of fertilizers and irrigation, avoiding deforestation, and increasing forest cover in other areas (afforestation). More than 70 percent of this would be spent in developing regions.

About half of the roughly $275 trillion in capital spending in the Net Zero 2050 scenario would be in the United States, China, and Europe. However, developing regions would spend more as a proportion of their GDP. Total spending ranges from 9 to 11 percent of GDP from 2021 to 2050 for developing regions such as sub-Saharan Africa, India and some other Asian countries, and Latin America, compared with about 4 to 7 percent for Europe, Japan, and the United States. (For more of our findings about the spending requirements of regions and countries, please see chapter 4.)

While the scale of capital deployed is substantial, it is important to put it in context. First and foremost, as we discuss later, the economic adjustments involved in reaching net zero in an orderly manner would prevent the further buildup of physical risks and the additional costs arising from a more disorderly transition. Second, in the long run, the up-front capital expenditures for a net-zero transition could result in operating savings for some sectors through reduced fuel consumption, improved material and energy efficiency, and lower maintenance costs. Much of this capital spending is already cost-effective and comes with a return. For example, research analyzing other net-zero scenarios has found that about 40 to 50 percent of spending can come with a positive investment case.[126] Moreover, technological innovation could reduce capital costs for net-zero technologies faster than expected.

Various challenges will need to be managed in the short run to achieve these outcomes. They include raising capital and securing financing at this scale, managing the technological uncertainty of investment, considering risk–return trade-offs, and driving capital flows to both developed and developing countries. Raising and deploying capital could be more challenging for specific sectors and geographies. See also Box E2 in the executive summary on the implications of how the transition is financed.

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[126] McKinsey research finds that about half of the required investments to reach-net zero emissions in Europe have a positive investment case. This means that switching to the relevant low-emissions technology would represent a cost saving at the cost of capital for each sector and segment. See Paolo D'Aprile, Hauke Engel, Godart van Gend, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020. The IEA also examined the actions required to be taken by consumers in the IEA Net Zero 2050 scenario such as switching to low-emissions vehicles. They find that 40 percent would result in overall cost savings relative to an Announced Policies scenario where governments follow through on their climate targets and commitments. See *World economic outlook,* IEA, 2021. On the macroeconomic level, higher levels of public and private investment could provide economic stimulus, leading to negligible net negative impacts, or even modest net positive impacts, on GDP growth (though as discussed, much depends on how the transition is financed and managed). For example, the European Commission found in conducting an impact assessment for proposed 2030 net-zero-aligned emissions targets for the European Union that raising policy ambition would result in a cumulative impact of between -0.7 percent and +0.55 percent on GDP by 2030 compared to a baseline forecast. See *Impact assessment: Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people,* Commission Staff Working Document SWD/2020/176, September 2020.

Costs: Some sectors would see cost increases in the Net Zero 2050 scenario, because of shifts in production processes and capital expenditures

The transition's economic implications reach beyond spending on physical assets. Production costs, which reflect changing operating costs as well as capital costs for new investment and asset depreciation, would also shift as processes are changed and assets transformed. And any changes in production costs could possibly affect the costs of consumer goods, if these costs are passed through.

In the Net Zero 2050 scenario, industrial sectors in particular could see cost increases from changes to production processes and capital expenditures. By bringing operating costs together with capital charges resulting from investment and with depreciation costs, we assessed the full production cost of various goods. In hard-to-abate sectors like cement and steel, our analysis suggests that production costs would increase by about 45 percent and 30 percent, respectively, by 2050, including because of implementation of technologies such as CCS in this scenario (Exhibit 9). In the power sector, delivered cost of electricity globally would increase in the near term but then fall over time from that peak. On the other hand, the total cost of ownership of electric vehicles is also expected to decrease over time relative to ICEs.

In power, the electrification of the economy means that power generation demand would dramatically increase: our global analysis suggests that by 2050, it would be about twice as high as today in the Net Zero 2050 scenario. Meeting this increased demand with low-emissions sources would require significant additional capital spending to build out not only capacity but also the accompanying transmission and distribution infrastructure and storage capacity.[127] Our analysis indicates that the global average delivered cost of electricity across generation, transmission, distribution, and storage would increase significantly before falling, in the scenario modeled here. The impact would be front-loaded: delivered cost of electricity would increase by 25 percent from 2020 levels by 2040, including operating costs, capital costs, and depreciation of existing and new assets (Exhibit 10). This is for two main reasons: firstly, investments will be needed in building renewables, grid and storage capacity, creating capital costs and depreciation charges. Secondly, some fossil-based power assets would continue to incur capital costs, even if they are underutilized or retired prematurely. Indeed, impacts could be significantly higher than those sized here (though it is important to note that delivered cost of electricity as sized here is not the same as consumer electricity prices). If the transition from high-emissions fossil fuel–based power assets and the ramp-up of low-emissions assets that replace them is not well managed, both energy costs and volatility could go up, and ensuring reliable power may be challenging. Various factors could

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[127] To assess cost changes for power, we first quantified the change in three main cost drivers: power generation capital charge and depreciation (at a weighted average cost of capital of 6.5 percent), power generation operating costs, and transmission, distribution, and storage investments. These were then translated into a delivered cost of electricity by dividing by electricity production in each time period. This metric indicates how the underlying costs are changing for the entire power sector. Our methodology is broader than other studies focused on the levelized cost of energy for new assets which often highlight the competitive cost position of renewables in the power mix. Our analysis also takes into account infrastructure spending on grids, capital charges, and depreciation of legacy assets even if they are prematurely retired or underutilized. See also Rupert Way et al., *Empirically grounded technology forecasts and the energy transition,* Institute for New Economic Thinking Oxford, working paper number 2021-01, September 2021. Note that our metric is different from the actual cost paid by consumers, and eventual energy prices for consumers could look substantially different. Consumer electricity prices depend on a multitude of factors, including decisions on how the power system transformation is paid for and over what time frame. For example, a key question is how to best manage coal generation decommissioning and write-down costs. Moreover not all expected changes in delivered costs are due to decarbonization. For instance, some transmission and distribution investments would happen regardless, as countries increase electricity access. This analysis does not take into account short-term variations in supply and demand, subsidies, or taxes.

contribute to this, including potential grid intermittency issues as renewable assets are scaled up, shortage of fossil fuel–based capacity to serve peak loads and provide backup for renewables, and shortage of coal and gas inputs for fossil fuel power plants, to name a few.[128] The potential impacts of such outages would be even greater with electricity being used more extensively than today across the economy, for example for heating, mobility, and industry. Conversely, it is also conceivable that innovation could help drive down costs at a faster rate than anticipated, and alternate approaches to grid design could also limit the spending need on transmission and distribution. Delivered cost of electricity in the first half of the century could then be lower than anticipated in the scenario.

This analysis represents a global average perspective. The picture could look quite different across regions depending on the current state of their power system, age of fossil power fleets, and availability of natural resources like sunshine and wind, among other factors.

After hitting their peak, costs could subsequently decrease; for example, by 2050, operating costs for generation could drop by more than 60 percent relative to today as the energy mix shifts to renewables. Some of the reduction in operating and other costs for generation would be offset by an increase in the costs associated with grid flexibility, transmission, and distribution. As a result, delivered cost of electricity in this scenario would still be about 20 percent higher in 2050 than 2020 levels. In the long run, the delivered cost of electricity in the second half of the century may well be lower than 2020 levels, although this will depend on innovations to grid design and evolution of the power system to manage flexibility issues.

In cement, the most significant decarbonization levers are improving energy efficiency, replacing fossil fuels with lower emissions fuels (waste and biomass), and reducing the clinker share in cement by substituting clinker with supplementary cementitious materials like fly-ash, granulated slag, limestone, and calcined clay. Once these readily achievable emissions reductions have been implemented, decarbonization involves more costly technological solutions. Thus, especially in the later years, both capital spending and operating costs could increase over time, driven in large part by the installation of CCS. As a result, production costs for a ton of cement in the net-zero transition would increase by 45 percent by 2050 relative to today, in the scenario modeled here.

Steel would follow a trajectory similar to cement's. Decarbonization in steel would require the industry to either retrofit existing basic oxygen furnaces with CCS or replace them with electric arc furnaces using scrap and gas-based or hydrogen-based direct reduced iron. Both of these alternatives have higher operating costs per ton of steel compared with a traditional blast furnace. The higher capital spending needs and the higher per-unit operating costs would increase steel production costs in the Net Zero 2050 scenario, making a ton of steel about 30 percent more expensive to produce by 2050. Continued innovation could lower the estimates here for both cement and steel.

Conversely, overall costs could go down for other parts of the economy, in particular mobility. For automotive (passenger cars), in the Net Zero 2050 scenario, EVs would account for approximately 50 percent of total new car sales by 2030, and low-emissions cars make up virtually all sales by 2050 globally. Consumers would incur higher up-front costs to buy zero-emissions vehicles, at least in the short term. Today, depending on the country and the size of the vehicle, the upfront cost of a battery-electric vehicle is generally about 30 to 90 percent more than that of an internal combustion engine car. This gap is expected to narrow over time with lower battery prices.[129] For Europe and the United States, for example, the up-front cost of electric cars could be lower than ICE-based cars as soon as 2035. Even with higher upfront costs, consumers would see a benefit over time. McKinsey analysis suggests that on a total cost of ownership basis, which takes into account purchase price, maintenance, fuel cost, and resale value, EVs would be cheaper than ICE cars in most regions by 2025, assuming battery costs fall as expected.

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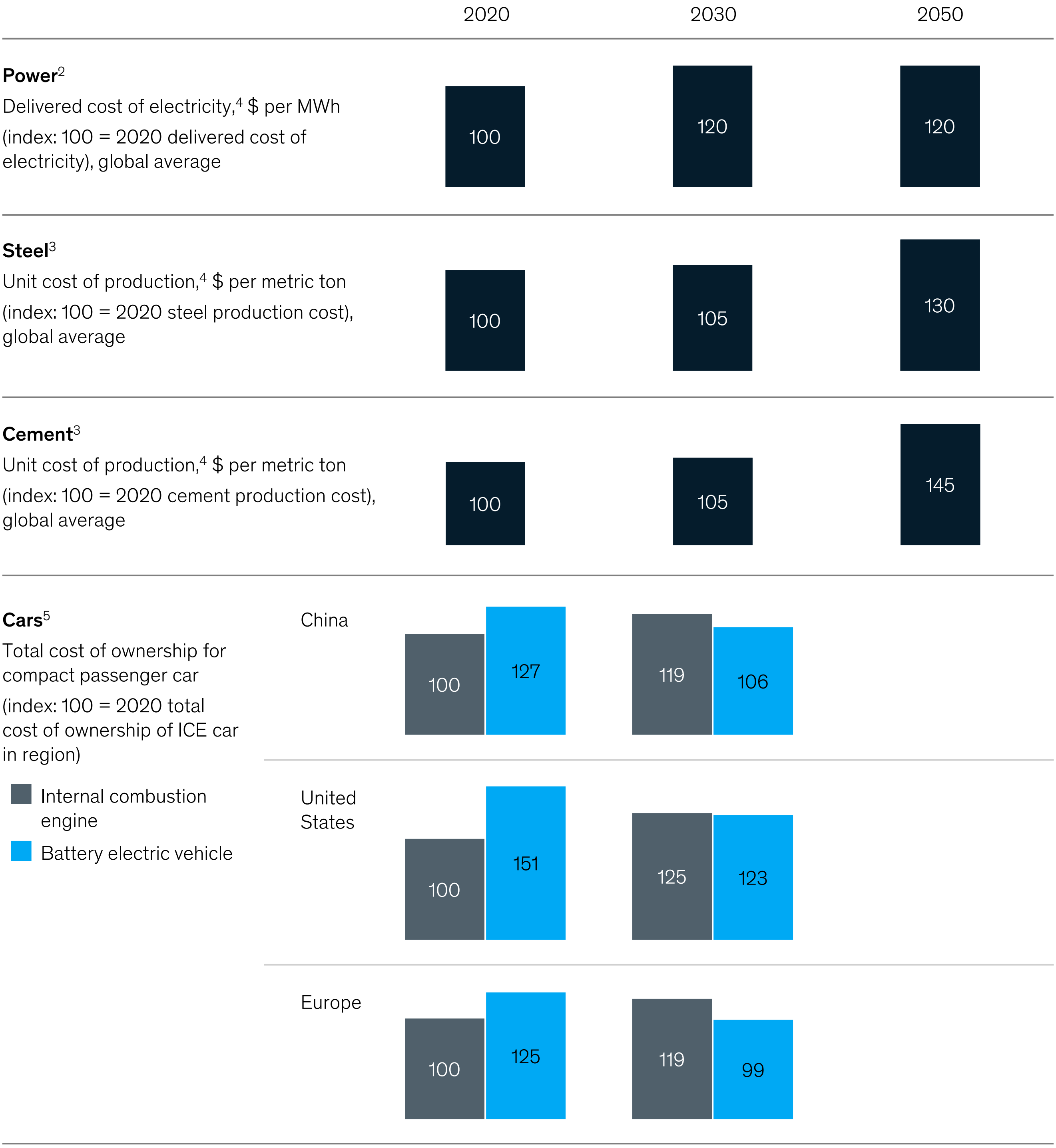
[128] For further details, see Box E5 in the executive summary.

[129] McKinsey Center for Future Mobility, price benchmarks in key markets.

Exhibit 9

Costs of producing electricity, steel, and cement would rise in the NGFS Net Zero 2050 scenario; total cost of ownership for ICE cars would rise but fall for EVs by 2030.

Costs, NGFS Net Zero 2050 scenario[1]



1. Scenario based on NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). For further details, see technical appendix.
2. Delivered cost of electricity including generation, transmission and distribution, and storage. Includes operating costs, depreciation, and capital costs. Depreciation includes both existing and newly built capacity; capital costs assumes weighted average cost of capital of 6.5%. This metric indicates how the underlying costs are changing for the power sector and is not the same as consumer electricity prices. The trends described here are global averages and would vary across regions.
3. Includes operating costs, depreciation costs, and capital charges across steel and cement production routes, including both existing and newly built capacity. Capital costs assumes weighted average cost of capital of 8%. Unit costs are weighted by the relative production volumes of different production routes.
4. Rounded to nearest multiple of 5 for power, steel, and cement.
5. Total cost of ownership accounts for purchase price, operating costs, for instance fuel and maintenance costs, and resale value; based on three years of ownership of a new car.

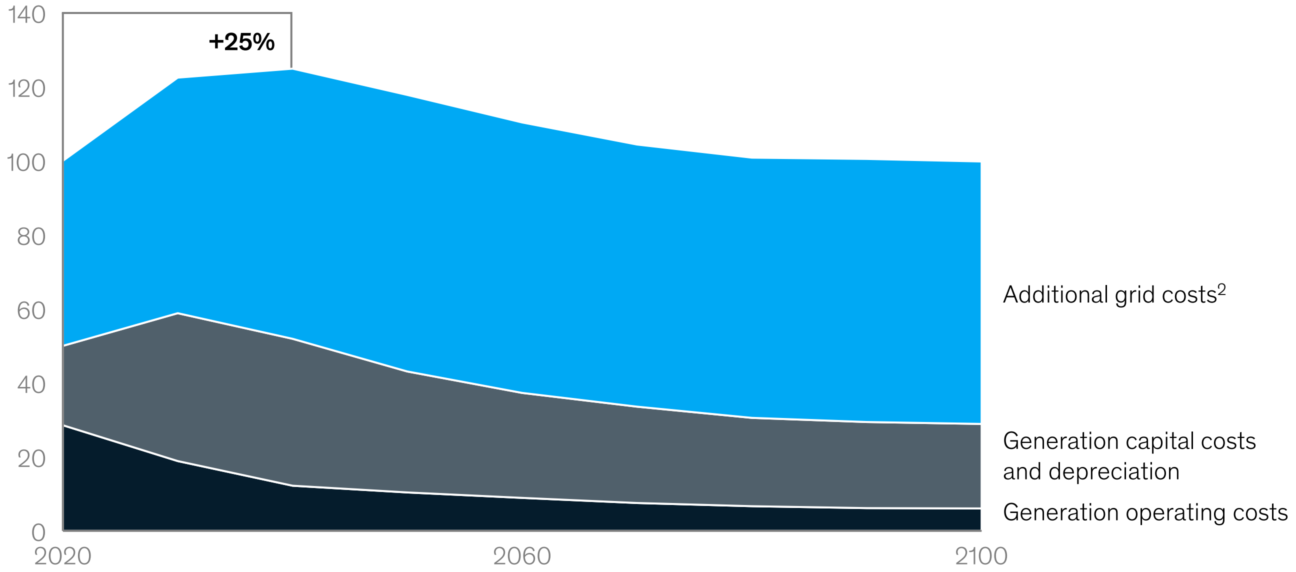
Source: NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2); GNR-GCCA 2019; Vivid Economics; International Energy Agency; McKinsey Sustainability Insights; McKinsey Power Solutions; McKinsey Center for Future Mobility Electrification Model (2021); McKinsey Basic Materials Insights; McKinsey–Mission Possible Partnership collaboration analysis; McKinsey Global Institute analysis

The total cost of ownership for an ICE car is expected to increase steadily as resale values fall due to usage and sale restrictions. For example, the total cost of ownership for battery-electric cars in Europe may be cheaper compared to that of ICEs by 2025, and the United States by 2030. Medium-duty BEV trucks covering 200-300 km a day are expected to reach total cost parity with ICEs by around 2025, with heavy-duty long-haul trucks reaching parity by 2030 in Europe and later in other regions. Faster declines in battery prices and local subsidies could accelerate the break-even point. Finally, as we discuss below, in some geographies, overall costs for buildings would also decrease.

Exhibit 10

Global average delivered cost of electricity in the NGFS Net Zero 2050 scenario would rise in the short run and then fall back from its peak.

Delivered cost of electricity,[1] $ per MWh, index (100 = 2020), NGFS Net Zero 2050 scenario, global average



1. This metric represents a full system cost for power, across generation, transmission, and storage. It includes operating costs, capital costs, and depreciation. To assess cost changes for power, we first quantified the change in three main cost drivers: power generation capital charge (at a weighted average cost of capital of 6.5 percent), power generation operating costs, and transmission, distribution and storage investments. These were then translated into the delivered cost of electricity by dividing by electricity production in each time period. This metric indicates how the underlying costs are changing for the power sector and is not the same as consumer electricity prices. The trends described here are global averages and would vary across regions.
2. Transmission and distribution plus storage.

Source: Network for Greening the Financial System scenario analysis 2021 phase 2 (Net Zero 2050 scenario) REMIND-MAgPIE (phase 2) model; Vivid Economics; World Resources Institute Power Plant Database; McKinsey Power Solutions; McKinsey Global Institute analysis

Consumers would face higher up-front costs, and may need to spend more in the near term on electricity if cost increases are passed through, with lower-income households most at risk

Consumers would be affected by the net-zero transition in various ways, although the extent of the impact could vary depending on the composition of their spending baskets and the degree to which production cost changes are passed on. Lower-income households in both developed and developing countries are naturally most at risk in the early years of the transition from potential rises in energy prices and high up-front capital costs of some low-emissions products, although all consumers could see some benefits over time.[130]

First, if significant emissions reductions are to be achieved, consumers may need to adjust their spending habits, for example, using more public transportation and shifting diets over time away from high-emissions food products such as ruminant protein from beef or lamb to other forms of protein such as poultry or other sources such as legumes. Research suggests that the price per calorie for processed red meat is more than six times higher than for pulses and nuts, and twice as high as white meat, fish and seafood, and eggs.[131]

Second, any rise in electricity prices would affect consumers. However, this depends on how cost recovery is allocated among customers, up to and including the extent any increases in delivered cost of electricity are passed through to end consumers. Electricity constitutes an important share of the spending by low-income households, and so any price increases would have a disproportionate effect on them unless subsidized.[132]

Third, in some cases, consumers would incur relatively high up-front capital costs related to road mobility and buildings, particularly in the early years of the transition. While this could come with longer-term operating cost savings, making or financing these capital expenditures may be more challenging for lower-income households.

Considering mobility, as discussed above, up-front expenditures are higher for EVs than ICEs today, though the gap is narrowing. An individual consumer, though, would see a benefit over the life of the vehicle, in terms of reduced total cost of ownership.

With buildings too, consumers may face higher initial costs, although the extent to which they can recuperate this through lower operating costs in the long run varies. In the Net Zero 2050 scenario, individuals and businesses would need to install heating and cooking systems and retrofit insulation. This would entail significant additional up-front spending. Currently, an electric heat pump is up to three times more expensive than a gas boiler in some regions for an equivalently sized unit. However, over time, the price difference would likely narrow.
The extent to which consumers can recuperate savings through lower operating expenditure is country-specific, because of varying energy prices and depending on how electricity and fossil fuel prices evolve in a net-zero transition, as well as the extent of improvements in energy efficiency from insulation and newer heating and cooking equipment.[133]

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[130] A comprehensive accounting of the effects on consumers would be complex, since effects vary based on such factors as a consumer's spending basket, whether companies pass through any additional operating or capital costs, and the transition's effect on government revenues and subsidies. Effects on consumers are likely to vary by region. For example, the climate transition will likely affect a higher proportion of developing countries' total spend basket. Individuals' incomes could also be affected by shifts in livelihood or changes in taxation that result from the transition.

[131] Derek Headey and Harold Alderman, "The relative calorific prices of healthy and unhealthy foods differ systematically across income levels and continents," *Journal of Nutrition,* volume 149, issue 11, November 2019.

[132] Some governments could potentially subsidize electricity to encourage a mix shift in energy consumption and ensure continued access and affordability.

[133] For more on the building sector, see Paolo D'Aprile, Hauke Engel, Godart van Gend, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020.

Fourth, higher production costs could also affect the price of consumer goods and services in other areas. In the near term, McKinsey analysis finds that zero-emissions container shipping fueled by green ammonia could be twice as expensive as standard shipping fueled by heavy oil in the Asia-Europe corridor. However, the extent to which this will flow through to higher costs for consumers will likely be country- and product-specific.[134] Likewise, rising costs in hard-to-abate sectors such as steel and cement could raise the cost of end products, depending on the fraction of the costs of these materials in final goods and services , and how costs are passed through.[135] Housing costs may similarly rise to a small extent if the increase in steel and cement costs for production is passed on to consumers.

Finally, while not the focus of this research, there is a set of consumer spending related to aviation which could be affected, most likely impacting high-income consumers more so than low-income ones given the composition of their spend basket. A WEF–McKinsey report estimated the cost of production for sustainable aviation fuel could be $900 to $2,300 per ton in 2050, depending on the pathway, compared with around $500 for conventional jet fuel.[136]

Jobs: The net-zero transition analyzed here could lead to a reallocation of labor, with about 200 million jobs gained and about 185 million lost by 2050

The scale of the economic transformation set out in this chapter would have consequences for the global labor market. The effect on jobs would be especially notable not so much for its overall size in terms of net losses or gains as for its concentrated, uneven, and re-allocative nature.

Our analysis of the NGFS Net Zero 2050 scenario suggests that the transition could result in an increase in demand for about 162 million direct and indirect jobs (referred to as "job gains") and a decrease in demand for about 152 million direct and indirect jobs (referred to as "job losses") in operations and maintenance by 2050 across different sectors of the economy. In addition, about 41 million jobs could be gained and 35 million lost related to direct and indirect jobs associated with spending on physical assets needed for the net-zero transition by 2050 (Exhibit 11). Jobs in the latter category, linked to higher capital spending, are likely to be more transitory than those in the former, related to operations and maintenance, as discussed below. Together, this results in about 202 million direct and indirect jobs gained and about 187 million lost by 2050.

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[134] For example, research has highlighted that the cost of jeans may only rise by 1 percent but this might vary for other product types. See *Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness,* Hydrogen Council and McKinsey & Company, February 2021.

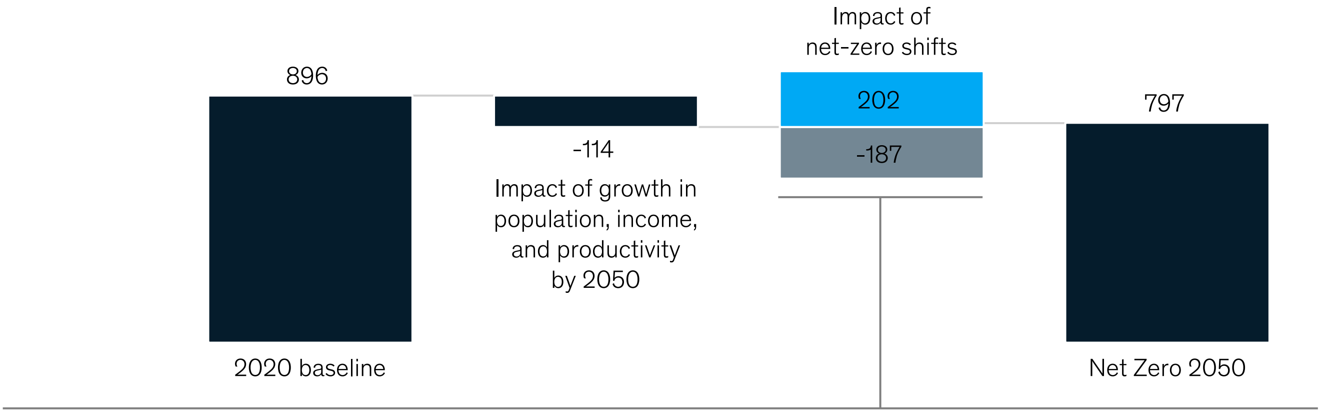
[135] See Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel, "The zero-carbon car: Abating material emissions is next on the agenda," McKinsey & Company, September 2020.

[136] *Clean skies for tomorrow: Sustainable aviation fuels as a pathway to net-zero aviation,* WEF and McKinsey, November 2020.

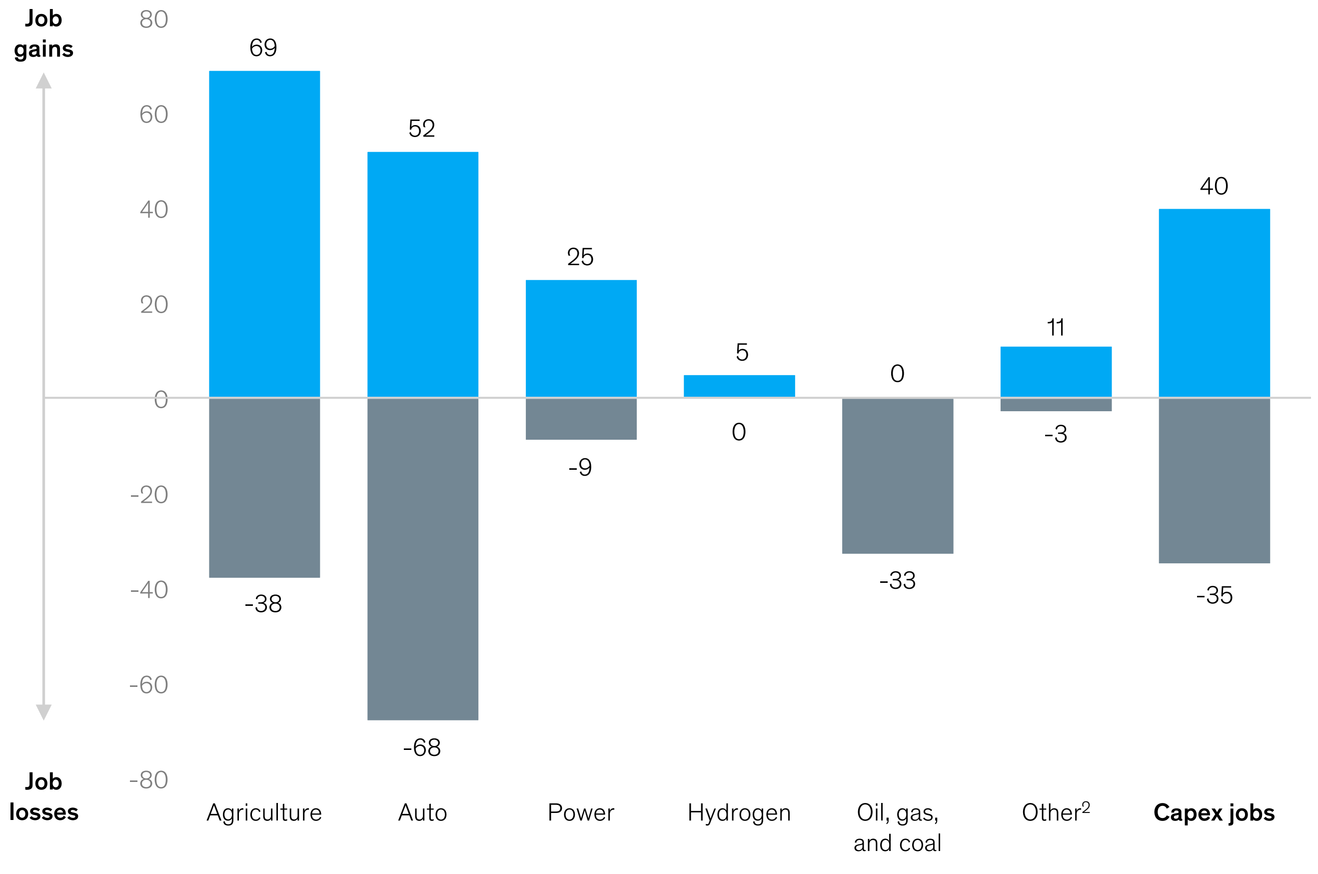
Exhibit 11

In the NGFS Net Zero 2050 scenario, about 200 million direct and indirect jobs could be gained and 185 million lost by 2050.

Total job shifts, direct and indirect, by 2050, million[1]



Total job shifts by sector,[1] direct and indirect, by 2050, million



1. Includes all direct and indirect jobs; based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall emissions today; a job is counted as a gross loss or a gain if it involves a shift in sector or subsector for a worker (indicating a changing job function), or geography of an existing job. Operations and maintenance jobs consist of those related to the operations and maintenance activities in the sector (direct jobs), and their supply chains (indirect jobs). Capex jobs are those arising from capital investment in the sector, associated with manufacturing and construction (direct jobs), and their supply chains (indirect jobs), and are not included in the 2020 baseline number. While calculating indirect jobs, we include upstream jobs from all other sectors of the economy such as financial services, wholesale trade, retail trade, transportation etc, but exclude a set of sectors for which we have done bottom-up calculations, including: Agriculture, forestry and fishing, mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. Impacts of a net-zero transition consist of job losses and gains directly associated with the transition, and do not include other macroeconomic forces like population or income growth. See technical appendix.
2. Other comprises mineral, forestry, cement, carbon abatement, steel, and biofuels.

Note: Figures may not sum to total because of rounding.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

When considering job losses and gains here, we only consider those which are directly attributable to the net-zero transition, rather than other factors like income or population growth (see Box 4, "Our methodology for estimating employment effects in the net-zero transition").[137]

Job gains would be largely associated with the transition to low-emissions forms of production, for example to renewable-power production, while the losses would particularly affect workers in fossil fuel–intensive or otherwise emissions-intensive sectors. The size of the job dislocation needs to be put in perspective in the context of other trends. For example, previous research by the McKinsey Global Institute suggests that automation, remote work, and e-commerce trends could lead to the loss of approximately 270 million to 340 million jobs in eight countries between 2018 and 2030, with commensurate job gains expected at a similar scale. Those figures are considerably higher than our estimate for global job losses and gains related to the net-zero transition, in the scenario analyzed here.

The net increase of about 15 million jobs reflects the net change in employment associated with shifts in economic activity in the specific energy and land-use systems modeled here for transition to the NGFS Net Zero 2050 scenario. It is important to put this number in context. First, this number is small relative to the net decrease of 114 million jobs—unrelated to the transition and driven by other factors such as productivity growth—that we find over the same period for the sectors analyzed here (in large part driven by the decrease of 184 million jobs in agriculture as productivity increases). Second, it is also small relative to the job losses and gains that underpin the net number and the overall scale of the global economy. Thus, the main issue at hand is the re-allocative and uneven nature of job shifts that underpin the net-zero transition.

Job gains associated with spending on physical assets for the net-zero transition would be higher in the earlier years of the transition. In construction, manufacturing, and other industries associated with the build-out of low-emissions physical assets, net job gains (gross job gains minus gross job losses) from the net-zero transition could be as high as about 37 million by 2030 and could still be five million by 2050 (see Exhibit 12). Capital expenditures in new electricity generation infrastructure and retrofitting buildings alone could result in more than 57 million gross job gains by 2030.[138]

While our analysis has focused on what can be expected from the foreseeable job shifts from the transition, historical analyses have found new technologies typically created many more jobs than they destroyed. This includes new jobs that are in occupations which cannot be envisioned at the outset; for example, one study calculated 0.56 percent of new jobs in the United States each year are in new occupations.[139] Thus, the true potential job creation from the adoption of new climate technologies is likely to be larger than the estimates here particularly when considering the numerous opportunities from a net-zero transition, as we discuss later.

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[137] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other low-emissions sources of electricity). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains, and include direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry, and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

[138] For more information, see *The future of work after COVID-19,* McKinsey Global Institute, February 2021.

[139] This implies that about 20 percent of the workforce today is employed in an occupation that essentially did not exist in 1980. Jeffrey Lin, "Technological adaptation, cities, and new work," *Review of Economics and Statistics,* volume 93, number 2, May 2011. See also *Jobs lost, jobs gained: What the future of work will mean for jobs, skills, and wages,* McKinsey Global Institute, December 2017. Most jobs created by technology are outside the technology-producing sector itself. Past estimates by MGI suggest that the introduction of the personal computer, for instance, has enabled the creation of 15.8 million net new jobs in the United States since 1980, even after accounting for jobs displaced. About 90 percent of these were in occupations that use the PC in other industries, such as call center representatives, financial analysts, and inventory managers.

Box 4

Our methodology for estimating employment effects in the net-zero transition

The transition to net zero will not be the only global trend affecting employment between 2021 and 2050. Significant shifts are likely across all job sectors as a result of other trends including population growth, sector-specific productivity enhancements, rising incomes, an aging population, and technological disruptions from automation and AI adoption.[1] Given these factors, we sought to disaggregate job gains and losses specifically associated with achieving net-zero emissions under the Net Zero 2050 scenario, from these other factors. When transition-related job changes are referred to in this report, figures include both technological and policy changes already planned or in the process of implementation as well as incremental changes required to achieve net zero by 2050. Figures exclude changes associated with the macroeconomic and within-sector productivity trends outlined above.

Our analysis captures potential effects of shift in demand for jobs across subsectors, sectors, and geographies; we refer to rising demand for jobs as "jobs gained," and diminishing demand for jobs as "jobs lost." In reality, this could manifest as a shift in job activity for individual workers. In an effort to describe a comprehensive view of job transitions tied to achieving net zero by 2050, calculations for gross job losses and gains include those arising from demand for new jobs (for example, CCS jobs that do not currently exist), diminished demand in some parts of the economy (for example, coal mining jobs, which are likely to be lower in 2050 under a net-zero scenario than under a no-transition case), demand for jobs shifting between subsectors within a given sector (for example, a job that shifts from coal to solar power generation counts as both one job lost and one job gained), and demand for jobs shifting across regions. While many such job losses and gains will occur between now and 2050 across sectors of the economy from the macroeconomic forces described previously, job losses and gains analyzed in this report are focused on sectors within the energy and land-use systems most closely tied to achieving the net-zero transition, and any indirect effects resulting from this. Thus, for various reasons, this analysis by design does not capture broad labor market shifts expected over the next three decades, but narrowly focuses on the shifts from a net-zero transition alone.

Throughout our discussion we account for both the jobs in our focus sectors (direct jobs) and the upstream jobs associated with final demand in our focus sectors (indirect jobs). The indirect jobs are calculated using multipliers derived from input-output tables that account for local and imported inputs to production in our focus sectors. Because the direct jobs of each sector we model are in some cases upstream jobs in another modeled sector (for example, an oil and gas job is an upstream job for the fossil-based power sector), we take a final step of netting out any double counting. This analysis has numerous uncertainties and we have needed to make assumptions, for example related to productivity growth within sectors and subsectors, and relative productivity levels across different technologies.

Our methodology does not account for any higher order impacts and assumes an orderly transition, one in which high emissions assets are ramped down and low emissions assets are ramped up to the levels needed, without constraints or challenges, including those related to financing the transition or securing job transitions. Finally, overall employment levels across the economy as a whole will also depend on fiscal and monetary policy that could be constrained by the aggregate financing requirement of the net-zero transition, which we do not model. See the technical appendix for further details.

This research seeks to build and expand on the vast existing literature on job implications of a net-zero transition.[2] Our results differ from those typically cited by other sources for several reasons. First, the emphasis of our research extends beyond calculating "net" job impacts; rather, we focus on the job reallocations (losses and gains) that the net-zero transition would entail, to capture the nature and magnitude of economic and societal adjustments needed. Second, we take a comprehensive view across 12 major economic sectors of job shift. And finally, we take an expansive view of jobs affected, including direct and indirect (upstream) jobs, O&M and capital expenditure jobs, and the consideration of job shifts across subsectors and geographies as part of total reallocations (gross gains plus gross losses). See the technical appendix for further detail.

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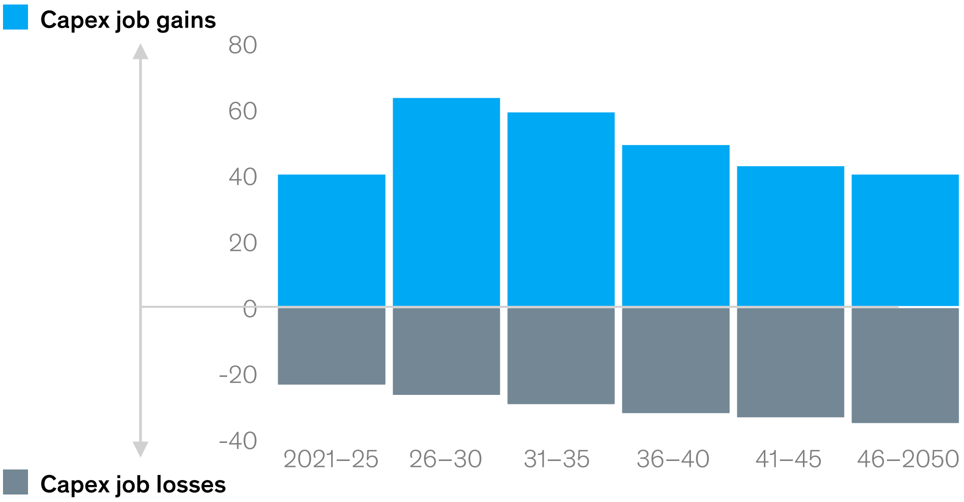
[1] See *The future of work after COVID-19,* McKinsey Global Institute, February 2021.

[2] See, for example, IEA, *World energy outlook 2021;* IRENA, *Renewable energy and jobs: Annual review 2021;* and ILO, *Greening with jobs,* 2018.

Exhibit 12

Direct and indirect job changes from capital expenditure will be front-loaded during the buildup of low-carbon assets in the NGFS Net Zero 2050 scenario.

Total annual capex-related job transitions,[1] million



1. Includes all direct and indirect capital expenditure–related jobs. Scenario based on the Network for Greening the Financial System Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall emissions today; a job is counted as a gross loss or a gain if it involves a shift in sector or subsector for a worker (indicating a changing job function), or geography of an existing job. Job losses and gains only include those directly associated with the impacts of a net-zero transition, and do not include other macroeconomic forces like population or GDP growth. See technical appendix.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

Job losses may also be higher than our analysis here. Our estimates of the employment transitions from the net-zero transition presuppose that it will take place in an orderly fashion, including for labor. In the event of a more disorderly transition, the labor market consequences could be more severe. Job transitions may happen more abruptly, reskilling and redeployment for workers would be more challenging, and job losses may also be more substantial as companies do not have sufficient time to ramp down high-emissions businesses and scale up low-emissions ones. Moreover, depending on the approach taken to finance the transition, job losses could be higher than presented here, if spending to build a net-zero economy reduces spending in other parts of the economy.

The shifts in employment in the net-zero transition are likely to be marked by their unevenness and concentration. Indeed, the overall numbers may understate the degree of disruption for individual workers in some sectors and geographies. A large proportion of jobs could be lost in certain sectors, such as coal mining, oil and gas extraction and production, fossil-based power, and livestock farming, while other sectors such as renewable-energy generation, EV production, energy crop production, and new sectors like hydrogen and biofuels could see considerable job gains. The job changes are also likely to be concentrated geographically. The combination of these losses and gains could result in potential structural and permanent shifts in the labor market. These shifts will require both business- and public-sector leaders to effectively prepare and plan for large-scale training and reskilling programs, labor transitions across industries and geographies, and new efforts to develop the future workforce needed to fill entirely new roles across sectors. We discuss these shifts more in the next section.

Potential job gains and losses would likely be concentrated, sparking transitions for workers across sectors, roles, skills, and geographies

The labor market shifts in our analysis mirror the changes in sectoral demand, with the heaviest job losses occurring in sectors or subsectors most exposed to decreases in demand, while gains would fall predominantly in sectors or subsectors experiencing increases in demand (for example, solar, wind, and other renewables). We detail the potential job gains and losses by sector in chapter 3. Of the 187 million job losses by 2050 in the net-zero transition scenario analyzed here, our analysis shows that approximately 62 million are direct operations and maintenance (O&M) jobs concentrated primarily in agriculture and food (about 34 million, related to diminished production of ruminant meat), automotive (13 million), and oil, gas, and coal extraction and production (about nine million).

Approximately 89 million additional jobs are indirect O&M jobs, mainly upstream from the automotive sector (55 million jobs), and upstream from oil, gas, and coal extraction and production (23 million).[140] The remaining 35 million losses are direct and indirect construction and manufacturing jobs, mainly related to oil, gas, and coal (18 million) and fossil fuel–based power (16 million). The most significant relative losses of direct O&M jobs in the scenario analyzed here would be in the internal combustion engine portion of the automotive sector. The agricultural sector would see the largest direct job losses in absolute terms, driven by the shift in animal-protein demand and associated livestock and feed-related jobs.

By contrast, low-emissions sectors would see job gains as demand and capital spending shift toward them. For example, the low-emissions power sector could see a threefold to fourfold increase in employment relative to today. The power sector overall could see the highest job gains relative to current numbers, adding about 25 million jobs in direct and indirect operations and maintenance, in addition to gains of 33 million jobs in construction, manufacturing, and associated sectors that support increases in low-emissions capacity and overall power demand by 2050.

Of the 202 million jobs gained by 2050 from the net-zero transition, about 81 million are direct O&M job gains, mainly in agriculture and food (61 million, related to expanding production of energy crops and poultry), automotive (nine million), electricity generation (six million), and hydrogen and CCS (three million).[141] An additional 81 million are indirect O&M job gains, about half from automotive and one-fourth from electricity generation. The rest of the job gains, about 41 million, are direct and indirect jobs created by capital spending primarily from the build-out of renewable electricity (three-fourths of the total), development of hydrogen and biofuels production, infrastructure supporting EVs, and retrofits of insulation in buildings.

These losses and gains could translate into job transitions for many workers, involving the movement of workers across skills, roles, companies, sectors, and geographies. We detail some of these in our discussion of the geographic dimensions of a net-zero transition in chapter 4.

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[140] In calculating indirect jobs for specific sectors, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect job shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See the technical appendix for details.

[141] While the agricultural sector would see overall net job gains from a net-zero transition, the trend would be one of declining agricultural jobs relative to today by 2050, due to an ongoing farm-to-nonfarm transition. The net-zero transition would only marginally offset this trend. For further details, see chapter 3.

One example of the skills transition is the shift of jobs in automotive under our scenario. Even as ICE vehicles are replaced with EVs, demand for vehicle repair and maintenance will continue. However, the skills required to work on EVs are different from those for ICE vehicles. Repairing and maintaining ICE vehicles involve technical expertise in mechanical equipment and physical repair of parts and components. EVs demand technical expertise in electrical equipment as well as the advanced electronic and computer systems deployed to run them, especially in regulating battery performance.[142]

Specific communities could be disproportionately affected because job losses could account for a large share of local employment. For example, jobs in fossil fuel extraction and refining are concentrated in locations with raw-material deposits and capital-intensive infrastructure. Often, they are the main source of employment for local communities. The decline of the fossil fuel industry would thus cause disproportionate job losses in these communities.

For example, analysis of data from the US Bureau of Labor Statistics finds that 10 percent or more of the employment in 44 US counties is in the coal, oil and gas, fossil fuel–based power, and automotive sectors (Exhibit 13). For example, in seven US counties in the states of Pennsylvania, Virginia, West Virginia, and Wyoming, more than 10 percent of workers are employed in coal mining.

Similar challenges may also exist for countries. For example, automotive production is a relatively large share of employment in Germany, Japan, Mexico, and South Korea, which would therefore be exposed to the transition and need to identify how they can best capture transition opportunities. A key challenge of the net-zero transition would thus be managing job losses that affect entire sectors or subsectors and are also geographically concentrated in specific communities or regions.

Disruptions would be substantially higher under a more disorderly transition

How the transition is managed will be decisive. The effects described here reflect the NGFS Net Zero 2050 scenario, in which gradual yet substantial reductions in emissions take place, resulting in a relatively orderly transition. However, the complexity of the transformation may well lead to the reality being more disorderly, and indeed it may not be feasible to limit warming levels to 1.5°C. This makes the case for action towards securing an orderly transition even more critical.

The key risks are threefold: the first concerns the choice of pathway to arrive at net-zero emissions, and whether this will be smooth or abrupt. The second relates to the measures taken by stakeholders to ease the adjustments needed for a net-zero transition. The third has to do with a range of constraints that could prove challenging even if the pathway chosen is a relatively smooth and gradual one.

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[142] As EVs replace ICE vehicles, demand for technical expertise in the automobile aftermarket will shift away from knowledge of ICE-specific components (for example, engine systems, transmissions, and fuel injection) and toward EV-specific components (for example, dedicated hybrid transmissions, batteries, BMS and inverters, heads-up displays, and advanced sensors like LiDAR). See “Why the automotive future is electric,” McKinsey & Company, September 2021.

Exhibit 13

More than 10 percent of the employment in 44 US counties is in coal mining, oil and gas extraction and refining, fossil-based power, and automotive manufacturing.

Low ▨ High

▨ Counties[1] with >10% of county employment in the examined sector

Coal mining

	% of	
County	**County employment**	**Sector employment**
McDowell, WV	18	3
Buchanan, VA	18	5
Boone, WV	16	3
Campbell, WY	15	17
Greene, PA	14	8
Mingo, WV	13	3
Wyoming, WV	11	2
Harlan, KY	8	2
Leslie, KY	8	1
Logan, WV	8	4
Knott, KY	7	1
Perry, KY	6	3
Pike, KY	6	5
Raleigh, WV	6	8
Letcher, KY	6	1
Bell, KY	4	1
Nicholas, WV	3	1
Somerset, PA	3	3
Floyd, KY	3	1
Wise, VA	3	1

Oil and gas extraction

	% of	
County	**County employment**	**Sector employment**
Upton, TX	41	0
Irion, TX	34	0
Dunn, ND	26	0
Hutchinson, TX	25	1
Reagan, TX	25	0
Hemphill, TX	22	0
Sterling, TX	20	0
Crockett, TX	16	0
Midland, TX	15	7
Winkler, TX	15	0
Woods, OK	14	0
Duchesne, UT	14	0
Burke, ND	14	0
Woodson, KS	12	0
Stephens, TX	12	0
Eddy, NM	11	2
Crane, TX	11	0
Richland, MT	10	0
Mountrail, ND	9	0
Lincoln, WY	9	0

Fossil-based power

	% of	
County	**County employment**	**Sector employment**
Stewart, TN	11	4
Indiana, PA	2	8
Dunklin, MO	1	1
Imperial, CA	1	6
Berkeley, SC	1	4
Sumner, TN	0	3
Schuylkill, PA	0	2
Anderson, TN	0	2
Oswego, NY	0	1
Cambria, PA	0	1
Clermont, OH	0	1
Northampton, PA	0	2
Darlington, SC	0	0
Colbert, AL	0	0
Madison, IL	0	1
Delaware, PA	0	3
Hamilton, OH	0	6
Lancaster, NE	0	2
Prince, MD	0	3
Dearborn, IN	0	0

Automotive manufacturing

	% of	
County	**County employment**	**Sector employment**
Clay, IL	31	0
DeKalb, TN	27	0
Crenshaw, AL	26	0
Washington, KY	26	0
Elkhart, IN	25	7
Howard, IN	25	2
LaGrange, IN	21	1
Marion, KY	18	0
Noble, IN	17	1
Madison, OH	15	1
Marshall, OK	15	0
Giles, TN	13	0
Champaign, OH	13	0
Shelby, OH	12	1
Calhoun, MI	11	1
Perry, IN	11	0
Nelson, KY	10	0
Tishomingo, MS	10	0
Gibson, IN	9	0
Shelby, KY	9	0

1. Top 20 US counties by % local employment in coal mining, oil and gas extraction and refining, fossil-based power, and automotive manufacturing. Based on an analysis of 3,273 counties and county equivalents (parishes, census area, municipalities) across the United States, Puerto Rico, and Virgin Islands.

Source: US Bureau of Labor Statistics

Many possible combinations of emissions-reduction trajectories and socioeconomic adjustments could limit warming to 1.5°C, and these scenarios could lead to higher or lower risks than those that we have analyzed under the NGFS Net Zero 2050 scenario. One of the key differences between various transition pathways is when the transition to net-zero emissions starts and how abruptly emissions are reduced to reach net zero.[143]

Some pathways to net-zero emissions assume that the decline in emissions begins immediately and progresses gradually to 2050. Others assume that reduction of emissions begins later and progresses more quickly to achieve the same amount of cumulative emissions. The latter could involve significant and abrupt changes in policy, high carbon prices, and sudden changes to capital spending practices—along with greater socioeconomic effects and a larger-scale response.[144]

Second, if actions are not taken to manage transition disruptions, this could lead to more challenges, especially for vulnerable communities—for example, if any rises in energy costs are passed through to low-income households, or if displaced workers are not provided appropriate support to reskill and redeploy. Finally, even if the pathway chosen is relatively orderly, given the scale of the transformation required, supply may not be able to scale up sufficiently, making shortages and price increases or volatility a feature. Other costs could also be incurred and investment needed beyond those mentioned in this report, for example related to the reskilling of workers, or economic diversification efforts. A key area where additional spend would be needed is related to adaptation investments (see chapter 1 for further details).

Quantifying the effects of these risks is challenging because of the many uncertainties; we instead describe various factors that could influence the scale of effects under a disorderly transition, as follows:

Risk of supply constraints. Rapidly scaling up demand for low-emissions assets and other products needed for the transition, without corresponding scale-up of supply, could lead to supply/demand imbalances, supply shortages, price increases, and inflation, for example associated with key commodities or equipment needed for a net-zero transition. This could occur even in a scenario where action begins now to reduce emissions in a relatively gradual manner, if the transition is not well managed.[145] In particular, a mismatch or mistiming between the ramping down of high-emissions activities and the ramping up of low-emissions activities could impair energy supply and affect energy access and affordability. This could

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[143] Another key difference between transition pathways is the assumptions made about the potential for carbon dioxide removal (CDR). In pathways with significant CDR, gross emissions can be higher because they are counterbalanced in part by removals. At the end of the scenario, they also allow the economy to converge on net-zero CO_2 emissions even with some low residual gross emissions in certain hard-to-abate sectors. In some transition scenarios, CDR is used in the second half of the century to compensate for overshooting carbon budgets earlier. In the NGFS Net Zero 2050 scenario, there is moderate use of CDR but only a "limited temporary overshoot" of temperature targets. The process and benefits of CDR on emissions reductions is still unproven at scale, and so brings risks of permanent and more significant climate effects. If no CDR is assumed, gross emissions would have to be cut even more sharply to limit warming to a given temperature target.

[144] Central banks and supervisors have raised concerns about risks from a disorderly transition. This could involve sudden and unanticipated shifts in capital allocation, labor markets, and financial market sentiment. The NGFS—the group of central banks and financial supervisors that produced the scenarios on which this report is based—has developed two such disorderly scenarios. The Delayed Transition scenario assumes annual emissions continue to increase until 2030 when strong policies are introduced to limit warming to below 2°C. The Divergent Net Zero scenario reaches net zero around 2050 but with higher costs because of divergent policies being introduced across sectors and regions and a quicker phase-out of oil use. For another example, see *Inevitable Policy Response 2021: Policy Forecast*, Principles for Responsible Investment, March 2021. The Inevitable Policy Response (IPR) provides a policy forecast for the most likely policy actions likely to be taken across different sectors of the economy as economies ratchet up their commitments under international climate agreements before 2025. IPR modeled the effect on sectoral stock market valuations of a response by 2025 that is forceful, abrupt, and disorderly because of the delay. Previous analysis from the IPR in 2019 found that while overall impacts would be manageable, there may be substantial disruptions at the sector and company levels. For example, the IPR calculation showed that the 100 worst-performing companies in the MSCI ACWI would lose about 43 percent of their current value, equivalent to $1.4 trillion, while the 100 best performers would gain 33 percent of current value, equivalent to $0.7 trillion. Automakers with the highest investments in EVs could see their value increase by 108 percent, and the world's largest listed coal companies could halve in value (-44 percent). The ten largest companies in the integrated oil and gas exploration and production sector could lose nearly one-third (31 percent) of current value, or $500 billion. See *Implications for strategic asset allocation,* Principles for Responsible Investment, 2019.

[145] For example, see "The raw materials challenge: How the metals and mining sector will be at the core of enabling the energy transition," McKinsey & Company, January 2022. The research describes a scenario where by 2030, based on the current pipeline of projects and without measures to incentivize further supply, copper and nickel demand could exceed supply by 5 million to 8 million and 700,000 to one million metric tons, respectively. See also 2022 *global outlook: Thriving in a new market regime,* Blackrock Investment Institute, 2022.

potentially result in a backlash that delays the transition. Investment needs may be higher than sized here, to maintain flexibility and redundancy in energy systems. Another risk is that stakeholders maintain two parallel energy systems in a manner that is inefficient and not cost effective. Thus the transformation of the energy system needs to be carefully managed. And there may be other constraints, including accessing the volume of financing required in the initial phases of the transition when many costs would be front-loaded.

Increased labor market disruption. A delayed, abrupt scenario would make it much harder for workers to transition. Even with the prospect of new jobs in growing sectors, the abrupt nature of the change would mean workers may have insufficient time to develop new skills and find their next job. In Organisation for Economic Co-operation and Development countries, unemployment in sectors such as agriculture and food, electricity, manufacturing, mining, and transportation lasts about five to seven months, on average.[146] If workers need to develop new skills to find employment (for example, when moving from industries with high fossil fuel intensity to others), this period can be even longer. Past research by the McKinsey Global Institute points to particular challenges for young workers who miss out on valuable experience if they are unemployed early in their careers. This disruption in employment may have a lasting scarring effect on productivity, employment, and career prospects.[147] Depending on the nature of support measures for displaced workers and communities, effects on specific sectors or geographies could be especially acute. More broadly, depending on the approach taken to finance the transition, job losses could be substantially higher than described here.[148]

Risk of asset stranding. A more abrupt transition could cause assets to be retired and replaced with low-carbon assets before their normal replacement cycles, as would occur in a gradual transition. Coal power plants typically have a lifetime of 40 to 60 years, while gas power plants have lifetimes of 30 to 50 years. While relatively older assets can largely be retired naturally over the course of a gradual transition, younger assets and any new assets built between now and 2050 face the risk of premature retirement or underutilization. These risks could be higher under a more abrupt transition. To illustrate this, we analyzed two NGFS scenarios consistent with limiting warming to less than 2°C from preindustrial levels. In the "Below-2°C scenario" where emissions reductions start immediately on a pathway to 2.0°C of warming, our analysis suggests that additional coal power capacity added is relatively small, only about $150 billion between 2020 and 2050, of which $100 billion would be prematurely retired or underutilized. But in the scenario where emissions reductions toward 2.0°C warming start later, a substantially larger amount of capacity is added; as much as $600 billion would be invested in coal-power capacity, with as much as $400 billion prematurely retired or underutilized.[149]

Greater risk of higher-order effects. Under any scenario, there are also higher-order effects which could occur, for example related to GDP or financial valuations, which we have not sized here. In a delayed or abrupt transition scenario in particular, effects could include a sharp decline in market prices for financial assets, with potential knock-on consequences for market liquidity and solvency of intermediaries, drops in economic performance for countries, sustained revenue losses for businesses, and enduring financial distress for individuals.

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[146] *Structural adjustment, mass lay-offs, and employment reallocation,* Organisation for Economic Co-operation and Development, 2019.

[147] *The future of work in America: People and places, today and tomorrow,* McKinsey Global Institute, July 2019.

[148] See Box E2 in the executive summary.

[149] Our definition of stranded assets represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years.

Increased physical climate risks. A delayed transition would heighten the physical risks of failing to limit warming to 1.5°C. Delay could result from inherent time constraints, such as construction times for low-carbon infrastructure and manufacturing assets or reskilling times for workers. For instance, the design and construction of renewables projects typically lasts two to six years in developed economies such as Europe and the United States, based on McKinsey estimates. If these timelines cannot be accelerated to match the pace of an abrupt transition, there is a risk that warming thresholds would be breached. This is turn raises the risk of substantially increasing adaptation spending on top of decarbonization efforts.

While significant, these economic adjustments would create growth opportunities and prevent further buildup of physical risk

While entailing substantial transformation, the changing demand outlook combined with the $3.5 trillion in incremental annual spending on physical assets in the NGFS Net Zero 2050 scenario, noted above, would create growth opportunities for companies and countries in the near term. We describe the opportunities for countries later in this report. The opportunities for companies are in the following three main areas:

Decarbonized forms of legacy products and processes: Companies that reduce the emissions intensity of their processes and products could gain advantages as the transition progresses. In some cases, decarbonizing processes and products can make them more cost-effective. For example, improving the energy efficiency of heating systems in steel plants lowers both emissions and operating costs. Even when decarbonizing adds to operating costs, companies can benefit from taking this step—for instance, if consumers are willing to pay more for lower-emissions products or if companies are subject to carbon-pricing mandates.

Low-emissions products and processes that replace established high-emissions options: Carmakers might make EVs instead of ICE vehicles, for example. Steelmakers can implement low-emissions production processes such as manufacturing steel with direct reduced iron–electric arc furnaces (DRI-EAF) powered by green hydrogen.[150] Utilities might set up wind or solar farms to generate renewable electricity, while energy companies could introduce biofuels and hydrogen.

Inputs, physical capital, infrastructure, and support services: New offerings will be needed to support production in the first two areas. These include, among others, mining raw materials such as lithium, cobalt, and rare-earth elements, as well as other inputs such as beneficiated iron ore for DRI-EAF steelmaking or new feed additives to mitigate methane emissions from livestock; manufacturing the physical assets needed to support decarbonization, such as solar panels, district heating systems, and long-duration batteries (to address the intermittency of solar and wind power); and building and operating infrastructure such as EV charging stations and hydrogen refueling stations.[151] A low-carbon

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[150] DRI is produced from the chemical reduction of iron ore into iron by either a reducing gas or elemental carbon produced from natural gas or coal, which can be used as an input, along with high-grade steel scrap, in the EAF method of steel production. Steel production in integrated blast furnaces or basic oxygen furnaces today uses iron ore and requires coal as a reductant. See Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, “Decarbonization challenge for steel,” McKinsey & Company, June 2020.

[151] For example, see “The raw materials challenge: How the metals and mining sector will be at the core of enabling the energy transition,” McKinsey & Company, January 2022. The research finds that requirement for additional supply will come not only from relatively large-volume raw materials—for example, copper for electrification and nickel for battery EVs, which are expected to see significant demand growth beyond their current applications—but also from relatively niche commodities, such as lithium and cobalt for batteries, tellurium for solar panels, and neodymium for the permanent magnets used both in wind power generation and EVs. Some commodities—most notably steel—will also play an enabling role across technologies, as additional infrastructure is needed.

economy will also require a broader enabling ecosystem to facilitate decarbonization activities and support a transition. Examples include financial products (for example, funding for renewables projects), risk management solutions, standard setting and certification services, improved data and tracking for emissions (such as via digital solutions), and training and education services.

The incremental capital spending on physical assets, which we estimate at about 3 percent of GDP annually through 2050 as discussed previously, and the broader economic transformations under a net-zero transition would have another essential feature: most importantly, reaching net-zero emissions and limiting warming to 1.5°C would prevent the buildup of physical risks and reduce the odds of initiating the most catastrophic impacts of climate change, including limiting the risk of biotic feedback loops and preserving the ability to halt additional warming.[152]

As the analysis of the shifts in demand, capital allocation, costs, and jobs highlights, the transition to net zero will amount to a full-scale economic transformation, one that will be universal in scope, significant in size, often front-loaded, and uneven in impact. Multiple challenges will need to be overcome, including the diversion of capital from high-carbon to low-carbon assets, the stranding of some physical assets, the movement of workers within and across industries and geographies, and the displacement of demand from existing goods and services to new or decarbonized products and services. The risk that such a transition could be disorderly is very real. At the same time, it is also clear that this transition could bring new opportunities for nations and businesses around the world and is crucial to avoiding the most catastrophic impacts of a changing climate. In the next two chapters, we look in detail at the potential shifts in the energy and land-use systems examined in this research and across geographies.

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[152] See Box E3 in the executive summary, chapter 1, and the bibliography for a detailed list of the academic literature and broader discussion related to physical climate risks.

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3. The net-zero transition in energy and land-use systems

In this chapter, we take a closer look at how a net-zero transition could affect the energy and land-use systems we described in previous chapters and, by extension, the economic sectors that participate in these systems. Using as a starting point the NGFS Net Zero 2050 scenario, we look at what the decarbonization implications would be for each.[153] We seek to measure the potential changes in demand and the necessary spending on physical assets to reach net-zero emissions, as well as the implications for costs and jobs. We also focus on key short-term risks and challenges, and on the opportunities in each sector, and identify key takeaways for stakeholders.

As part of this exercise, we estimated how exposed to the transition 55 economic sectors within our seven energy and land-use systems—power, industry, mobility, buildings, agriculture, forestry and other land use, and waste—could be. We did this analysis using four metrics. These are, first, each sector's direct scope 1 emissions, which indicate exposure to potential demand shifts, spending requirements on physical assets, and cost changes from having to alter production processes. Second, the emissions from their products, which indicates exposure to shifts in demand—for example, if consumers shift their preferences, thereby potentially influencing capital spending and costs. Third, supply chain emissions, which may expose the sector to cost shifts as its core inputs are affected by the transition. And fourth, emissions from purchased electricity, which could indirectly expose the sector to the effects of changes in the world's energy mix.[154] In each case, emissions were normalized based on the output of the sector. We also added up these metrics to create an overall exposure score, an indicator of the overall life-cycle emissions intensity of the sector.

A key finding that emerges from this analysis is that sectors with the highest degree of exposure account for about 20 percent of global GDP. These are sectors that directly emit significant quantities of greenhouse gases, such as the coal and gas power sector ("emitters in core operations"), or that sell products that emit greenhouse gases when used, such as the fossil fuel sector ("producers of fossil fuel energy" and "producers of fossil fuel–dependent products"). Another approximately 10 percent of GDP is in sectors with high-emissions supply chains, such as construction. The remaining 70 percent of GDP is generated by sectors that have less direct exposure but are nonetheless dependent on the more exposed sectors through interconnected economic and financial systems, and thus could be indirectly affected.[155] The heat map in Exhibit 14 highlights the types of exposure for the 25 most exposed sectors.

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[153] The NGFS Net Zero 2050 scenario contains detailed data for some but not all of the seven energy and land-use systems. Where necessary, we collaborated with Vivid Economics to create sector-specific decarbonization pathways that were consistent with the broader NGFS Net Zero 2050 scenario. See the technical appendix for details.

[154] The second point on emissions from products concerns downstream scope 3 emissions. The third point, on supply chain emissions, relates to upstream scope 3 emissions. The fourth point on electricity emissions relates to scope 2 for electricity use. For purposes of this research "scope 1" emissions are direct greenhouse emissions that occur from sources that are controlled or owned by an organization; "scope 2" emissions are associated with the purchase of electricity, steam, heat, or cooling. "Scope 3" emissions are the result of activities from assets not owned or controlled by the reporting organization but that the organization indirectly impacts in its value chain; thus scope 3 emissions result from emissions across an organization's value chain that are not within the organization's scope 1 and 2 boundary. *See Greenhouse gases at EPA,* United States Environmental Protection Agency. Similar definitions can also be applied when considering the scope 1, 2, and 3 emissions for a sector. See the technical appendix for details of methodology and metrics in the estimate.

[155] Other higher-order effects not considered here, for example, impacts on financial asset valuations, could increase the exposure of some of these latter sectors.

Exhibit 14

Sectors that produce fossil fuel energy or whose products depend on it are most exposed to the net-zero transition. (1 of 2)

Sector transition exposure score

Low □░▒▓■ High

Emissions intensity[1] (kt CO_2e per $ million)

░ 0.1 ▒ 0.1–0.2 ▓ 0.2–1.0 █ >1.0

					Emissions from …			
Sector archetype	**Sector**	**% of GDP**	**% of scope 1 emissions**	**Sector transition exposure score**[2]	**Own operations (scope 1)**[3]	**Products (scope 3)**[4]	**Electricity used (scope 2)**[5]	**Other inputs (scope 3)**[6]
Producers of fossil fuel energy	Mining and extraction of energy-producing products	1.9	9.6	■	█	█	▒	░
	Coke and refined petroleum products	0.7	2.5	■	▓	█	░	▓
Producers of fossil fuel-dependent products	Machinery and equipment	1.5	0.1	■	░	█	░	▒
	Other transportation equipment	0.6	0.0	▓	░	█	░	░
	Motor vehicles	1.4	0.0	▓	░	█	░	░
	Fabricated metal products	0.9	0.1	▒	░	▓	░	▓
	Electrical equipment	0.9	0.0	■	░	▓	░	▒
Emitters in core operations	Sewerage and waste	0.5	4.7	■	█	░	░	░
	Electricity and other utilities	1.8	23.3	■	█	░	▓	▓
	Agriculture and forestry	3.7	25.4	■	█	░	░	░
	Cement and other nonmetallic mineral products	0.7	5.0	▓	█	░	▒	▒
	Air transportation	0.5	1.7	▓	█	░	░	▒
	Water transportation	0.4	1.5	▓	█	░	░	▒
	Iron, steel and other basic metals	0.9	6.2	▓	▓	░	▒	▒
	Chemicals	1.3	2.8	▒	▓	░	▒	▒
	Land transportation	2.0	2.2	▒	▓	░	░	░

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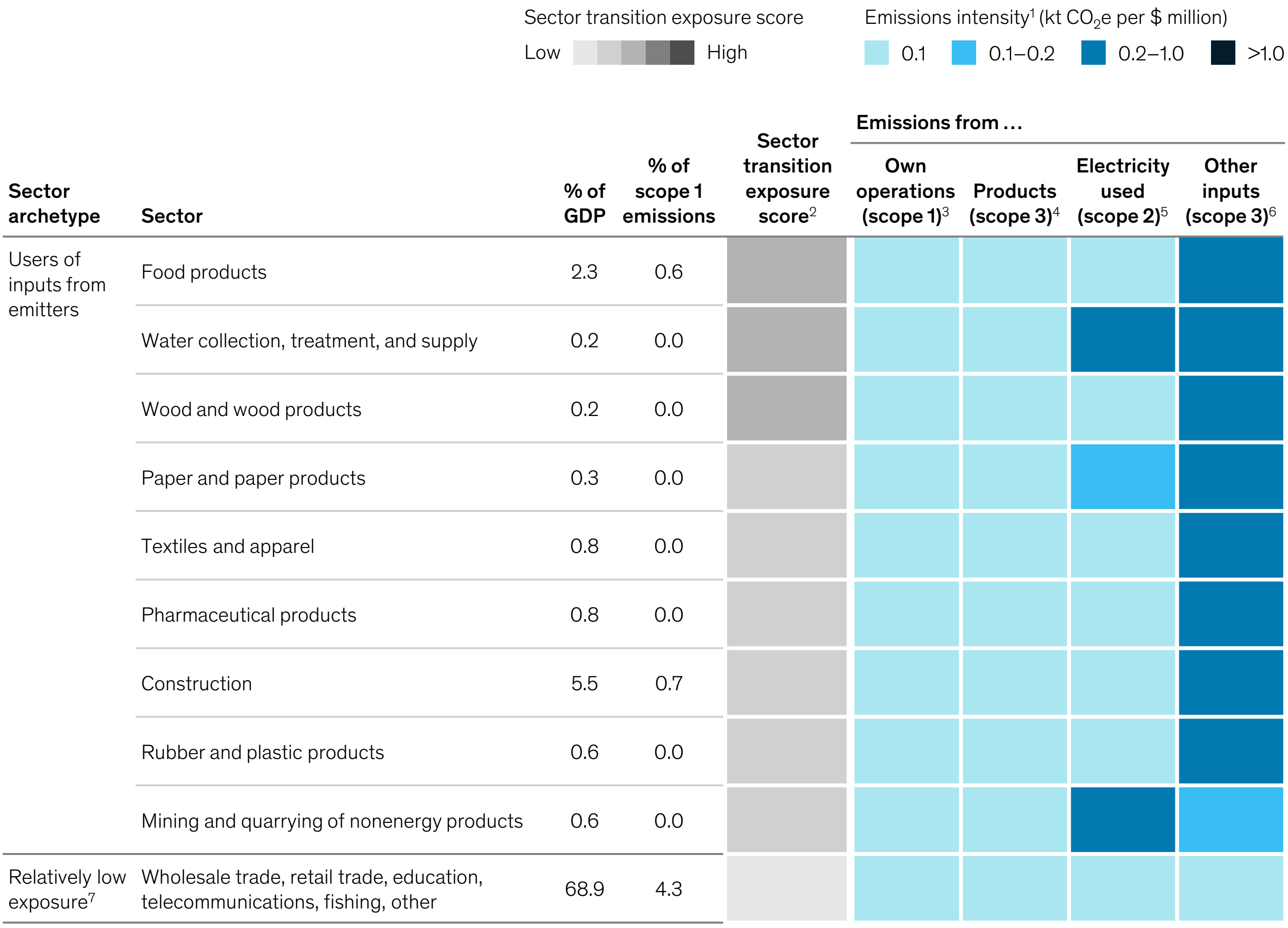
1. Emissions intensity is calculated using CO_2 equivalent emissions, taking into account CO_2, CH_4, and N_2O. These gases are converted to CO_2 equivalent using the GWP100 methodology. For each of the 4 emissions-intensity metrics, the relevant scope of CO_2 equivalent emissions—ie, 1, 2, 3 (inputs), or 3 (products)—is divided by the gross output of the sector to derive an intensity measure (ie, kt CO_2e / $M). Gross outputs for each sector derived from WIOD.
2. A sector's transition exposure score is calculated as the sum of its life-cycle emissions intensity—ie, sum of scope 1, 2, 3 (inputs), and 3 (products) emissions intensities—and then indexed from 0–100, with 0 being no scope 1, 2, or 3 emissions, and 100 being the highest life-cycle emissions intensity.
3. These are emissions that result directly from the operations of a sector (eg, burning of coal during steel production).
4. These are emissions that result from the use of the products of a sector (eg, burning of oil during the driving of ICE vehicles).
5. These are emissions that result from the use of electricity by a sector (eg, burning of natural gas to produce electricity).
6. These are emissions that result from the use of inputs from an emitting sector.

Source: World Input-Output Database; Emissions Database for Global Atmospheric Research; McKinsey Global Energy Perspectives; IPCC; OECD; IHS Global; Penn World Tables; McKinsey Global Institute analysis

Exhibit 14 (continued)

Sectors that produce fossil fuel energy or whose products depend on it are most exposed to the net-zero transition. (2 of 2)



Sector transition exposure score: Low ░ ▒ ▓ ▆ █ High

Emissions intensity[1] (kt CO_2e per $ million): ○ 0.1 ◔ 0.1–0.2 ◑ 0.2–1.0 ● >1.0

Sector archetype	Sector	% of GDP	% of scope 1 emissions	Sector transition exposure score[2]	Emissions from … Own operations (scope 1)[3]	Products (scope 3)[4]	Electricity used (scope 2)[5]	Other inputs (scope 3)[6]
Users of inputs from emitters	Food products	2.3	0.6	▓	○	○	○	◑
	Water collection, treatment, and supply	0.2	0.0	▓	○	○	◑	◑
	Wood and wood products	0.2	0.0	▓	○	○	○	◑
	Paper and paper products	0.3	0.0	▒	○	○	◔	◑
	Textiles and apparel	0.8	0.0	▒	○	○	○	◑
	Pharmaceutical products	0.8	0.0	▒	○	○	○	◑
	Construction	5.5	0.7	▒	○	○	○	◑
	Rubber and plastic products	0.6	0.0	▒	○	○	○	◑
	Mining and quarrying of nonenergy products	0.6	0.0	▒	○	○	◑	◔
Relatively low exposure[7]	Wholesale trade, retail trade, education, telecommunications, fishing, other	68.9	4.3	░	○	○	○	○

1. Emissions intensity is calculated using CO_2 equivalent emissions, taking into account CO_2, CH_4, and N_2O. These gases are converted to CO_2 equivalent using the GWP100 methodology. For each of the 4 emissions-intensity metrics, the relevant scope of CO_2 equivalent emissions—ie, 1, 2, 3 (inputs), or 3 (products)—is divided by the gross output of the sector to derive an intensity measure (i.e., kt CO_2e / $M). Gross outputs for each sector derived from WIOD.
2. A sector's transition exposure score is calculated as the sum of its life-cycle emissions intensity—ie, sum of scope 1, 2, 3 (inputs), and 3 (products) emissions intensities—and then indexed from 0–100, with 0 being no scope 1, 2, or 3 emissions, and 100 being the highest life-cycle emissions intensity.
3. These are emissions that result directly from the operations of a sector (eg, burning of coal during steel production).
4. These are emissions that result from the use of the products of a sector (eg, burning of oil during the driving of ICE vehicles).
5. These are emissions that result from the use of electricity by a sector (eg, burning of natural gas to produce electricity).
6. These are emissions that result from the use of inputs from an emitting sector.
7. Sectors include: fishing; printing and reproduction of recorded media; computer, electronic, and optical products; furniture and other manufacturing; repair and installation of machinery; accommodation and food service activities; administrative and support service activities; education; human health and social work; real estate activities; financial services; insurance; activities auxiliary to financial services and insurance activities; professional, scientific, and technical activities; information and communication; public administration and defense; compulsory social security; wholesale trade; retail trade; warehousing; postal and courier activities; other service activities. Other higher-order effects not considered here, for example, impacts on financial asset valuations, could increase the exposure of some of these sectors.

Source: World Input-Output Database; Emissions Database for Global Atmospheric Research; McKinsey Global Energy Perspectives; IPCC; OECD; IHS Global; Penn World Tables; McKinsey Global Institute analysis

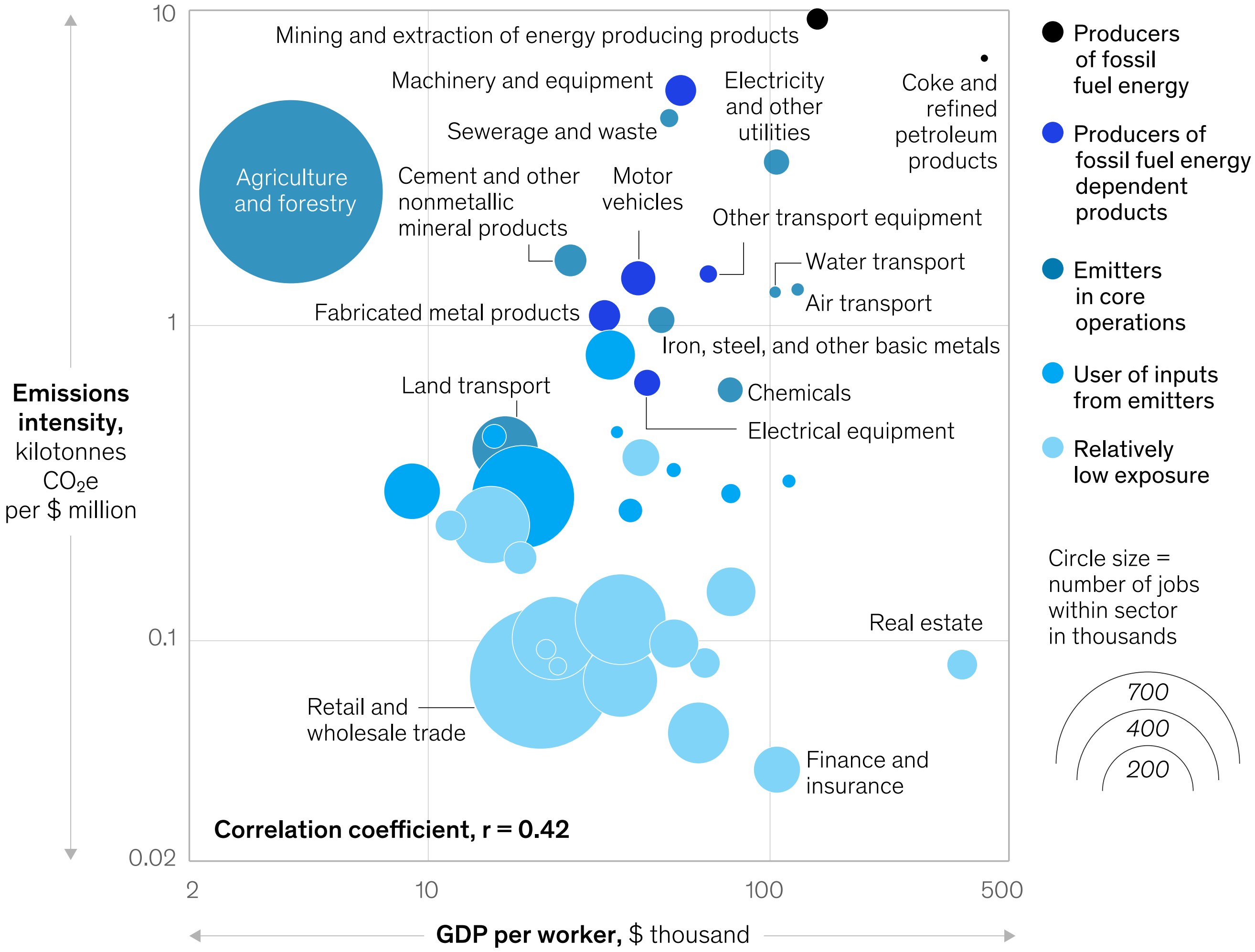
As part of this analysis, we also gauged the vulnerability of a sector's workforce to the net-zero transition. We compared overall emissions intensity across the categories described previously, which provides an indication of which sectors may be more prone to employment shifts and transformations from the transition, with its GDP per worker, which serves as a proxy for sector profits and wages, and thus the ability of workers to adjust financially to the transition. From this analysis, we see that 10 of the 55 sectors have relatively high exposure to the transition and relatively low GDP per worker. Some 15 percent of GDP is in these sectors, which include agriculture, forestry, cement, automotive, and land transportation (Exhibit 15). An additional nine sectors have high transition exposure and relatively high GDP per worker. These sectors account for approximately 11 percent of GDP and include extraction and refining of fossil fuels, power, and chemicals. While workers in these sectors may be better prepared financially to adjust to the transition, they too may require varying degrees of support, based on the nature of their skills and ability to transition to other areas of the economy.

Below we illustrate how the transition could play out in the energy and land-use systems through eight deep dives into fossil fuels and new sectors including hydrogen and biofuels, power, industry (steel and cement), road mobility, buildings, food and agriculture, and forestry and other land use. The organization of this system view largely follows the energy and land-use systems framework used above, with two changes: we do not include the waste system, and we break out fossil fuels, hydrogen, and biofuels as a separate category because of their cross-cutting nature. The infographic accompanying each section contains charts illustrating the most relevant of the economic shifts that we examined in detail, namely demand, capital spending, costs, and jobs.

Exhibit 15

Sectors with high emissions intensity vary in their level of GDP per worker and number of workers.

Sector emissions intensity vs sector GDP per worker[1] (logarithmic scale)



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1. Sector GDP per worker is based on dividing the sector's GDP by the respective sector's jobs. Sector GDP is the sum of the sector's GDP in the 69 countries in our analysis; sector jobs is the sum of the sector's jobs in the 69 countries in our analysis. Emissions intensity is calculated using CO_2-equivalent emissions, and takes into account CO_2, CH_4, and N_2O. These gases are converted to CO_2 equivalent using the GWP100 methodology.

Source: OECD; ILO; World Input-Output Database; IHS Connect; World Bank; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; UN Population estimates; International Renewable Energy Agency (IRENA); MINSTAT; INDSTAT; McKinsey Nature Analytics; McKinsey Global Institute analysis

Fossil fuels, hydrogen-based fuels, and biofuels: Adapting to the shift toward low-carbon energy sources

Combustion of fossil fuels produces 83 percent of global CO_2 emissions. Four percent of global CO_2 emissions and 33 percent of methane come from fossil fuel extraction.[156] The Net Zero 2050 scenario analyzed here foresees a significant reduction in the use of fossil fuels as the use of other energy sources increases (Exhibit 16).[157] At the same time, this would create opportunities for alternate energy carriers including hydrogen and biofuels.

Paths to decarbonization. For fossil fuel production, a key decarbonization action would entail reductions in emissions from operations. Energy-efficiency improvement is one element of this approach: McKinsey research has found that a 10 percent increase in oil and gas production efficiency can deliver a 4 percent reduction in emissions intensity.[158] Electrifying the equipment used in extraction and refining would help decarbonize these activities, provided that the electricity came from zero-emissions sources.[159] In addition, fossil fuel producers could manage fugitive methane emissions with equipment such as vapor-recovery units and practices such as proactive leak detection. Finally, carbon capture and storage could be used to reduce the emissions from oil and gas processes that produce highly concentrated streams of CO_2. Captured CO_2 could be reinjected into oil reservoirs, increasing the efficiency of oil production through a process called enhanced oil recovery.[160]

Shifts in demand, capital spending, costs, and jobs. Beyond decarbonization of fossil fuel production and direct emissions, a key implication of the net-zero transition examined here would be a potential shift in the energy mix—specifically, a reduction in demand for fossil fuels and growing demand for other energy sources such as electricity, hydrogen, and biofuels (see Box 5, "Prospects for hydrogen and biofuels in the net-zero transition"). Compared to today, oil and gas production volumes in 2050 in the NGFS Net Zero 2050 scenario would be 55 percent and 70 percent lower, respectively, and coal production for energy use would be all but eliminated.[161]

Our analysis shows that by 2050, the transition described by the Net Zero 2050 scenario could lead to about 33 million fewer direct and indirect operations and maintenance jobs in the primary energy industry and its supply chain.[162] These job losses are concentrated in fossil fuel production (13 million from coal mining, eight million from oil and gas extraction, 12 million from petroleum refinement and coke production).[163] Because many of these jobs are located near existing deposits and infrastructure, a decline in demand would have a disproportionate impact on specific communities.

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[156] EMIT database, McKinsey Sustainability Insights, September 2021. Data from 2019.

[157] The analysis in this section is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In some cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[158] Paul Gargett, Stephen Hall, and Jayanti Kar, "Toward a net-zero future: Decarbonizing upstream oil and gas operations," McKinsey & Company, December 2019.

[159] Chantal Beck, Sahar Rashidbeigi, Occo Roelofsen, and Eveline Speelman, "The future is now: How oil and gas companies can decarbonize," McKinsey & Company, January 2020.

[160] Ibid.

[161] Demand and technology trajectories for fossil fuels will vary based on the scenario examined.

[162] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other low-emission sources). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. See technical appendix for further details.

[163] O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains. Includes direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. While calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

Exhibit 16

In the NGFS Net Zero 2050 scenario, the fossil fuel, hydrogen, and biofuels sectors would see demand shifts, capital reallocation, and job transitions.

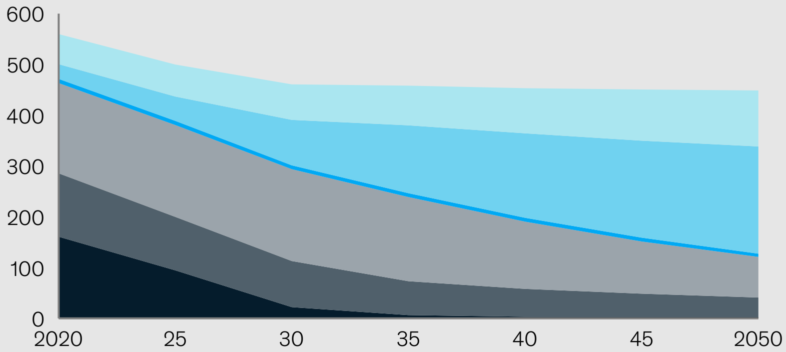
Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

Combustion of coal, oil, and gas =

83% CO_2 emissions today

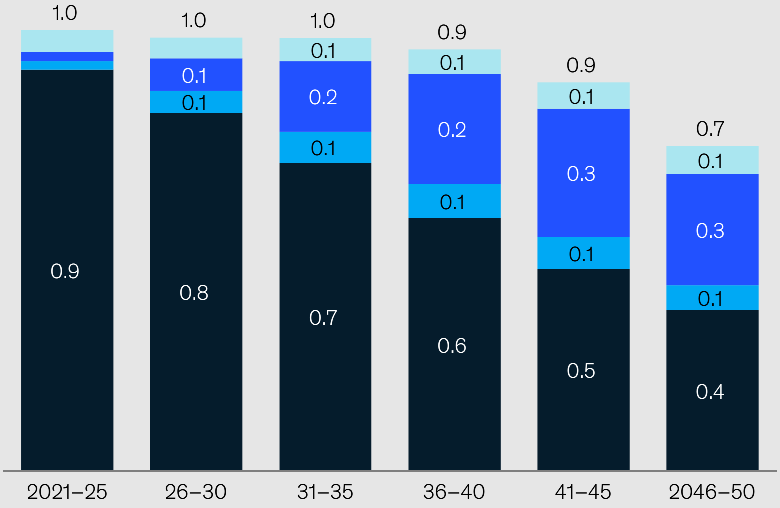
Demand for fossil fuels would drop sharply in the NGFS Net Zero 2050 scenario as end-use sectors move to lower-emissions sources of energy.

Primary energy, exajoule



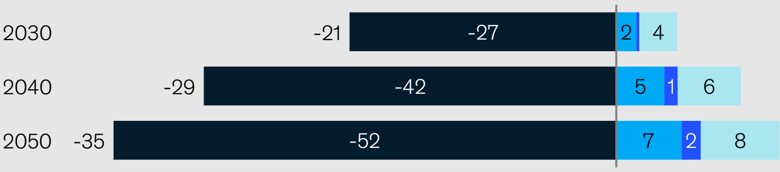
Capital spending on liquid fuels and heat supply would shift away from fossil fuels in the NGFS Net Zero 2050 scenario.

Annual capital expenditures, 2021–50,[2] average over 5-year period, $ trillion



Jobs would be lost in fossil fuel production, while jobs would be gained in other primary energy source industries including biofuels, hydrogen, and carbon capture.

Employment shifts[3], net changes associated with a net-zero transition, million jobs (includes direct and indirect O&M and capex jobs)



1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Capital expenditures include the following components: for hydrogen, electrolyzer installment costs, housing, and indirect costs; for oil, gas, and coal, capital spending on extraction of conventional fuel; for biofuels, capital spending on plant and equipment. Costs do not include margin. Capital expenditures for other energy sources (e.g., renewable electricity) not shown here.
3. For job shifts associated with the power sector, see other sections of Chapter 3. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains. Capex jobs are those arising from capital expenditures in the sector, associated with manufacturing, construction, and their supply chains. Includes direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing, mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. Job losses and gains described in this analysis refer to those tied specifically to transition-related changes. Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Hydrogen Insights; McKinsey Sustainability Insights; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

Box 5

Prospects for hydrogen and biofuels in the net-zero transition

The net-zero transition will lead to the increased uptake of new energy carriers, specifically hydrogen, biofuels, and biomass. These industries may be centered in regions with considerable sunlight, wind, or sources of biomass.

Hydrogen. In the net-zero transition, hydrogen could serve many purposes—for example, as an industrial feedstock for industry, a fuel, or a chemical for long-term energy storage. In the NGFS Net Zero 2050 scenario, hydrogen production, excluding captive production for industrial end uses (for example, refineries, chemical production), would increase more than tenfold between now and 2050.

Currently, hydrogen production mainly involves steam-methane reforming and autothermal reforming technologies—emissions-intensive processes that result in gray hydrogen. For a net-zero transition, this type of hydrogen would be replaced by carbon-neutral green or pink hydrogen. Green hydrogen is made with electrolysis powered by low-emissions energy, while pink hydrogen is made with electrolysis powered by nuclear energy. Blue hydrogen, produced through gray steam-methane and autothermal reforming processes plus carbon capture and storage, can bridge the transition to green.

As the price of low-emissions energy drops, production costs for green hydrogen are likely to decrease, and output is likely to grow.[1] Recent analysis by the Hydrogen Council in collaboration with McKinsey shows that the production costs of green hydrogen could decline 60 percent from 2020 to 2030. At that rate, green hydrogen could reach cost parity with traditional production methods by 2028 in regions that are optimal for low-emissions energy production, and between 2032 and 2034 in locations with average potential for low-emissions energy—assuming a carbon cost of about \$50 per metric ton of CO_2 equivalent (tCO_2e) by 2030, \$150 per tCO_2e by 2040, and \$300 per tCO_2e by 2050.[2]

Our analysis suggests that, in the NGFS Net Zero 2050 scenario, expanding capacity for making hydrogen would require average annual capital spending of close to \$55 billion between now and 2050.[3] A substantial number of jobs could be created: according to our analysis, hydrogen production could see an increase of approximately five million direct and indirect operations and maintenance jobs, with an additional two million jobs related to capital expenditure on hydrogen infrastructure by 2050.

Biofuels and biomass. Biofuels are transportation fuels, such as biodiesel, ethanol and biojet, produced from purpose-grown agricultural cash crops, and sometimes from agricultural and food sector waste and byproducts. Today, biofuels are blended with fossil fuels to make diesel and gasoline. Indeed, hydrogen-based synthetic fuels and biofuels have already been approved by aircraft manufacturers for use in aviation, and could also be used in shipping. National regulations in individual countries are playing the main role in shaping biofuels markets.

Our analysis suggests that in the NGFS Net Zero 2050 scenario, sustainably produced biofuels would reach a material share of final energy consumption in 2030. Their production would increase more than tenfold between 2020 and 2050, requiring annual average capital spending of about \$175 billion. Demand for biomass would increase during the net-zero transition, mainly as a result of the uptake of biofuels. How the biomass supply would meet this increased demand is unclear. Questions surround the feasibility of producing biomass from waste cycles and the availability of appropriate land for growing bioenergy crops. The uptake of biofuels could also lead to about six million direct and indirect O&M job gains by 2050, with an additional two million jobs related to capital expenditures associated with the build-out of biofuel infrastructure.

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[1] For example, costs of solar and wind power have decreased by about 80 percent and 40 percent, respectively, in the past decade. See Jason Finkelstein, David Frankel, and Jesse Noffsinger, "How to decarbonize global power systems," McKinsey & Company, May 2020.

[2] These costs reflect pure production costs and assume a dedicated renewable and electrolysis system for renewable hydrogen. They do not include costs required for baseload supply of hydrogen (for example, storage and buffers) or for redundancies, services, and margins; they also do not include any cost for hydrogen transportation and distribution. See *Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness,* Hydrogen Council and McKinsey & Company, February 2021.

[3] This includes the cost of energy.

For example, in seven US counties in the states of Pennsylvania, Virginia, West Virginia, and Wyoming, more than 10 percent of workers are employed in coal mining.[164] Countries whose economies have a large share of economic activity related to fossil fuel production—such as Qatar, Saudi Arabia, and the United Arab Emirates—would also be exposed to such a transition (see chapter 4 for details). On average, about 15 percent of GDP in these countries involves extracting and refining fossil fuel products. Our analysis also suggests that, in 2050, other fuel sectors could see a gain of 11 million direct and indirect O&M jobs as a result of the net-zero transition. These job gains are in the biofuels industry and its upstream supply chain (six million) and in the hydrogen industry and its supply chain (five million).

Short-term risks and challenges. As the energy transition unfolds, perhaps the greatest challenge will be how to manage the ramping down of high-emitting forms of energy, with the ramping up of low-emissions ones, to ensure reliable and affordable energy provision. To adjust to the net-zero transition, the world's biggest fossil fuel producers might consider not only decarbonizing their operations, as described above, but also rebalancing their business portfolios. More broadly, regions reliant on fossil fuel–based sectors would need to consider measures for economic diversification.

Opportunities. As the energy mix shifts in the Net Zero 2050 scenario, our analysis suggests that markets for hydrogen and biofuels in particular would expand along with the market for zero-emissions electricity. These developments could create possibilities for economic development in various geographies. Houston's largest chamber of commerce, the Greater Houston Partnership, has outlined a blueprint for future economic growth that identifies opportunities for the city to gain as many as 560,000 additional jobs by leading in the energy transition; however, Houston could lose up to 650,000 jobs by taking no action by 2050.[165] This includes jobs related to solar, wind, hydrogen, CCS, and EVs, among others. Many of the world's leading fossil fuel resource–producing regions, including Egypt, Oman, Saudi Arabia, and the United Arab Emirates, have high solar potential, which would be in demand in a net-zero economy. Norway and the United Kingdom have high wind power density, which allows countries to generate renewable wind power and green hydrogen (see chapter 4).[166] The transition toward low-carbon primary energy could create growth potential for companies that supply equipment and services to such industries. Electrolyzer manufacturers, for example, could see increasing demand for their products, given their role in the hydrogen value chain.

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[164] "Quarterly census of employment and wages," US Bureau of Labor Statistics.

[165] *Houston: Leading the transition to a low-carbon world,* Greater Houston Partnership, June 2021.

[166] Global Solar Atlas; Global Wind Atlas; World Bank.

Potential stakeholder responses. Regions whose economic activity now relies heavily on fossil fuels may need to invest in low-carbon industries that can power growth and provide jobs. For example, Saudi Arabia unveiled plans for one of the world's largest green-hydrogen projects in 2020.[167] The Greater Houston Partnership's report, mentioned above, calls for Houston to develop emerging technologies such as CCS, low-carbon hydrogen, and energy storage; attract companies in "new energy" industries; and support capital spending in a broad range of energy value chains—an agenda that takes advantage of the region's technical workforce, energy and transportation infrastructure, and other attributes.[168]

In some regions, economic-diversification programs would likely require targeted adjustment financing from governments or multilateral institutions. Another important adjustment would be reskilling and redeploying workers. The Scottish government, for example, invested in retraining and reskilling workers in the oil and gas sector as North Sea oil production declined, enabling 89 percent of participants to find new jobs after completing the program.[169]

McKinsey research suggests that oil and gas companies are adapting to the net-zero transition by following one of three courses.[170] Some are becoming resource specialists by focusing on improving their capital returns and operating performance while reducing and offsetting their operational emissions. Others are seeking to become diversified energy players; for example, BP announced a plan to increase its low-carbon spending tenfold by 2030.[171] Finally, some oil and gas companies are turning themselves into low-carbon pure plays by divesting legacy high-carbon portfolios and investing in new low-carbon businesses.

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[167] John Parnell, "World's largest green hydrogen project unveiled in Saudi Arabia," greentechmedia.com, July 7, 2020.

[168] Ibid.

[169] *Case study: Oil & Gas Transition Training Fund, Scotland,* Platform for Coal Regions in Transition, 2019.

[170] Chantal Beck, Donatela Bellone, Stephen Hall, Jayanti Kar, and Dara Olufon, "The big choices for oil and gas in navigating the energy transition," McKinsey & Company, March 2021.

[171] "From international oil company to integrated energy company," BP, August 4, 2020.

Power: A major expansion of renewable and other low-emissions capacity would bring investment opportunities, but the risk of rising delivered costs of electricity and volatility would need to be managed

The NGFS Net Zero 2050 scenario envisions widespread electrification that would happen as fossil fuels are replaced with electric power. This, along with population growth and increased energy access, would substantially lift power consumption relative to today.[172] A successful transition to net zero for the power system would require a scale-up of renewable and other, low-emissions power generation to meet increased demand for electricity. While this would bring capital spending opportunities, it would also raise risks of asset stranding (Exhibit 17). The challenge of rising energy costs and securing reliable power would also need to be effectively managed.

Paths to decarbonization. Globally, the power system accounts for 12.9 $GtCO_2$ per year, about 30 percent of all CO_2 emissions.[173] Decarbonization would involve replacing fossil fuel plants for power generation with low-emissions sources, for example, solar, wind, or nuclear. The growth of renewables like solar and wind raises the question of how to deal with their daily and seasonal intermittency and ensure reliability (reliability more broadly for transmission and distribution will become increasingly important as a much larger portion of energy production shifts toward the power system). Some fossil fuel plants would remain in use to ensure flexibility of the grid, which would need to go hand-in-hand with storage technologies, the use of carbon capture, utilization, and storage, and power-to-gas-to-power conversions, as well as demand management and long-distance interconnections to pool renewable assets across a larger geographic area.[174] Another consideration would be managing the physical footprint of renewable technologies, which is much higher than that of traditional fossil fuels.[175]

Shifts in demand, capital spending, costs, and jobs. In the NGFS Net Zero 2050 scenario, power generation would scale substantially and roughly double compared with today. The greatest increases in demand would be in sub-Saharan Africa (a sevenfold increase compared with today), India (fourfold), and emerging markets in Asia (threefold). About 95 percent of electricity generation in this scenario in 2050 would come from sources other than fossil fuel combustion.

Increasing power generation in line with the NGFS Net Zero 2050 scenario would require annual capital spending on physical assets from 2021 to 2050 that we estimate at about $1 trillion in power generation, $820 billion in the power grid, and $120 billion in energy storage. This is more than twice today's spending.[176] The increase stems from higher electrification needs of the economy because of growth as well as the net-zero transition, and from investment in a system which is moving from high fuel-driven variable costs to one which is dominated by capital deployment with relatively low operating expenses.

Asset stranding could be large. The risk of asset stranding may be especially acute in China and India, which have coal plants that are less than 15 years old on average (compared with over 30 years old in the United States).[177] Our analysis of the scenario suggests that about

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[172] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In some cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[173] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[174] See also Jason Finkelstein, David Frankel, and Jesse Noffsinger, "How to decarbonize global power systems," McKinsey & Company, May 2020; and Rory Clune, Ksenia Kaladiouk, Jesse Noffsinger, and Humayun Tai, "A 2040 vision for the US power industry: Evaluating two decarbonization scenarios," McKinsey & Company, February 2020.

[175] Current power technologies such as coal and gas require about 12 acres per megawatt of power generation. In contrast, solar and wind power require approximately 43 and 71 acres of land per megawatt, respectively. Thus, switching to wind and solar power would likely increase land use by a factor of three to six. See *The footprint of energy and land use of US electricity production,* Strata, 2017.

[176] Spending may be even higher than sized here, for example if additional investment is needed to maintain flexibility and redundancy.

[177] See *World energy outlook 2021,* International Energy Agency, December 2021.

$2.1 trillion of the sector's capital stock could be stranded by 2050.[178] Eighty percent of this amount is today's capacity, and 20 percent is capacity that would be built between 2020 and 2050.

Another key challenge to be managed is the effect of the power transition on the delivered cost of electricity. Even under a relatively orderly transition, the scenario modeled here finds that capital spending to replace fossil fuel power capacity and build out transmission, distribution, and storage capacity to improve grid reliability and flexibility would increase the global average delivered cost of electricity in the near term. We estimate that the fully loaded unit cost of electricity production across generation, transmission, distribution, and storage would increase about 25 percent by 2040 from 2020 levels (including operating costs, capital costs, and depreciation of existing and new assets).[179] This is for two main reasons: firstly, investments will be needed in grid and storage capacity, creating capital costs and depreciation charges. Secondly, some fossil-based power assets would continue to incur capital costs, even if they are underutilized or retired prematurely.

Cost increases could be even larger and more volatile than estimated here, for example if grid flexibility is not well managed and power generation is insufficient to meet demand, or if young fossil fuel assets need to be abruptly retired. Substantial near-term risk will need to be managed to ensure that energy prices for consumers do not rise and create affordability issues.[180] In the long run, there is more uncertainty on the outlook for costs. The delivered cost of electricity could well be lower than 2020 levels given the lower operating costs for generation from renewables, depending on innovations in grid design and evolution of the power system to manage flexibility issues. It is also important to note that the delivered cost of electricity as sized here is not the same as consumer electricity prices, as discussed also in chapter 2. This analysis represents a global average perspective. The picture could look quite different across regions depending on the current state of their power system, age of fossil power fleets, and availability of natural resources like sunshine and wind, among other factors.

Our analysis suggests that approximately six million direct jobs would be added in operations and maintenance for renewable power and approximately four million direct jobs would be lost in fossil fuel–based power under a net-zero transition by 2050.[181]

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[178] Based on cumulative value of prematurely retired and underutilized assets from 2020 to 2050, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years. We use this approach based on the age of the asset and its utilization (similar to a book value approach) to capture the effect of the production dynamics shifting, rather than any market dynamics or other factors. Other research has found similar effects on the power sector. See, for example, *Stranded assets and renewables: How the energy transition affects the value of energy reserves, buildings and capital stock,* International Renewable Energy Agency, 2017; and David Nelson et al., *Moving to a low-carbon economy: The impact of policy pathways on fossil fuel asset values,* Climate Policy Initiative, October 2014.

[179] To assess cost changes for power, we first quantified the change in three main cost drivers: power generation capital charge and depreciation (at a weighted average cost of capital of 6.5 percent), power generation operating costs, and transmission, distribution, and storage investments. These were then translated into a delivered cost of electricity by dividing by electricity production in each time period. This metric indicates how the underlying costs are changing for the entire power sector. Our methodology is broader than other studies focused on the levelized cost of energy for new assets which often highlight the competitive cost position of renewables in the power mix. Our analysis also takes into account infrastructure spending on grids, capital charges, and depreciation of legacy assets even if they are prematurely retired or underutilized. See also Rupert Way et al., Empirically grounded technology forecasts and the energy transition, Institute for New Economic Thinking Oxford, working paper number 2021-01, September 2021. Note that our metric is different from the actual cost paid by consumers, and eventual energy prices for consumers could look substantially different. Consumer electricity prices depend on a multitude of factors, including decisions on how the power system transformation is paid for and over what time frame. For example, a key question is how to best manage coal generation decommissioning and write-down costs. Moreover not all expected changes in delivered costs are due to decarbonization. For instance, some transmission and distribution investments would happen regardless, as countries increase electricity access. This analysis does not take into account short-term variations in supply and demand, subsidies, or taxes.

[180] See also Box E5 in the executive summary.

[181] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other renewables). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains, and include direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

Exhibit 17

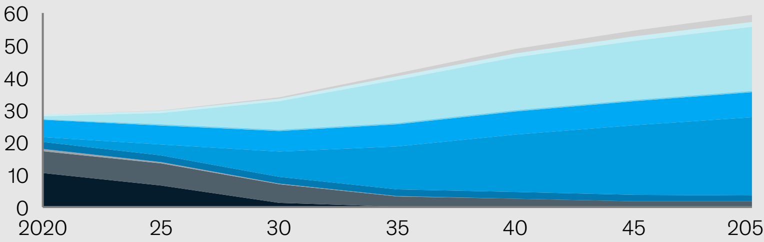
In the power sector, the NGFS Net Zero 2050 scenario would bring investment opportunities and near-term unit cost increases.

Emissions today
30% CO_2 (scope 1)

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

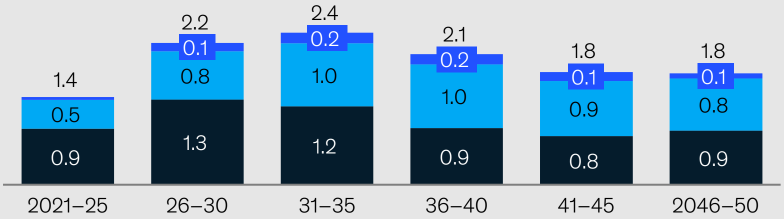
Demand for electric power, particularly from renewable sources, would rise in the NGFS Net Zero 2050 scenario as sectors switch from fossil-based energy sources to electricity.

Electricity generation by source, GWh



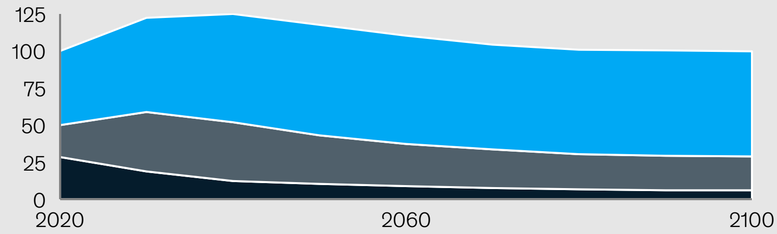
Average annual capital spending would rise in the NGFS Net Zero 2050 scenario compared to today, as generation capacity, transmission and distribution networks, and storage infrastructure are built out.

Annual capital expenditures, 2021–50,[2] average over 5-year period, $ trillion



Delivered cost of electricity would increase in the near term because of significant capital spending and depreciation but would fall in the long run due to lower operating costs in the NGFS Net Zero 2050 scenario.

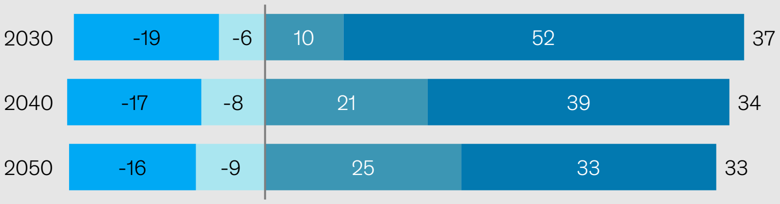
Delivered cost of electricity,[3] net-zero scenario, $ per MWh (index: 100 = 2020), global average



Jobs in the power sector are more numerous in the NGFS Net Zero 2050 scenario, largely driven by the increase in demand for renewable electricity associated with the transition.

Includes direct and indirect jobs

Employment shifts, gross changes associated with a net-zero transition, million jobs[4]



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1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Capital expenditures include capital spending on all generation types (fossil fuels and renewables), transmission and distribution networks, batteries, and inverters.
3. Delivered cost of electricity across generation, transmission and distribution, and storage. Includes operating costs, depreciation, and capital costs, for existing and new assets. Capital costs assumes weighted average cost of capital of 6.5%. This metric indicates full system costs and is not the same as consumer electricity prices. The trends described here are global averages and would vary across regions.
4. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains. Capex jobs are those arising from capital expenditures in the sector, associated with manufacturing, construction, and their supply chains. Includes direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, agriculture, forestry and fishing, mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (eg, the shift from fossil fuel energy production to solar, wind, and other renewables), and not those arising from technological, policy, or other factors. Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021), Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Power Solutions; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

A massive power-infrastructure build-out could result in a gross gain of about 27 million direct jobs in construction, manufacturing, and upstream sectors by 2030, slowing to a gain of approximately 16 million direct jobs by 2050.

Short-term risks and challenges. Lack of system resiliency due to insufficient flexible generation, land constraints for permitting renewables, coupled with the scale-up of power demand from buildings and mobility could disrupt the power system. Securing reliable access to power will be a key imperative for the sector. Asset impairment could also be substantially higher under a delayed and abrupt transition, if new fossil-power assets are built that then need to be prematurely retired or underutilized.

Opportunities. The power sector holds some of the largest opportunities for value creation, given the expansion and capital spending expected in the sector. Opportunities would arise not only for low-emissions power producers but also for providers of low-emissions generation equipment, electricity-storage hardware, and related services. This includes solar-panel and wind-turbine manufacturers, battery manufacturers, companies involved in extracting and refining minerals needed for batteries and solar panels (for example, lithium, rare-earth elements, copper, and nickel), and construction and other companies responsible for building and operating new generation capacity and transmission and distribution networks. Finance providers and companies offering project development support for the influx of new low-emissions projects required over the next decade could also see opportunities. Finally, companies that develop technologies to enable grid expansion, grid integration, and flexibility solutions for power (for example, power system integration) could also see increased demand for their products.

Potential stakeholder responses. Several measures could help facilitate the reallocation of capital toward low-emissions power generation. Some regions have established multiyear energy strategies that include targets for retiring fossil fuel plants and compensation programs for the owners of these assets, which may result in these costs not being reflected in customers' bills.[182] Incentives could also help in markets where low-emissions sources would not be cost competitive with conventional sources.

Managing up-front capital spending on physical assets and delivered cost of electricity increases is another consideration. Short-term increases in energy prices could prove challenging for lower-income consumers, many of whom spend more of their income on energy than other households, even though they consume less energy per capita.[183] Various social support schemes could mitigate impacts of rising energy prices, either directly with subsidies or by assisting households with installation of rooftop solar power, battery systems, and other equipment to minimize their grid-connection charges.

Finally, continued technological and market innovation would be needed to manage grid intermittency and ensure reliability. Enabling the electricity grid to accommodate significantly more renewable energy would likely require continued innovation of storage technologies. It would also entail thoughtful grid design and require interconnection and system-balancing coordination among grid operators to balance demand and supply, for example, between generators and grid operators. Managing intermittency would also require continued innovation on the demand side—for example, by modulating load through demand response and management as adoption of distributed energy resources (for example, small-scale solar, energy storage, and controllable appliances) increases. This would require capital spending on grid modernization technologies from utilities (advanced metering infrastructure and distributed-energy-resource-management systems) and broad uptake of updated utility rate structures to reward demand-side measures.

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[182] See, for example, Julian Wettengel, "Spelling out the coal exit—Germany's phase-out plan," Clean Energy Wire, July 3, 2020.

[183] Thirty-one percent of all US households experience some form of energy insecurity. Marilyn A. Brown et al., "High energy burden and low-income energy affordability: Conclusions from a literature review," *Progress in Energy,* volume 2, October 2020.

Steel industry: Investing in low-emissions production while managing higher costs

Steel occupies an essential place in modern life as one of the most important materials for construction, equipment and machinery, and durable goods. Globally, steel production accounts for 3.4 $GtCO_2$ per year, about 8 percent of all CO_2 emissions.[184] Production of a metric ton of steel results in 1.8 metric tons of CO_2 emissions on average.[185] Efforts to decarbonize steelmaking operations would require capital spending to retrofit production assets or replace them with alternatives that emit less CO_2. Decarbonization could potentially increase production costs by about 30 percent by 2050 compared with today, according to our analysis, which is based on a scenario consistent with the NGFS Net Zero 2050 scenario (Exhibit 18).[186] To adjust to the transition, steel producers would need to assess their emissions, identify a net-zero strategy, engage with the broader ecosystem, and decide on a technologically and economically viable way to decrease their carbon footprint.[187]

Paths to decarbonization. Nearly three-quarters of crude steel today is made from iron ore in blast furnace–basic oxygen furnace (BF-BOF) plants. These plants release carbon when coking coal is burned and used as a reducing agent. Reducing emissions would require providing the high-temperature heat that is essential in steelmaking as well as mitigating process emissions from the steel-reducing process. However, while several promising alternation technology options exist, there is still uncertainty over the ultimate preferred route. One key decarbonization action could be replacing blast furnaces with electric arc furnaces; powering EAFs with 100 percent carbon-neutral electricity would eliminate energy-related emissions.[188] However, process emissions associated with feedstock would also need to be abated. Feedstock for EAFs consists of either scrap-based steel—the increased use of which would reduce emissions—pig iron, or direct reduced iron. Availability of scrap would limit the extent to which scrap-based EAF can be used. Today, natural gas is used in the direct reduction of iron, but if green hydrogen made with renewable power were used instead, this process would be close to emissions free. Another option involves using carbon capture, utilization, and storage with traditional steelmaking techniques, although this approach remains technologically premature and has yet to be proven economically.[189]

Shifts in demand, capital spending, and costs. In the net-zero scenario analyzed here, global demand for steel would increase modestly and be about 10 percent higher in 2050 than today. In some cases, downstream users of steel may try to reduce their supply-chain emissions and seek alternative materials, such as cross-laminated timber in buildings and construction. However, the bigger shift is likely to be related to the mix of production, which would substantially change, with low-carbon steel rising from almost one-quarter of all production to almost all production by 2050.[190] EAF would be the main mode of steel production by 2050, accounting for nearly 65 percent of overall output. BF-BOF plants would still account for the remaining 35 percent of steel production. Most of this production would be decarbonized by installing CCS equipment. There is, however, some uncertainty in these estimates as to which technologies will prevail.

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[184] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[185] *Steel's contribution to a low carbon future and climate resilient societies,* World Steel Association, 2020.

[186] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In this and some other cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[187] While this discussion is focused on the emissions reduction in the steel manufacturing process, the upstream mining industry that produces the inputs to the steelmaking process also generates emissions and has additional important considerations in the social and governance impacts of these processes. That is, however, outside the scope of this analysis.

[188] For more details on decarbonization of the steel sector, see Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey & Company, June 2020.

[189] Ibid.

[190] DRI-EAF with natural gas for flat products and 100 percent scrap EAF for long products are usually <0.6 tons Scope 1 & 2 CO2 per ton of steel (t/t), and the lowest existing emissions routes. In the near future the advent of hydrogen will lower the emissions further to possibly <0.3 t/t Scope 1 & 2 CO_2.

Exhibit 18

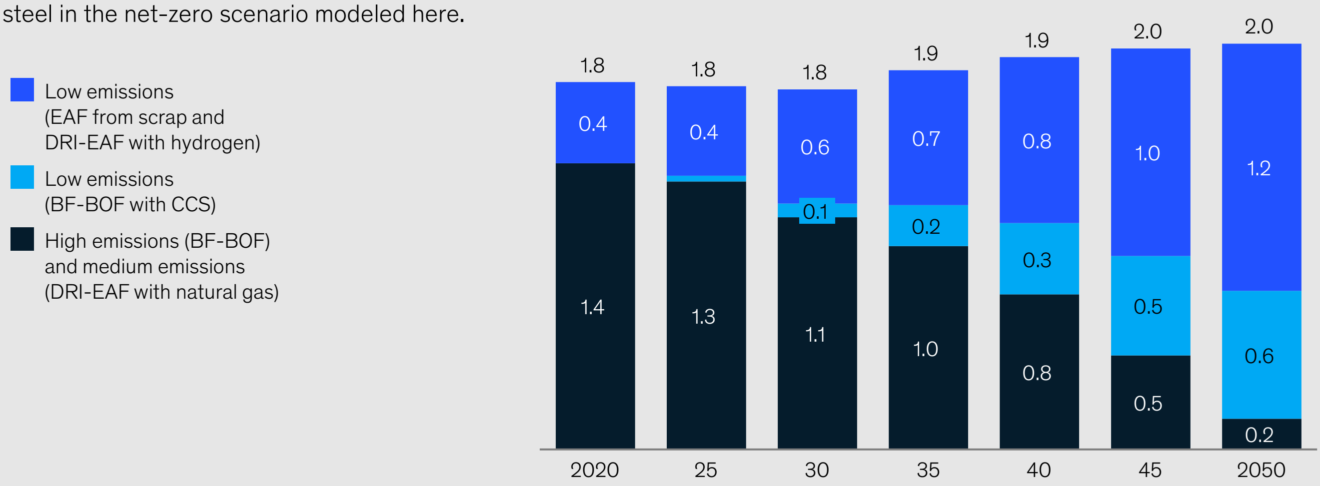
A net-zero transition in the steel sector could result in cost increases and require increased capital spending to decarbonize production.

Emissions today
8% CO_2 (scope 1)

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

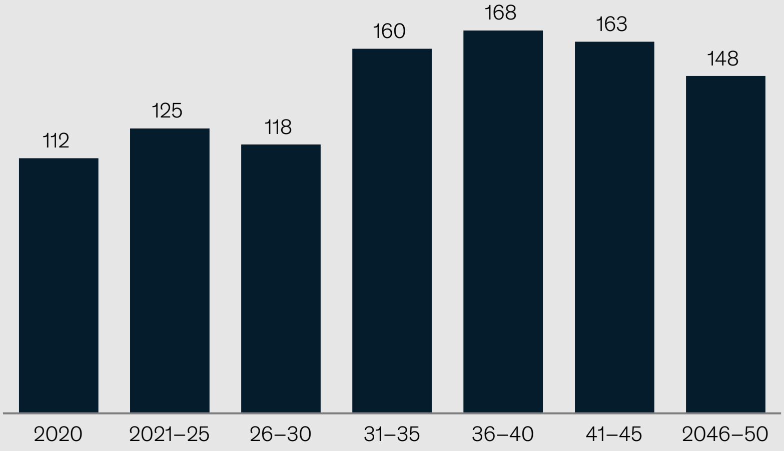
Production would shift toward low-emissions steel in the net-zero scenario modeled here.

Global steel production, Gt



Spending would be required in the net-zero 2050 scenario modeled here to build new low-emissions production capacity (eg, hydrogen-based DRI-EAF) and install CCS.[2]

Annual capital expenditures, 2021–50, average over 5-year period, $ billion



Costs for steel in the net-zero scenario could increase because of the up-front capital spending and higher operating costs associated with CCS and hydrogen-based DRI-EAF production.

Steel unit cost of production,[3] (index: 100 = 2020), global average

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1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Capital spending includes plant, equipment, and maintenance costs. Assumes global weighted average unit capex cost with weighting toward China, European Union, United Kingdom, United States, Mexico and Canada.
3. Includes operating costs, depreciation costs, and capital charges across steel production routes, and including both existing and newly built capacity. Financing cost assumes weighted average cost of capital of 8%. Unit costs are weighted by the relative production volumes of different steel routes. Unit cost of production is rounded to nearest multiple of 5.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System scenario analysis 2021 phase 2 (Net Zero 2050 scenario) REMIND-MAgPIE model; Vivid Economics; McKinsey Basic Materials Insights; McKinsey–Mission Possible Partnership collaboration analysis; McKinsey Global Institute analysis

This is based on downscaling of the NGFS Net Zero 2050 scenario; other scenarios may expect a smaller role for BF-BOF production with CCS in the long run, and a bigger role instead for EAF than described here.

Meeting this demand while remaining within emissions limits via low-emissions production routes would require cumulative capital spending of about $4.4 trillion over the next 30 years, an annual average of about $145 billion per year. Approximately one-quarter of the capital spending in the Net Zero 2050 scenario would be used to retrofit existing BF-BOFs with CCS technology. For hydrogen-based DRI, further capital spending would be required to scale production of green hydrogen and to build out pipeline infrastructure.

In this scenario, our analysis suggests that steel production costs would increase by about 30 percent in 2050 compared with today.[191] Most of the increase would result from the higher operating costs associated with CCS and hydrogen-based DRI. These cost increases are sensitive to the extent to which costs of green hydrogen production can be lowered, and innovation could lower the estimates sized here. The rise in production costs may have potential knock-on price impacts on a range of consumer and industrial goods, from refrigerators to heavy machinery. The size of the potential impacts will depend on the share of steel intermediate inputs in the final product.

Short-term risks and challenges. As discussed above, uncertainty still remains on the eventual route for steel decarbonization. Factors such as the cost evolution of hydrogen and CCS routes as well as variations across regions could influence the pathway taken. A key challenge for steel producers will also be managing any cost increases they may experience as a result of the net-zero transition.

Opportunities. Depending on the premium that customers are willing to pay for low-emissions steel—and on the evolution of regulation involving, for example, carbon prices—low-emissions steel producers could gain a competitive advantage in a net-zero transition. Other players in the steelmaking ecosystem also stand to benefit from a shift toward low-carbon steel production. For example, companies that supply feedstock, equipment, and energy for EAF and DRI-EAF production (including steel scrap, beneficiated iron ore, pelletizing equipment, low-emissions power, hydrogen electrolyzers, and green hydrogen) could see increased demand. Demand for related services, such as construction and maintenance of CCS solutions and maintenance of DRI-EAF facilities, could also rise.

Potential stakeholder responses. The shift to hydrogen-based steel relies in part on the broad availability of green hydrogen on an industrial scale. However, green hydrogen is expensive today. To be cost competitive with current fuels, estimates suggest its cost would need to fall more than 60 percent.[192] Scaling up hydrogen production would require close coordination between steelmakers and the hydrogen and power sectors.

The economics of decarbonized steel production are likely to be influenced by incentives in the form of government-led policy measures such as carbon pricing and carbon border taxes. Steelmakers could work with regulators to ensure support for decarbonization spending that would help to preserve local jobs and meet growing demand for low-emissions steel. Governments could also consider the use of subsidies and loans to help steelmakers with the up-front capital expenditures associated with the use of hydrogen-based DRI and CCS.[193] These actions would help stimulate demand for low-carbon steel. Incentives may also come from the financial sector, if the cost of financing for low-emissions technology falls. Steel consumers may also provide the right incentives by demonstrating a willingness to pay the higher costs of low-carbon steel. Already, various auto manufacturers for example, have announced plans to eliminate carbon emissions from their value chains.[194] The shift toward net-zero steel production would thus likely depend on a collaborative effort among regulators, governments, and industry stakeholders to change the economics of production, facilitate access to required capital, and stimulate demand.

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[191] Factoring in operating costs, capital charges, and depreciation.

[192] *Path to hydrogen competitiveness: A cost perspective,* Hydrogen Council, January 2020.

[193] Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," McKinsey & Company, June 2020.

[194] Ibid.

Cement industry: Managing higher costs and shifts in demand

Cement production accounts for emissions of 2.6 $GtCO_2$ per year, or roughly 6 percent of the global total, placing the industry among the highest-emitting industrial sectors.[195] About 40 percent of the emissions from cement production come from the fossil fuels used to power the precalciners and kilns in cement plants. The rest comes from the chemical process of calcination.[196] The scenario modeled here, consistent with the NGFS Net Zero 2050 scenario, suggests that decarbonization of cement would entail capital spending and higher operating costs (Exhibit 19). Opportunities could arise across the low-emissions cement industry and its value chain as well as in the markets and value chains for alternative materials.[197]

Paths to decarbonization. Today, the decarbonization pathway for the cement sector may be less technologically certain than for other sectors. If used together, several established techniques have the potential to cut emissions from cement production.[198] Energy-efficiency measures would focus on kilns, which consume about 90 percent of the energy used in cement manufacturing. Switching to alternative fuels, such as biomass, would also lower emissions because they are less carbon-intensive than fossil fuels, although their use depends on availability and local supply chains. Cement production could be decarbonized further with measures to alter the composition of cement or concrete. Clinker, an intermediate input, could be replaced with materials that release no CO_2, such as natural and calcined pozzolans, or industrial byproducts such as fly ash and blast-furnace slag.[199]

That said, traditional levers alone will only likely allow the cement and concrete industry to contribute about one-third of the reduction in emissions required to limit warming across the economy to 1.5°C, and so various other innovative technologies would be needed.[200] Collectively, these represent approaches to reduce emissions, redesign buildings and infrastructure, and repurpose the carbon dioxide produced in the construction process.

Carbon capture, utilization, and storage, used today in just a handful of commercial pilot plants, could be a potential solution.[201] Carbon curing could also be used to sequester CO_2 in concrete.[202] Recycling technologies can also be used to reduce the carbon footprint of concrete. Recycled concrete paste can be carbonated with CO_2 from flue gas and used as supplementary cementitious material.

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[195] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[196] For details, see Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020

[197] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In this and some other cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[198] For details, see Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020; and Thomas Hundertmark, Sebastian Reiter, and Patrick Schulze, "Green growth avenues in the cement ecosystem," McKinsey & Company, December 2021.

[199] Pozzolans are finely ground silica- or silica-and-aluminum-based powders that form cement when mixed with water.

[200] Sebastian Reiter and Patrick Schulze, "Green growth opportunities in the cement ecosystem," McKinsey & Company, December 2021. See also "Glasgow at COP26, 2021: Decarbonizing the built environment," McKinsey & Company, Global Infrastructure Initiative, October 2021.

[201] This method isolates and collects carbon dioxide from exhaust vents and either recycles it for further industrial use (for example, in the production of glass and plastics) or safely stores it underground. While still relatively nascent, expanding the scale of CCS would depend on the economics of storing and sequestering carbon, regulation, and the availability of customers for captured CO_2.

[202] This technology injects CO_2 captured during cement production to accelerate the curing process and "lock in" CO_2 in the end product. Current low-carbon cement technologies can sequester up to 5 percent of CO_2, with the potential of 30 percent. For details, see Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020.

Reducing demand for cement through the collection and recycling of concrete waste is another way to lower emissions. Given its performance characteristics and the widespread availability of raw materials, cement-based concrete would remain a preferred construction material globally. However, over time, other materials could play a role. The adoption of alternate building materials such as cross-laminated timber, for example, could be a pathway to reduce emissions, though uncertainty remains about how much of a role they can play.[203] Alternative insulation materials such as double-glazed tinted glass, advanced insulation foam, as well as entirely new technologies like biocement, created from naturally grown materials, are also being considered. Other potential shifts include the application of modular construction methods and building information modeling systems, which can enable more efficient construction and reduce the need for cement and concrete.[204]

Shifts in demand, capital spending, and costs. In the net-zero scenario examined here, demand for cement would be about 6 percent higher in 2050 than today but would shift toward the low-emissions techniques described above.

Our analysis suggests that the industry would require capital spending on physical assets of about $60 billion on average per year over the next 30 years in the Net Zero 2050 scenario to build low-emissions production capacity and add CCS equipment to existing plants. Separately, large spending on infrastructure, such as pipelines and tanks to collect CO_2 and store or deliver it to customers, would also be necessary.

These decarbonization measures could make an average metric ton of cement approximately 45 percent more expensive in the net-zero scenario than today. The production cost of cement would go up because CCS would add operating costs and require up-front capital expenditures. There could be wide regional variations in these costs, depending on the economics of CCS and other factors; for example, biomass could also become scarcer as a result of rising demand from other industries. Innovation could also lower the estimates here.

The economics of emissions abatement could be improved by bringing down the costs of CCS and increase the availability of alternative fuels and clinker substitutes, for example via local regulations. Regulatory differences in carbon prices, which our analysis does not include, could also have a significant influence on whether a metric ton of cement becomes more or less expensive during the net-zero transition than it would have been otherwise.

Short-term risks and challenges. As discussed above, uncertainty still remains on the eventual route for cement decarbonization. A key challenge for cement producers will also be managing any cost increases they may experience as a result of the net-zero transition.

Opportunities. The net-zero transition could create opportunities to develop low-emissions cement, including more broadly across the ecosystem, depending on how regulations and customer and investor preferences evolve.[205] Products such as carbon-cured concrete, for example, could justify the cost of a green premium among environmentally conscious buyers. Producers of alternative materials could also see demand go up if construction companies look to replace cement in buildings and other structures. New opportunities could also include prefabrication, modular housing, and building information management services. Low-emissions cement requires different feedstock and clinker substitutes, alternate energy sources including biomass, and new equipment, mainly related to CCS. Among others, companies that produce recycled material from construction and demolition waste, increasingly used, could see rising demand.

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[203] For further details about the role that such building materials could play, see Ed Thomas, *Investigating the potential of cross-laminated timber panels made from low-grade hardwoods for building construction,* US Forest Service, 2017.

[204] Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers, "Laying the foundation for zero-carbon cement," McKinsey & Company, May 2020.

[205] Sebastian Reiter and Patrick Schulze, "Green growth opportunities in the cement ecosystem," McKinsey & Company, December 2021.

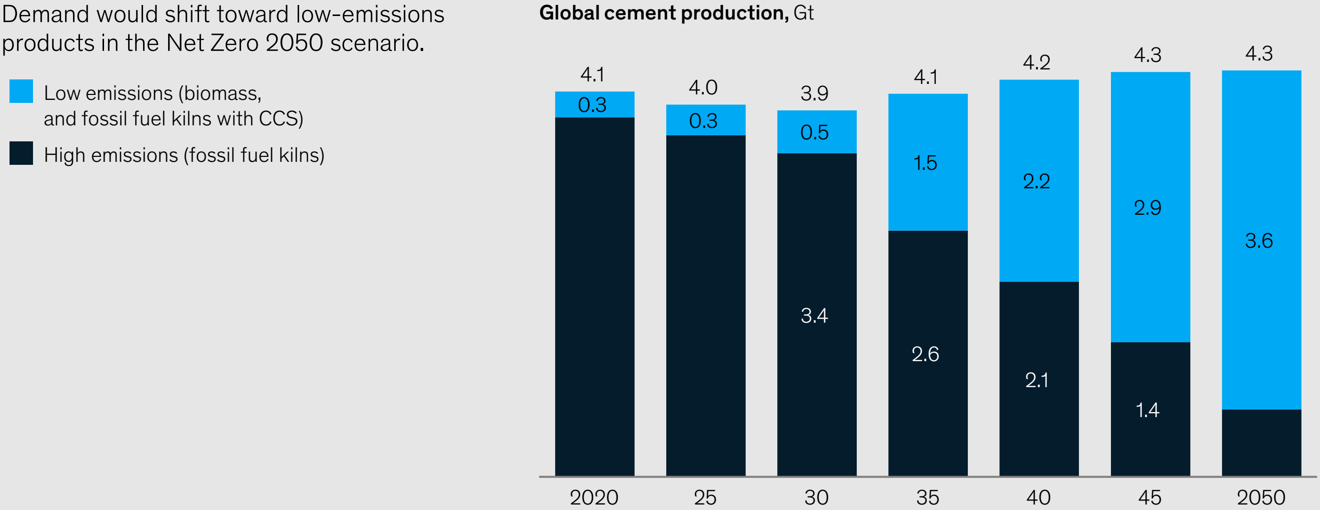
Exhibit 19

A net-zero transition in the cement sector could result in cost increases and require increased capital spending to decarbonize production.

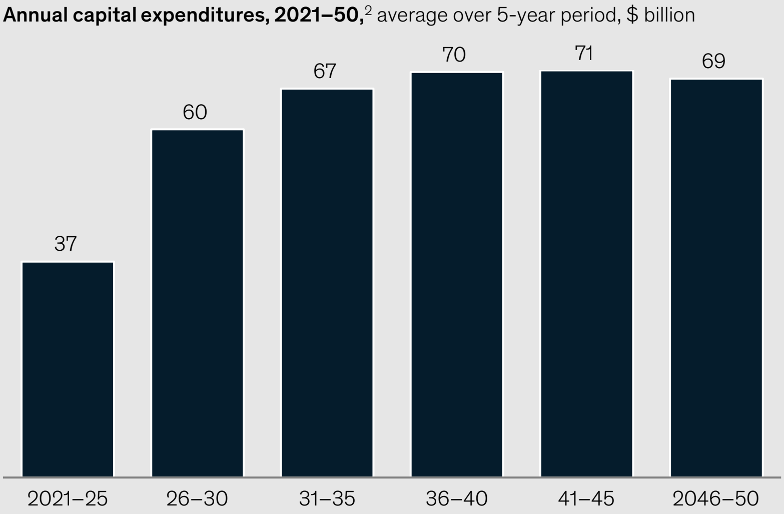
Emissions today
6% CO_2 (scope 1)

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

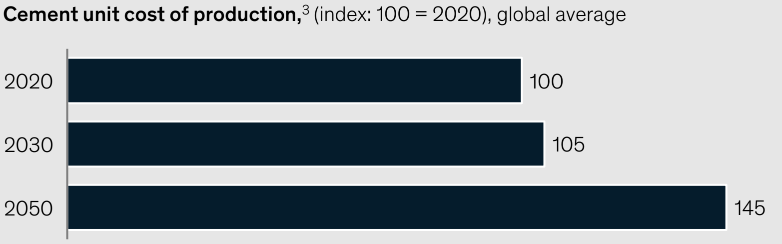
Demand would shift toward low-emissions products in the Net Zero 2050 scenario.



Capital spending would be required to build low-emissions production capacity and add CCS equipment to existing plants.



Low-emissions cement would cost more because of higher capital expenditures and operating costs.



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1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Capital expenditures include the following components: plant, equipment and maintenance costs, CCS capex. CCS capital spending does not include CO_2 transportation, storage and usage. Capital spending associated with increased clinker substitution has not been sized.
3. Includes operating costs, depreciation costs, and capital charges across cement production routes, including both existing and newly built capacity. Financing cost assumes weighted average cost of capital of 8%. Unit costs are weighted by the relative production volumes of different cement routes. Unit cost of production is rounded to nearest multiple of 5.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System scenario analysis 2021 phase 2 (Net Zero 2050 scenario) REMIND-MAgPIE model; GNR-GCCA 2019; Vivid Economics; McKinsey Basic Materials Insights; McKinsey Sustainability Insights; McKinsey Global Institute analysis

Potential stakeholder responses. Given the nature of the cement industry, and the decarbonization actions involved, the entire ecosystem would need to participate. This includes governments and regulators, customers, investors, developers and owners of projects, construction companies, providers to new technologies like alternate building materials, and, finally, cement producers. Broader stakeholders in the ecosystem would need to play a role to create the right conditions and incentives to help support decarbonization efforts.

Governments can consider various incentives to improve the economics of decarbonized cement. These include subsidies to compensate for the large up-front capital expenditures required to decarbonize, as well as R&D investment to bring down the costs of CCS, alternative fuels, and low-emissions production methods. Regulations on CO_2 emissions could also affect the relative costs of conventional and low-emissions cement. Because cement markets are local, local policies will likely be differentiators. A key challenge for many potential decarbonization technologies will be applying them at industrial scale. The cement industry is distributed across many players, and many innovations are still in the prototype or pilot stage. Getting decarbonization technologies to industrial scale will require sufficient capital spending (including venture capital and private equity funds) to drive R&D and support large-scale rollout.

For companies, a combination of individual initiatives and collective action could help lessen the impacts of the net-zero transition. To manage their exposure to cost and demand shifts, companies might build road maps of actions they might take under different scenarios, pursue technological advancements to help drive down costs, and rethink their products and portfolios. Industry platforms can help companies align their actions and jointly pursue innovations that could benefit them all. More broadly, new partnerships with innovators and suppliers will be crucial to securing new forms of low-emissions inputs and driving innovation.

Mobility: Shifting to low-emissions vehicles and managing up-front capital costs and job reallocation

The movement of people and goods by land, air, and sea is vital to the international economy. Most of this activity is powered by fossil fuels. Mobility accounts for emissions of approximately 8.1 $GtCO_2$ per year, or 19 percent of overall CO_2.[206] In this section, we focus our analysis on road mobility, the segment of the mobility system that accounts for about 75 percent of transportation emissions. (For other modes of transportation, see Box 6, "The net-zero transition in aviation, shipping, and rail.") In the mobility scenario modeled here, consistent with the NGFS Net Zero 2050 scenario, road transportation would undergo a substantial shift to battery-electric and fuel cell-electric vehicle sales by 2050.[207] This would involve a ramp-up in capital spending, job reallocations, and a reduction of passenger vehicle total ownership costs over time (Exhibit 20). Companies throughout the mobility system, not just OEMs but also suppliers, as well as manufacturers and operators of EV charging infrastructure, could tap into the opportunities created by the net-zero transition.

Paths to decarbonization. Decarbonizing road transportation primarily means replacing ICE vehicles that run on fossil fuels with those that have low or zero emissions. Battery-powered electric vehicles are currently a key zero-emissions technology for passenger cars. Fuel cell electric vehicles combine hydrogen stored in a tank with oxygen from the air to make electricity to power vehicles, with water as a byproduct. Fuel cell technology will likely be prominent in trucks with high range requirements. New supply chains and manufacturing capabilities would need to be established, especially for batteries. BEVs and FCEVs also require corresponding infrastructure: electric charging stations for BEVs and hydrogen fueling stations for FCEVs, plus upstream production of electricity and hydrogen. Also essential is an increase in the supply of low-emissions electricity and hydrogen (for example, green hydrogen), so that tailpipe emissions are not replaced with emissions from elsewhere but are eliminated. Other decarbonization actions could include reducing overall private vehicle miles, via modal shifts to public transportation and alternative forms of mobility such as pooled and shared options. Manufacturers are also considering how to reduce lifecycle emissions associated with materials and decarbonize the production processes used to make vehicles.[208]

Shifts in demand, capital spending, costs, and jobs. In the net-zero scenario analyzed in this report, sales of low-emissions cars would increase from 5 percent of global new-vehicle sales in 2020 to almost 50 percent by 2030, and much higher in some regions such as Europe.[209] By 2050, they would account for virtually all new car sales in this scenario.[210] Similar trends would hold true across different categories of road mobility examined here: passenger cars, buses, two- and three-wheelers, and trucks.

The transition of all vehicle types to low-emissions models in the net-zero scenario would result in additional capital spending required for companies in the vehicle supply chain and for vehicle owners. This spend on new vehicles alone is estimated to be an annual average of $3.4 trillion per year over the next three decades in the net-zero scenario. Building out EV charging networks and hydrogen distribution and fueling systems would require additional annual capital spending of $100 billion over the next 30 years.

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[206] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[207] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In this and some other cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[208] Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel, "The zero-carbon car: Abating material emissions is next on the agenda," McKinsey & Company, September 2020.

[209] The McKinsey Center for Future Mobility projects that by 2035, the largest automotive markets for passenger vehicle sales (the European Union, the United States, and China) will be fully electric. "Why the automotive future is electric," McKinsey & Company, September 2021.

[210] For cars, EV share of annual sales would rise from 5 percent today to 80 percent by 2050, and FCEV from less than 1 percent today to 20 percent globally in the Net Zero 2050 scenario.

Box 6

The net-zero transition in aviation, shipping, and rail

Aviation accounts for approximately 13 percent of transportation emissions, shipping represents 11 percent, and rail contributes about 1 percent.[1] To reach net-zero emissions, these sectors would need to make significant shifts in their assets and operations.

Aviation: Decarbonizing aviation would require switching to aircraft that run on sustainable aviation fuel (SAF) in the near term. SAF can be produced from sustainable feedstock such as forestry waste and other forms of biomass. Because biomass production sequesters carbon (subsequently released when biomass-derived fuels are burned), SAF could reduce the life cycle emissions of aviation by 70 to 100 percent on a net basis, according to some estimates.[2] Governments could consider policies to hasten the transition to SAF. Many countries have mandated blending of SAF with conventional fuel.[3] These decarbonization solutions, however, could raise consumer prices; the UK Climate Change Committee estimated that SAF with marginal greenhouse gas removals could add more than $40 to a return ticket from London to New York.[4] In the longer term, aircraft that run on electricity and hydrogen could also be developed. This would require further research and innovation as well as the build-out of hydrogen infrastructure.

Shipping: The shipping sector can be decarbonized in a similar fashion to aviation: with more efficient vessels, sustainable fuels, and eventually zero-emission vessels. This shift could be costly, since the price gap between alternative fuels and fossil fuels is particularly evident in the shipping sector. And because ships are long-lived capital assets (the average age of a merchant vessel is just over 20 years), shipping companies have little incentive to replace relatively young assets with lower-emissions models.[5] For example, in the near term, zero-emissions container shipping fueled by green ammonia could be twice as expensive as standard shipping fueled by heavy oil in the Asia-Europe corridor. However, the extent to which this will flow through to higher costs for consumers will likely be country- and product-specific.[6]

Rail: Rail transportation emits six to 41 grams of carbon dioxide equivalent (CO_2e) per passenger kilometer traveled, compared with 150 grams for an economy long-haul flight and 255 grams for a domestic flight.[7] A shift from other modes of transportation to rail would therefore help decarbonize the transportation sector as a whole. The European Union, for example, has launched the €450 million Shift2Rail initiative to make rail more economical and convenient for passengers by improving technology, interoperability, and efficiency.[8] Decarbonizing rail transportation would involve phasing out diesel trains in favor of electric or hydrogen-fueled trains. Progress varies by geography: the EU has electrified more than 50 percent of its railways, compared with less than 1 percent in the United States.[9]

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[1] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[2] Alex Dichter, Kimberly Henderson, Robin Riedel, and Daniel Riefer, "How airlines can chart a path to zero-carbon flying," McKinsey & Company, May 2020.

[3] *Sustainable aviation fuels guide,* International Civil Aviation Organization, December 2018.

[4] *The sixth carbon budget (aviation),* Climate Change Committee, December 2020.

[5] "Age distribution of the world merchant fleet in 2019–2020, by vessel type," Statista.

[6] Research has highlighted that the cost of jeans may only rise by 1 percent, but this might vary for other product types. *Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness,* Hydrogen Council and McKinsey & Company, February 2021.

[7] *Which form of transport has the smallest carbon footprint?* Our World in Data, October 2020.

[8] *Rail research and Shift2Rail,* European Commission.

[9] "Percentage of the railway lines in use in Europe in 2018 which were electrified, by country," Statista; and Richard Nunno, *Electrification of US railways: Pie in the sky, or realistic goal?* Environmental and Energy Study Institute, May 2018.

Exhibit 20

For the road mobility sector, a net-zero transition could involve a shift to low-emissions electric vehicles, job reallocation, and lower total cost of passenger car ownership over time.

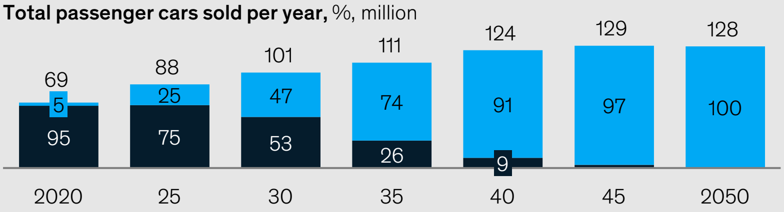
Emissions today
19% CO_2 (scope 1)

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

The net-zero scenario modeled here would see a strong shift of demand toward low-emissions vehicles.

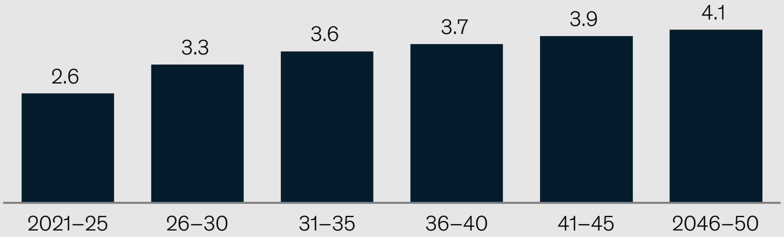
🟦 Battery-electric vehicles and fuel-cell electric vehicles[2]
■ Internal combustion engine

Total passenger cars sold per year, %, million



Spending would be required to support the shift to low-emissions vehicles.

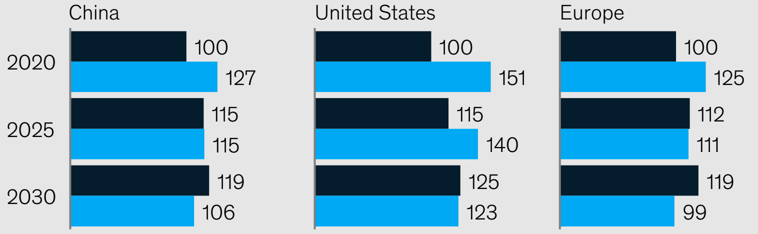
Annual spending on vehicles (including passenger cars, trucks, buses, and 2 and 3 wheelers) and infrastructure, 2021–50, average over 5-year period, $ trillion



Total cost of passenger car ownership would be lower for electric vehicles than for internal combustion engine vehicles over time.

■ Internal combustion engine
🟦 Battery-electric vehicle

Total cost of ownership, compact passenger cars, 2021–30, internal combustion engine cars in region (index: 100 = 2020)[3]



Job reallocation would be needed between internal combustion engine–based value chains and low emissions–based value chains

Includes direct and indirect jobs

🟦 Capex (losses)[4]
▢ Operations and maintenance (losses)[4]
▨ Operations and maintenance (gains)[4]
■ Capex (gains)[4]

Employment shifts, gross changes associated with a net-zero transition, million jobs

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1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Low-emissions vehicles include battery electric vehicles (BEVs) and hydrogen-powered fuel cell electric vehicles.
3. Total cost of ownership accounts for purchase price, operating costs, for instance fuel and maintenance costs, and resale value; based on 3-year ownership of a new car.
4. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains. Capex jobs are those arising from capital expenditures in the sector, associated with manufacturing, construction, and their supply chains. Includes direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing, mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020 and 2021); Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

The automotive industry's shift to electrification will disrupt the entire supply chain and create a significant change in the market for automotive components. Demand for critical components for electrification such as batteries and electric drives would grow, while components only used in ICE vehicles such as conventional transmissions, engines, and fuel injection systems would see a decline. Specific geographies, for example Germany, Japan, Mexico, and South Korea where automotive production is a relatively large share of employment, would be exposed to the transition and need to identify how they can best capture opportunities. As production shifts toward EVs, trade flows could be reconfigured more broadly. Given the weight of EV batteries, their production may be located closer to final-assembly locations. Sources of battery minerals are concentrated in a small number of countries, where production would need to be scaled up substantially, also opening up opportunities (for further details, see chapter 4).

Consumers would incur higher up-front costs to buy low-emissions vehicles, at least in the short term. Today, depending on the country and the size of the vehicle, the up-front cost of a battery-electric vehicle is generally about 30 to 90 percent more than that of an internal combustion engine car. This gap is expected to narrow over time with lower battery prices.[211] Even with higher upfront costs, consumers would see a benefit over time. McKinsey analysis suggests that the total cost to own an EV, which takes into account the purchase price, maintenance, fuel cost, and resale value, would be cheaper than an ICE car in most regions by 2025, assuming battery costs fall as expected. In contrast, the total cost of ownership for an ICE car is expected to increase steadily as fuel prices increase and resale values fall due to usage and sale restrictions. There are regional differences: for example, the total cost of ownership for battery-electric cars in Europe may be cheaper than ICEs by 2025 and in the United States by 2030. Medium-duty BEV trucks covering 200–300 km a day are expected to reach total cost parity with ICEs by around 2025, with heavy-duty long-haul trucks reaching parity by 2030 in Europe and later in other regions. Faster declines in battery prices and local subsidies could accelerate this break-even point.

For workers in the auto industry, our analysis suggests that the transition to low-emissions vehicles would result in a reallocation of labor to different activities.[212] Today, the broader automotive industry employs about 34 million workers across the passenger car value chain, including those working directly for automotive OEMs as well as indirectly for upstream suppliers (including parts makers, raw materials, and services that support production). As a result of the transition described by the Net Zero 2050 scenario, demand for direct operations and maintenance jobs in ICE-related vehicle manufacturing could be lower by about 13 million by 2050.[213] However, demand could increase by about nine million for direct O&M jobs related to low-emissions vehicles manufacturing. The difference between losses and gains is due to the higher productivity of low-emission vehicle manufacturing. Gains in automotive jobs related to capital spending (for example, constructing manufacturing plants and charging infrastructure) would be about three million in 2050 under the Net Zero 2050 scenario.

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[211] McKinsey Center for Future Mobility, price benchmarks in key markets.

[212] The jobs analysis includes component suppliers, OEMs, maintenance and repair, and vehicle-related infrastructure such as filling stations and charging stations. It does not include jobs in primary energy or power; please see the related sections of chapter 3 for more about those sectors.

[213] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other renewables). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains, and include direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

Short-term risks and challenges. A key challenge for the sector will be ensuring sufficient scale-up of production capacity for low-emissions vehicles at the pace needed to drive the net-zero transition, including securing the necessary raw materials, as well as building support infrastructure such as charging stations. Measures may be needed to support higher up-front costs consumers would need to incur (despite longer-term total cost of ownership savings). Finally, for economic regions that are reliant on traditional ICE-based production jobs, efforts may be needed to help workers adjust.

Opportunities. Prior McKinsey analysis has shown that the shift to low-emissions vehicles could create opportunities for companies across the value chain.[214] These include: manufacturing EV batteries and fuel cells and producing the materials needed to make these essential components; building, making, and operating BEV-charging and FCEV-refueling infrastructure; and creating digital solutions to integrate the new vehicle energy infrastructure with the power grid. The net-zero scenario could also feature a rise in e-hailing and micro mobility services (e-bikes and scooters).[215]

Potential stakeholder responses. Decarbonizing road mobility would likely require stakeholder responses to manage the near-term added costs associated with low-emissions vehicles. Governments could consider providing financial support for R&D and capital spending as well as using regulatory mechanisms.

Pure EV players have already emerged, and many traditional automotive OEMs have announced plans to wind down production of ICE vehicles and ramp up EV production. OEMs are already investing in innovation and working closely with new and existing suppliers. Reducing material emissions is another opportunity for the automotive industry to help reduce overall emissions—potentially through collaborations with other ecosystem players to capture abatement opportunities collectively. For example, a coalition of OEMs could harvest high-grade aluminum from end-of-life vehicles.[216] More broadly, the entire mobility ecosystem, from EV manufacturers and suppliers to financers, dealers, energy providers, and charging station operators, will need to work to make the transformation successful.

Job transitions in the road mobility sector could require support because making and maintaining EVs and ICE vehicles takes different skills. Governments could also consider providing workers with various forms of assistance, including help relocating and retraining.

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[214] For more information, see Timo Möller, Asutosh Padhi, Dickon Pinner, and Andreas Tschiesner, “The future of mobility is at our doorstep,” McKinsey Center for Future Mobility, December 2019.

[215] Ibid.

[216] Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel, “The zero-carbon car: Abating material emissions is next on the agenda,” McKinsey & Company, September 2020.

Buildings: Retrofitting buildings and equipment with low-emissions energy sources and raising energy efficiency for new construction

Commercial and residential real estate provides people with shelter and wealth-building assets. Heating and cooking in homes, offices, and other buildings create approximately 2.8 $GtCO_2$ per year, or 6 percent of global emissions.[217] Eliminating these emissions would involve two shifts. One would be replacing appliances and heating systems that run on fossil fuels with models that run on low- or zero-emissions sources. The other would be improving the energy efficiency of buildings and appliances. In the scenario modeled here, consistent with the NGFS Net Zero 2050 scenario, these shifts would require significant capital spending in the near term that stakeholders would likely need new incentives to make.[218] Across the buildings sector, companies that offer equipment, services, and financing to enable decarbonization could see growth prospects (Exhibit 21).

Path to decarbonization. Emissions reductions in the buildings sector would be achieved by phasing out the use of fossil fuels for cooking and heating in favor of low-emissions energy sources such as low-emissions electricity and hydrogen. This would require changes to buildings and equipment—for example, replacing gas or oil boilers with electric heat pumps, and gas stoves and ovens with electric models. It would also require the build-out of infrastructure such as district heating systems that can run on low-emissions sources and municipal hydrogen networks.[219] Improving the energy efficiency of buildings and appliances would also help reduce emissions. Energy efficiency of buildings has increased to some extent, although there are still significant opportunities to reduce energy consumption by making appliances more efficient and upgrading buildings' insulation and airflow. McKinsey research has found that better insulation can reduce the heat demand of poorly insulated houses by up to 80 percent.[220] Buildings have long life spans, so the transition would involve both retrofitting existing structures and ensuring that new construction generates low emissions.

Shifts in demand, capital spending, costs, and jobs. The scenario analyzed here, consistent with the NGFS Net Zero 2050 scenario, would involve markedly higher demand for, and spending on, low-emissions heating and cooking equipment compared to today. In the net-zero scenario, such equipment for both existing and new buildings would exceed 390 million units by 2050, triple the amount today. As a result, the scenario would require increased capital spending estimated at an average of $1.7 trillion per year.

This spending would be partly offset by the resulting reductions in operating costs. On a per-dwelling basis, capital spending would likely fall over time as the costs of low-emissions equipment fall with economies of scale. The initial cost of a low-emissions heating system today exceeds that of a fossil fuel–based system. Currently, an electric heat pump is up to three times more expensive than a gas boiler in some regions for an equivalently sized unit.[221] However, by 2050, that gap is expected to narrow significantly, because low-carbon

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[217] EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[218] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In this and some other cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[219] District heating systems are found in various levels around the world and can be powered by both low-emissions sources and fossil fuels. The Nordic countries get 65 percent of their heat from district heating. Outside Europe, large district heating systems supplied by low-emissions energy are almost nonexistent (in the United States they are heavily based on gas, in China mostly from coal). See Dave Keating, "What role can district heating play in the energy transition?" *Energy Monitor,* February 2021. For municipal hydrogen networks, an intermediate step could involve upgrading municipal gas networks to blend hydrogen with natural gas to create so-called green gas.

[220] See Paolo D'Aprile, Hauke Engel, Godart van Gendt, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020.

[221] For more on the building sector, see Paolo D'Aprile, Hauke Engel, Godart van Gend, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020.

technologies are likely to get less expensive as innovation continues and their production scales up. In the net-zero scenario, heat pumps are expected to constitute approximately 90 percent of new heating unit sales by 2050, compared with 35 percent today. Other moves to decarbonize buildings would require capital spending on centralized infrastructure and networks. For example, setting up district heating networks requires installing systems of insulated pipes to distribute heat as well as building central heating sources in places where local supplies of waste heat (such as factories) cannot provide all the heat that buildings require.

The extent to which consumers could recuperate higher capital costs through lower operating costs in the long run would vary. It will depend on how country-specific relative energy prices evolve in the transition and the extent of energy efficiency improvements achieved from insulation and newer heating and cooking equipment.[222] In some markets, lifetime costs, taking into account annualized capital costs and operating costs, are likely already lower for low-emissions systems today.

Our analysis indicates that jobs would be created across the sector as a result of the net-zero transition, mainly because of the labor required to perform millions of building retrofits and to make and install new low-emissions technologies (for example, installing electric heat pumps, adding insulation, and replacing windows). Capital expenditure to develop and install additional insulation alone could add four million to six million jobs per year between 2025 and 2035, when most retrofits would take place. As of 2050, these jobs would diminish to about one million per year.[223]

Short-term risks and challenges. Despite the long-term cost advantages of decarbonizing buildings, owners of commercial and residential buildings may lack incentives to invest in energy-efficiency improvements or new equipment. In some cases, incentives could be split between owners and tenants: owners would pay the up-front capital costs, but tenants may enjoy the savings on energy bills. The high up-front capital costs may be particularly burdensome for low-income households. In other cases, homeowners may be reluctant to accept the inconvenience and expense of making these shifts and retiring young assets that have relatively long lives. A multitude of varying building standards and scattered ownership could prove challenging, too.

Opportunities. The net-zero transition will create opportunities for companies that support the decarbonization of existing building stock. Manufacturers and installers of low-emissions and efficiency-enhancing building materials and systems, as well as the services ecosystem that manages retrofit projects and maintains these systems, could experience significant new demand as the retrofit cycle accelerates. There could also be growth in demand for digital systems used to increase the efficiency of buildings and track their energy use and greenhouse gas emissions. Because of accelerated retrofits, builders and building owners could require more engineering, technology, and performance-management services.

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[222] For more on the building sector, see Paolo D'Aprile, Hauke Engel, Godart van Gend, Stefan Helmcke, Solveigh Hieronimus, Tomas Nauclér, Dickon Pinner, Daan Walter, and Maaike Witteveen, "How the European Union could achieve net-zero emissions at net-zero cost," McKinsey & Company, November 2020.

[223] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other renewables). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains, and include direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

Exhibit 21

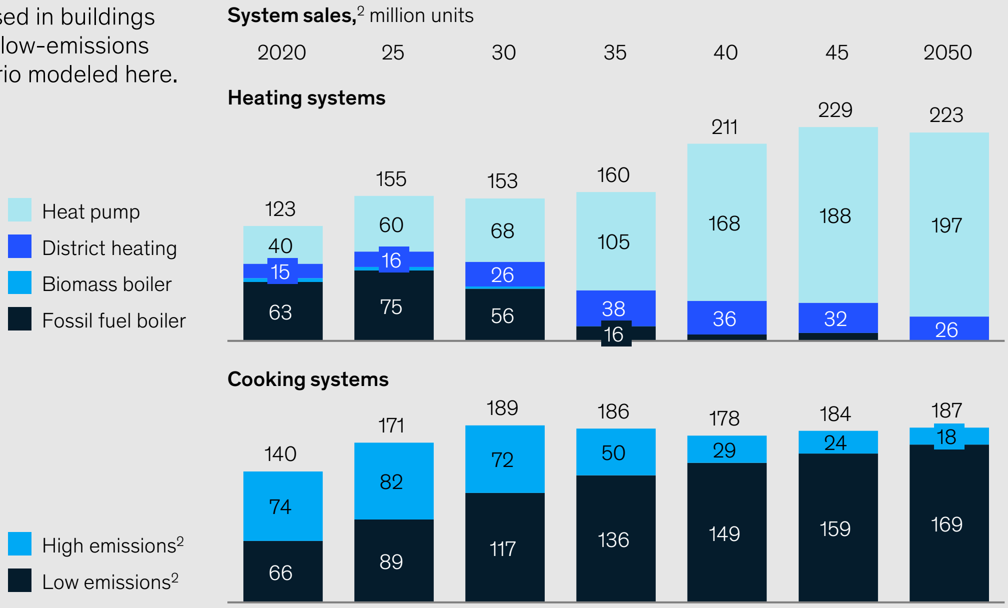
A net-zero transition in the buildings sector would entail a shift towards low-emissions equipment.

Emissions today
6% CO_2 (scope 1)

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

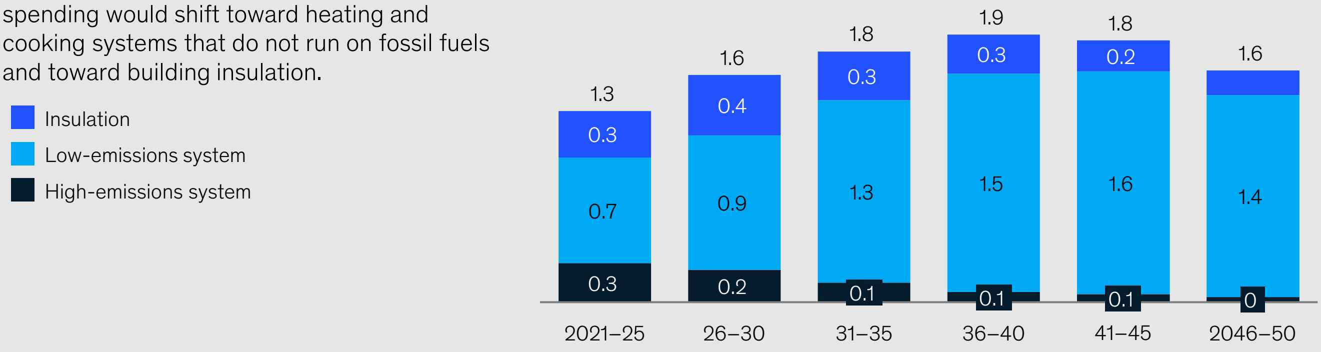
Demand for the equipment used in buildings would shift toward electric or low-emissions models in the net-zero scenario modeled here.

System sales,[2] million units



In the net-zero scenario modeled here, spending would shift toward heating and cooking systems that do not run on fossil fuels and toward building insulation.

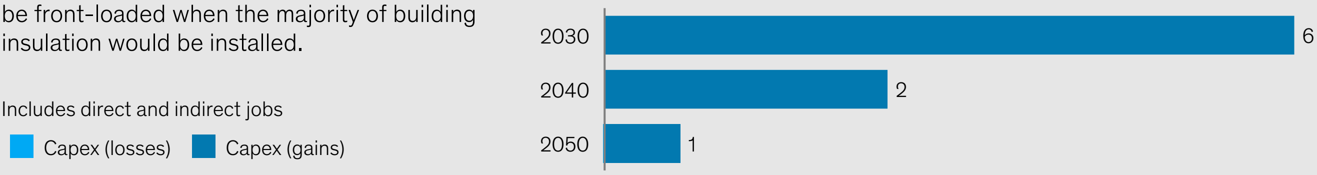
Annual spending on physical assets, 2021–50,[3] average over 5-year period, $ trillion



Job gains associated with the transition would be front-loaded when the majority of building insulation would be installed.

Employment shifts, gross changes associated with a net-zero transition, million jobs[4]

Includes direct and indirect jobs



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1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. High-emissions systems include fossil fuel–based cooking units. Low-emissions systems include non-fossil fuel–based cooking units. Heating and cooking system sales based on NGFS variables using REMIND-MAgPIE model, downscaled by VIVID Economics. See technical appendix for further details.
3. Includes spending in both the residential and commercial sectors.
4. Employment shifts include those associated with the labor required to perform millions of building retrofits and to install new low-emissions technologies. While this analysis focuses specifically on jobs associated with installation of insulation, additional jobs will likely be associated with other retrofits including replacement of windows and installation of low-emission technologies such as electric heat pumps. Capex jobs are those arising from capital expenditures in the sector, associated with manufacturing, construction, and their supply chains. Includes direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Sustainability Insights; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

Potential stakeholder responses. Creative financial structures can help address any financing challenges faced by end consumers. Financial institutions could devise products that support retrofits or new development of low-emissions buildings that would also help them meet their own goals for reducing financed emissions.

Policy makers have a variety of options for accelerating the net-zero transition in the buildings sector. These include providing incentives to banks to finance building decarbonization or offer subsidies for retrofits and purchases of electric or low-emissions equipment. The US Department of Energy offers energy-efficient mortgages that allow buyers to qualify for a more expensive home if the home is energy efficient or will be after upgrades. For existing homeowners, the financing program offers home-improvement loans that can be used for making energy-efficiency upgrades.[224] Policy makers could also consider ways of lowering the up-front cost of energy equipment, for example via rebate programs. Consumer research by the European Commission also underscores the importance of a clear, widespread public-information campaign on the need for change and the ongoing cost benefits of switching in the form of lower energy bills.[225] Other approaches include amending building codes and regulations to let owners retrofit buildings in ways they currently can't or to mandate energy-efficiency standards, including the use of low-emissions equipment, in new construction.

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[224] "Financing energy-efficient homes," US Department of Energy.

[225] *Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU,* European Commission, November 2019.

Food and agriculture: Reforming production and changing consumption patterns

Food and agriculture contribute substantially to emissions: 140 metric megatons (Mt) of methane (38 percent of the world's total), 0.5 metric gigatons (Gt) of CO_2 (1 percent of global CO_2 emissions), and 8 Mt of nitrous oxide (79 percent of global emissions).[226] Most farming-related emissions are caused by methane from production of ruminant livestock, mostly beef and lamb (Exhibit 22).[227]

Paths to decarbonization. Reducing agricultural emissions would require farmers to implement lower-emissions practices and technologies.[228] Adopting zero-emissions machinery, including tractors, harvesters, and dryers, is a key lever and would also likely deliver cost savings.[229] In livestock production, farmers could change animal feeding and breeding practices, such as using feed additives that inhibit methane emissions.[230] Emissions reductions can also be achieved in crop production; for example, improved fertilization practices can reduce methane emissions from rice cultivation by about 40 percent.[231] Better fertilizer practices can also help reduce upstream carbon use (during fertilizer production) and nitrous oxide emissions. Actions to reduce emissions and increase carbon sequestration would also improve resilience to physical climate changes and support economic growth and development.[232] On the demand side, shifting diets that are currently high in protein from ruminant animal products toward plant-based foods or lower-emissions animal protein sources such as poultry is another path to reducing emissions. Any such diet shifts would need to be balanced with nutritional imperatives: in some parts of the world, raising protein consumption—including through the use of ruminant-based protein sources—is vital to improving health outcomes for the population.[233] Diets are highly personal choices and closely linked to local customs and traditions. Improving the availability, quality, and affordability of plant-based alternatives and ruminant-meat substitutes could help. Improving supply chains and changing consumer behavior would help reduce food waste, thereby cutting emissions by reducing the amount of food that needs to be produced. Finally, agriculture also has a broader role to play in supporting the net-zero transition through the production of energy crops.

Shifts in demand, capital spending, costs, and jobs. Based on the scenario analyzed here, annual capital spending on physical assets of more than $60 billion would be needed over the next three decades to enable emissions-efficient farming, including spending on low-emissions farm equipment and instituting improved farming practices such as efficient use of fertilizer and anaerobic digesters.[234] The up-front expense for individual farming operations could be significant, especially for smallholder farmers.

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[226] EMIT database, McKinsey Sustainability Insights, September 2021; Data for 2019.

[227] *By the numbers: GHG emissions by livestock,* FAO.

[228] Agricultural practices are also tied to forestry emissions. See next section on forestry in this chapter.

[229] Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, "Agriculture and climate change: Reducing emissions through improved farming practices," McKinsey & Company, April 2020.

[230] *Carbon farming: Reducing methane emissions from cattle using feed additives,* Department of Primary Industries and Regional Development, Government of Western Australia, updated December 2020. See also Jan Hartger and Mathijs Harmsen, *Non-CO_2 greenhouse gas mitigation in the 21st century,* Utrecht University Repository, June 2019; Matthew Bell et al., "Effect of breeding for milk yield, diet and management on enteric methane emissions from dairy cows," *Animal Production Science,* volume 50, number 8, January 2010; and *Lower methane production through breeding,* Viking Genetics, February 2020.

[231] Bruce A. Linquist et al., "Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis," *Field Crops Research,* volume 135, August 2012.

[232] *Socio-technical innovation bundles for agri-food systems transformation,* Cornell Atkinson Center for Sustainability, 2020.

[233] Walter Willett et al., "Food in the Anthropocene: The EAT–*Lancet* Commission on healthy diets from sustainable food systems," *The Lancet,* volume 393, number 10170, February 2019.

[234] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In this and some other cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

Exhibit 22

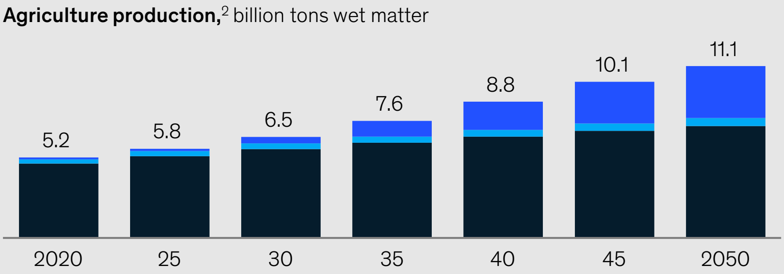
A net-zero transition in the agriculture sector would entail reforming production practices and could mean changed consumption patterns.

Emissions today
1% CO_2 38% CH_4

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

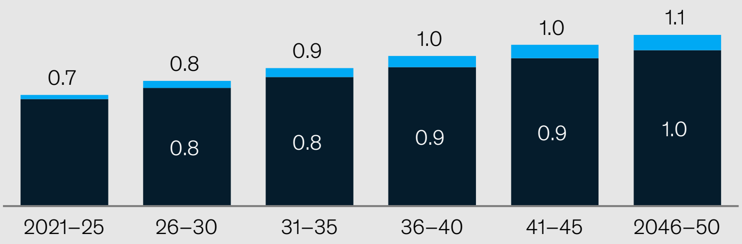
NGFS Net Zero 2050 scenario includes 12% annual growth in biomass production between 2020 and 2020 and 2050

Agriculture production,[2] billion tons wet matter



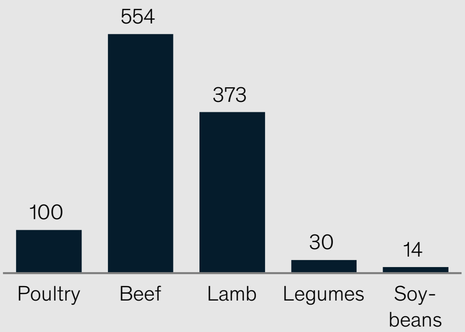
In the net-zero scenario modeled here, capital spending would be required to implement GHG-efficient production techniques.

Annual capital expenditures,[4] **2021–50,** average over 5-year period, $ trillion

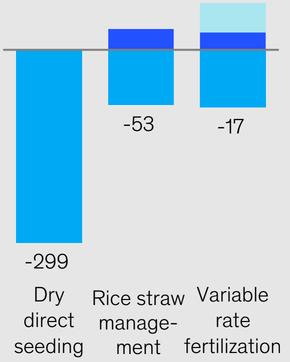


It costs less to produce protein-rich foods other than beef and lamb, and certain emissions-efficient farming methods are also cost-effective.

Production cost per calorie[3]
(index: 100 = poultry)



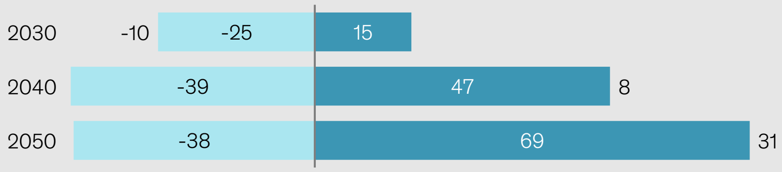
Capital and operating costs of emissions-efficient methods,[3]
$ per hectare



Job losses would primarily be driven by diet shift from ruminant meat to poultry; job gains would primarily be driven by increased demand for biomass used to produce biofuels

Includes direct and indirect jobs

Employment shifts, gross changes associated with a net-zero transition, million jobs



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1. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Agricultural production based on NGFS variables using REMIND-MAgPIE model. See technical appendix for further details.
3. Production costs per calorie and investment cost of implementing 25 greenhouse gas-efficient farming practices using the McKinsey Agriculture Practice's library of costs and GHG-efficient farming levers. Production costs include operating and capital costs.
4. Capital expenditures include spending on new farm equipment and infrastructure as well as cost to maintain existing equipment; unit cost projections by agriculture products were provided by the McKinsey Agriculture Practice database.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Sustainability Insights; McKinsey Agriculture Practice; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

In regard to costs, McKinsey analysis found that 15 of the 25 most promising measures in emissions-efficient farming (including zero emissions on-farm machinery and equipment, variable rate fertilization, and dry direct seeding) bring long-term cost savings—that is, the operating costs outweigh the capital spending required over the long term—or are cost neutral to individual farmers.[235] However, each measure entails significant up-front costs, for example, capital expenditures on equipment and financing of working capital. Other challenges include limited access to technology and a lack of scale: smallholdings account for three out of four farms around the world.

More broadly, our analysis of the global agricultural production patterns consistent with the net-zero scenario indicates average annual capital spending requirements of $840 billion. This is compared to $900 billion under an agriculture scenario in line with the NGFS Current Policies scenario. That sees stronger growth in ruminant meat production as consumers do not shift their diets and both has a higher emissions intensity and involves higher capital expenditures.[236] Consumers could see savings from changing diets, since the price per calorie of red meat is estimated to be higher, at roughly twice that of poultry, fish, and eggs and more than six times higher than that of pulses and nuts.[237]

As these shifts occur, the nature of jobs within the agricultural sector could be affected. Our analysis indicates that about 61 million direct jobs could be created across the sector by 2050 as a result of the transition described by the Net Zero 2050 scenario.[238] These are primarily jobs related to poultry farming as diets shift, and jobs created by increased demand for biomass crop production. Our analysis also indicates that about 34 million direct jobs could be lost across the sector, primarily in ruminant meat production, resulting in about 27 million net job gains due to the net-zero transition by 2050. Given the large extent of self-employment in the agricultural sector, it is likely that many of the job gains and losses would be experienced in reality as job shifts, for example, a farmer who over time transitions activities toward poultry or biomass crop production. However, the ease of these transitions would depend on factors including access to regional markets, shifts in required equipment, and local climatological limitations such as soil makeup and annual rainfall. Such potential shifts need to be seen in the broader farm-to-nonfarm transition that has been under way; global agricultural employment declined by about 115 million net jobs between 1991 and 2020.[239] This trend is likely to continue on a similar order of magnitude through ongoing productivity improvements and technological changes. Over the next 30 years, the net direct job gains specifically due to the transition of about 27 million would only somewhat offset larger expected job losses due to those productivity increases. The sector overall is expected to see reduced employment in line with historical trends.

Short-term risks and challenges. Smallholder farmers lacking access to capital may need financial support to make the transition to higher productivity and emissions-efficient methods. Any diet shifts could also influence demand for specific products, and farmers may find it challenging to shift their activities.

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[235] "Agriculture and climate change: Reducing emissions through improved farming practices," McKinsey & Company, April 2020.

[236] The NGFS Current Policies scenario accounts for currently legislated policies and cost reductions in key low-emissions technologies. See technical appendix for further details.

[237] Harold H. Alderman and Derek D. Headey, "The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents," *Journal of Nutrition,* volume 149, number 11, November 2019.

[238] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other renewables). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains, and include direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

[239] Max Roser, *Employment in agriculture,* OurWorldInData.org. ILO database.

Opportunities. The shift toward emissions-efficient practices could stimulate demand for the supplies and equipment that enable on-farm decarbonization. Companies could develop and commercialize technologies—such as gene editing for disease resistance or for enhanced carbon sequestration—and vaccines and feed additives to inhibit enteric fermentation. The shift away from production of ruminant-animal protein and toward other proteins would likely lead to other business and economic opportunities.[240] Rising use of bioenergy could lift demand for biomass from agriculture and forestry residues.

Potential stakeholder responses. Given the breadth and scale of the agricultural sector, support for on-farm interventions would likely vary based on geography, farm type and structure, and farm output. Smallholder farmers lacking access to capital may need financial support to make the transition to higher productivity and emissions-efficient methods. Repurposing existing agricultural supports could cover a substantial amount of this cost. Research has found that 51 countries allocate approximately $570 billion in public support each year to agricultural producers that are responsible for two-thirds of global food production.[241] Researchers have also identified other measures to support the cost of agricultural transitions beyond repurposing subsidies. These include public-private collaboration to create financial intermediation vehicles that pool capital and unlock financing, and promoting the adoption of greenhouse-gas-efficient farming practices by ensuring that farmers are paid premiums for their improved practices.[242]

Changes in agricultural jobs and activities would likely need support through improved access to information, technology, training, and well-designed safety nets to foster greater resilience among rural communities. Many of the measures being deployed in any case to support farmers—for example, agricultural extension services, reskilling to support the farm-to-nonfarm transition, and training—can be adapted to the needs of a net-zero transition, including to help farmers adopt new agricultural practices.

On the demand side, changing long-standing food-consumption patterns—in parts of the world where it is feasible to do so without nutritional impacts—will likely require extensive efforts, including consumer education. More broadly, the net-zero transition could be supported by mechanisms that reward farmers and consumers for adopting lower-emissions practices, such as including agricultural emissions in emissions trading schemes, carbon pricing regimes, offset programs, and grant and subsidy programs.

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[240] Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, “Agriculture and climate change,” McKinsey & Company, April 2020.

[241] *Incentivizing food systems transformation,* World Economic Forum and McKinsey & Company, January 2020.

[242] For more, see *Incentivizing food systems transformation,* World Economic Forum and McKinsey & Company, January 2020.

Forestry and other land use: Financing forest protection and restoration while supporting people's livelihoods

Forests, including tropical rainforests, boreal forests, peatlands, permafrost forests, and coastal and freshwater forested wetlands, sequester and store significant amounts of carbon, making them vital to Earth's climatic equilibrium. They also support biodiversity and provide numerous environmental, social, and economic benefits, including increasing resilience to climate change and providing livelihoods for rural communities.[243] However, each year, about ten million hectares of land—an area roughly the size of South Korea—are deforested, mainly to clear land for commercial or subsistence agriculture.[244] Forestry and other land use accounts for nearly 14 percent of annual global CO_2 emissions, 5 percent of methane emissions, and 5 percent of nitrous oxide emissions.[245] However, these estimates may insufficiently account for the role of forestry (see Box 7, "Accounting for the role of forests in managing emissions"). Deforestation contributes to emissions in two ways: first, CO_2 is released into the atmosphere through slash-and-burn deforestation, decomposition of felled trees, soil disturbance, and forest degradation. Second, the forests' future capacity for carbon sequestration is lost. Protecting and restoring forests would help counter climate change. Such an effort would require capital spending, along with actions to address the socioeconomic impacts on the millions of people who make their living in and around forests (Exhibit 23).

Paths to decarbonization. Preventing deforestation has substantial abatement potential and is cheaper to implement than the solutions available in many other sectors. Reducing deforestation in tropical areas is especially economical, at a cost of less than $3 per metric ton of CO_2, including land-acquisition costs and operating costs.[246] Avoiding deforestation also has lower maintenance costs than reforestation projects and thus tends to be cheaper for the same land cost.[247] Although measuring the effects of deforestation is challenging and trees absorb CO_2 at widely varying rates (depending on their species, location, and the concentration of CO_2 in the atmosphere), estimates suggest that over a 30-year period, a tree can store an additional 60 to 85 percent as much carbon as is released when the tree is cut down or burned, and that overall emissions could be even higher considering uncertainties around secondary emissions and forgone carbon sequestration resulting from deforestation.[248] Halting deforestation prevents emissions immediately, whereas the benefits of nature restoration can take longer to realize: forests take an average of 25 to 30 years to grow and, in some cases, up to a century to fully mature. Nonetheless, in addition to preventing deforestation, nature restoration via reforestation, afforestation, peatland restoration, and coastal restoration would aid decarbonization because growing trees and plants sequester and store carbon. McKinsey research has found that approximately 250 million hectares could be sustainably reforested today, especially in the tropical forests of countries such as Brazil, Colombia, and Indonesia, and in the temperate forests of China,

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[243] See "Why investing in nature is key to climate mitigation," McKinsey & Company, January 2021. The UN Food and Agriculture Organization estimates that nearly one-third of humanity "has a close dependence on forests and forest products." *The state of the world's forests 2020: Forests, biodiversity, and people,* FAO, 2020.

[244] *The state of the world's forests 2020: Forests, biodiversity, and people,* FAO, 2020.

[245] Nitrous oxide emissions come from the oxidation of nitrogen fixated in soil that can be exposed and released by land-use change. Methane emissions come from incomplete combustion of organic matter caused by slash-and-burn practices and from the decomposition of organic material. EMIT database, McKinsey Sustainability Insights, September 2021. Data for 2019.

[246] Compare the cost of reducing deforestation in tropical areas with the cost for other areas, such as $236 per tCO_2 for reforestation of temperate broadleaf and mixed forest, and $177 per tCO_2 for deserts and xeric shrublands. For more, see "Valuing nature conservation," McKinsey & Company, September 2020.

[247] Justin Adams et al., *Consultation: Nature and net zero,* World Economic Forum and McKinsey & Company, January 2021.

[248] Research indicates that forgone carbon sequestration and forest degradation are highly underestimated in current evaluations of deforestation emissions. Estimates are associated with large uncertainties, including lack of data (especially on secondary effects) and variations in carbon sequestration due to tree species, location, and concentration of CO_2 in atmosphere. Overall secondary emissions and forgone carbon sequestration resulting from deforestation could be up to nine times higher than direct emissions alone; see Sean Maxwell et al., "Degradation and forgone removals increase the carbon impact of intact forest loss by 626%," *Science Advances,* volume 5, issue 10, October 2019. For further details, see chapters 1 and 3. See also Richard Houghton and Alexander Nassikas, "Global and regional fluxes of carbon from land use and land cover change 1850–2015," *Global Biogeochemical Cycles,* volume 31, issue 3, February 2017; Nancy L. Harris et al., "Baseline map of carbon emissions from deforestation in tropical regions," *Science,* volume 336, June 2012; and Richard Houghton and Alexander Nassikas, "Negative emissions from stopping deforestation and forest degradation globally," *Global Change Biology,* volume 24, issue 1, 2017.

Mexico, and the United States.[249] Well-managed reforestation is a source of negative emissions that can be used to offset hard-to-abate emissions in sectors such as cement and steel, and it can be done right now.[250] Protection and restoration of wetlands (including peatlands, permafrost wetlands, and coastal and freshwater wetlands) hold similar carbon-removal potential and, in some instances, are cheaper than reforestation.[251] While offering substantial benefits, restoration projects must be managed so as not to damage biodiversity, deplete local water resources, or otherwise cause harm via actions such as planting native species alongside nonnative species and establishing monoculture plantations.[252]

Shifts in demand, capital spending, and jobs. Our analysis suggests that in the NGFS Net Zero 2050 scenario, deforestation would be reduced by more than half by 2025 to prevent emissions and preserve carbon sinks, and extensive reforestation would begin now. Forested land would increase by 160 million hectares between 2020 and 2030 and then stay relatively stable. This rapid forest protection and restoration program would help achieve carbon-sequestration of more than 350 metric megatons of CO_2 per year by 2030.[253]

To achieve the outcomes modeled by the net-zero scenario would require annual average capital spending of $40 billion in avoided deforestation and land restoration. Almost all of this total capital would be deployed in the next decade, primarily to acquire land. Avoiding deforestation and land restoration would affect operating costs for labor, monitoring, compliance, as well as payments to countries or communities that preserve forests. This investment is critical given the role forests can play in enhancing natural CO_2 removals from the atmosphere. If this investment, or actual CO_2 removals per dollar invested, proves insufficient, it would place an even greater onus on the rest of the economy to eliminate carbon emissions in order to maintain an even chance of limiting warming to 1.5 degrees Celsius.

Halting deforestation would have a significant impact on forest-border communities, where many residents are subsistence-level farmers whose livelihoods depend on clearing forests for agriculture.[254] Up to 90 percent of deforestation is driven by such expansion of agricultural land.[255] Since agriculture is a primary driver of deforestation activities, a key lever will involve improved agricultural practices, to aid food production without expanding agricultural land area.

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[249] For further information, see *The case for negative emissions,* Coalition for Negative Emissions, June 2021.

[250] This is because trees sequester carbon and store it as biomass as they grow, reducing carbon in the atmosphere.

[251] Justin Adams et al., *Consultation: Nature and net zero,* World Economic Forum and McKinsey & Company, January 2021.

[252] Shaun C. Cunningham et al., "Balancing the environmental benefits of reforestation in agricultural regions," *Perspectives in Plant Ecology, Evolution and Systematics,* volume 17, number 4, July 2015.

[253] The analysis in this deep dive is focused on a hypothetical path and is not meant to serve as a projection or prediction. This research does not take a position on the feasibility, likelihood, or nature of a 1.5°C path. Instead, we seek to demonstrate the shifts that would need to take place if the goal of 1.5 degrees is to be attainable, and a relatively orderly transition achieved. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2), which limits global warming to 1.5°C "through stringent climate policies and innovation, reaching net-zero CO_2 emissions around 2050, giving at least a 50 percent chance of limiting global warming to below 1.5°C by the end of the century, with no or low overshoot." While high-emissions activities fall rapidly and steeply during the scenario, they do not necessarily reach net zero in all sectors. Residual CO_2 emissions from these activities are counterbalanced by removals. In some cases, variables were downscaled by Vivid Economics to provide more sector granularity, which we often continue to refer to as being based on or consistent with the NGFS Net Zero 2050 scenario. See the technical appendix for further details.

[254] Notably, a transition away from agriculture can also play a role in shielding people from the risk of decreased ability to work that results from rising heat and humidity levels. See *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[255] *The state of the world's forests 2020: Forests, biodiversity, and people,* FAO, 2020.

Box 7

Accounting for the role of forests in managing emissions

Accounting for carbon emissions in forestry and other land use can be challenging because there is great uncertainty over factors such as carbon-sequestration rates, natural emissions, and anthropogenic emissions. Conventional accounting for emissions typically fails to account for forgone carbon sequestration, forest degradation, indirect emissions that occur as a result of deforestation, indirect emissions such as those from forest fires caused by a changing climate, and emissions from land classified as unmanaged.[1]

Other methodological choices can also cause emissions from deforestation to be underestimated. For instance, the United Nations Framework Convention on Climate Change and the FAO calculate deforestation rates on the basis of net changes in global tree cover—a method that may not fully account for emissions and removals. A large, old tree stores a lot of carbon, which is released when the tree is cut down and burned, whereas a smaller, younger tree planted to replace it stores much less carbon. Using tree cover as a proxy for emissions could thus overlook the carbon released by the loss of older trees. Nor does it account for differences in the carbon-sequestration capacity of various tree species.

Methodological choices can also understate the importance of forestry and other land use relative to other systems. Forestry emissions are typically presented on a net basis: carbon emissions (deforestation) minus carbon removals (such as reforestation, sequestration, and afforestation). The resulting net emissions are much smaller than the gross emissions from this system; studies have shown that gross emissions in land use and land-use change are up to five times larger than net emissions. This gap between net and gross emissions is much smaller in other systems because carbon sequestration is not significant for other sectors.[2]

Beyond emissions, preserving forests has many other benefits, such as temperature regulation, rainfall regulation, water filtration, prevention of soil erosion, and crop pollination, that are not considered in most accounting methods. Evaluating these benefits is challenging because they are mainly nonmarket benefits, but they are thought to be large. For instance, an FAO study estimated that the 1.1 million hectares of forest in the Beijing municipality provided environmental services such as soil protection worth $5.3 billion.[3]

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[1] Edge effects can lead to forest degradation. Edge effects come into play when two different habitats border each other—in this instance, forests and artificial habitats such as roads or cropland—and affect species within a certain range of that border. Deforestation creates many new edges in forests and produces predominantly negative edge effects, including increased sunlight, wind exposure, and higher temperatures. Existing fauna and flora may not be able to survive the altered conditions on newly created edge land. What's more, the drier edge climate increases the risk of forest fires, which can affect non-edge sections.

[2] Richard Houghton and Alexander Nassikas, "Negative emissions from stopping deforestation and forest degradation, globally," *Global Change Biology,* volume 24, number 1, August 2017.

[3] Yuanzhao Hou, Shuirong Wu, and Gongying Yuan, "Valuation of forest ecosystem goods and services and forest natural capital of the Beijing municipality, China," *Unasylva,* volume 61, number 1, January 2010.

Exhibit 23

A net-zero transition in the forestry and other land-use sector would entail reducing deforestation and accelerating reforestation.

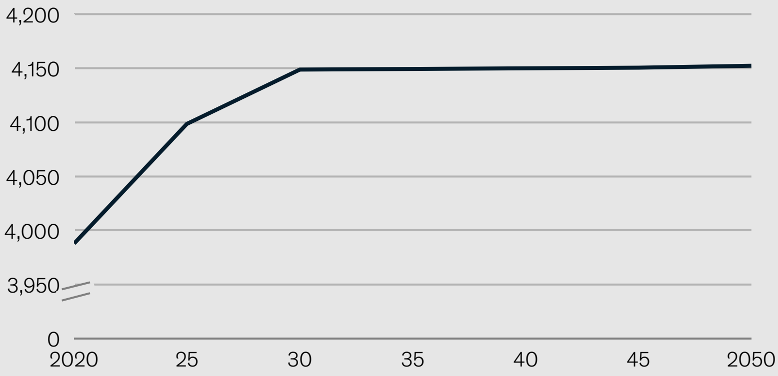
Emissions today

14% CO_2 5% CH_4

Based on the Network for Greening the Financial System (NGFS) Net Zero 2050 scenario[1]

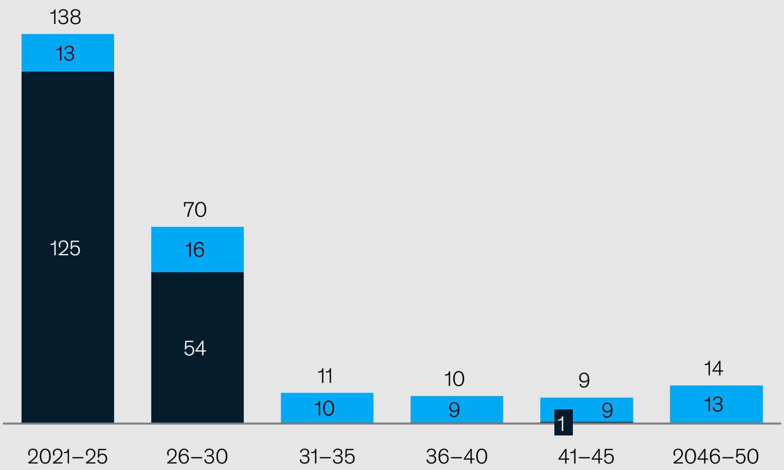
Forested land would increase quickly in the Net Zero 2050 scenario to achieve carbon-sequestration goals.

Forest cover, million hectares



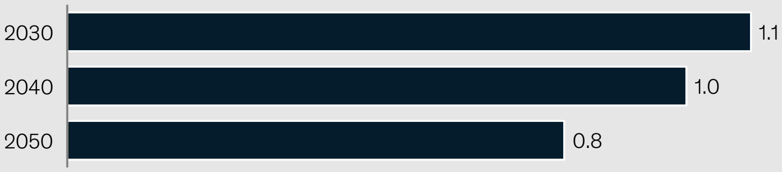
About $1.3 trillion in capital would be deployed in the Net Zero 2050 scenario, mostly for afforestation. More than 80% of this capital needs to be deployed before 2030.[2]

Annual capital expenditures, 2021–50,[3] average over 5-year period, $ billion



Job gains would be concentrated in the transition's early years, when more reforestation occurs.

Employment shifts, gross changes associated with a net-zero transition, million jobs[4]



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1. Our analysis of the forestry and other land use sector focuses on land restoration. It does not encompass timer or biomass production. This analysis is a hypothetical scenario and is not meant to serve as a projection or prediction. It is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). In some instances, variables were downscaled to provide more sector granularity by Vivid Economics. See technical appendix for further details.
2. Includes afforestation (planting trees in a new location, where there was no forest) and reforestation (adding trees to an existing forest that was depleted). Deforestation is inferred from the NGFS Land Cover variables and considers the natural growth of forests, assumed to be equal to the change in forest area minus land restoration, plus the natural growth of forest.
3. Capital expenditures include land purchase or the implicit imputed rents of protecting land, site preparation (eg, fencing, office set-up, labor), accreditation costs and other expenses required to convert project to carbon credits, planting (seeds and labor).
4. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains. Indirect jobs are those created in the supply chain of the sector. Includes direct and indirect jobs. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing, mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction.

Note: Figures may not sum to 100% because of rounding.

Source: EMIT database by McKinsey Sustainability Insights (September 2021); Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Nature Analytics; Jobs baseline (ILO, OECD, MinSTAT, INDSTAT, IHS, WIOD, IEA, US BLS, India NSS-Employment Survey, China-NBS, IRENA); Jobs multipliers (McKinsey Economics Analytics Platform, GTAP, Asian Development Bank, US BEA, OECD, Oxford Economics); McKinsey Global Institute analysis

Our analysis suggests that the transition described by the Net Zero 2050 scenario would see the addition of approximately one million direct afforestation jobs by 2050.[256] Most would be jobs related to soil preparation, planting, and management.[257] This number could be even higher, since more jobs could be required in the forest sector to prevent and contain wildfires, protect watersheds, prevent flooding and erosion, and restore areas affected by extreme weather. Finally, while not sized here, there is also an important role for jobs related to the management of forests: plantations can reduce pressure on unmanaged forests and can have positive impacts on climate-change mitigation depending on the end use of the wood harvested and the use of wood residues.[258] Managing plantation forests for timber and carbon requires care and a well-trained workforce, and it can generate employment and revenue for local populations that can be used in turn to further expand the forest area.

Short-term risks and challenges. Incentives will need to be realigned in order to prevent deforestation. For example, landowners in forest-border zones earn revenues from clearing forest to increase crop or livestock production. There are few, if any, subsidies or means of compensation for preserving forestland. Financial returns on reforestation, afforestation, and avoiding deforestation can also be uncertain because they depend heavily on future carbon prices.

Opportunities. Forest protection and restoration projects could help generate revenue from the sale of carbon credits in carbon markets, including voluntary carbon markets. The Taskforce on Scaling Voluntary Carbon Markets has estimated that the market for carbon credits could be worth upward of $50 billion a year by 2030.[259] Forests also provide biomass, which can be used as construction material in bioenergy production or as feedstock for bioplastics and other bio products. Biomass management will need to be implemented carefully to ensure a net-zero climate impact.[260] Curbing activities that damage forests would need to go hand-in-hand with economic diversification, especially in communities where deforestation is integral to people's livelihoods. This diversification, in turn, could create new opportunities in industries such as ecotourism: McKinsey research has identified an opportunity to create or safeguard 30 million jobs in ecotourism if nature conservation on land and in international waters doubled by 2030.[261]

Potential stakeholder responses. Current international efforts to prevent deforestation aim to financially reward countries for conserving their forests.[262] Results from such programs have been mixed. The structure of incentives can influence whether forestry projects are supported and compliance is achieved. As discussed above, carbon markets could also play an important role in forest protection. Initiatives to provide nonagricultural economic opportunities in forest regions and to institute compensating mechanisms could reduce agriculture-driven deforestation.

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[256] Scope of forestry and other land use employment analysis limited to jobs related to new afforestation and new deforestation, not all current logging jobs.

[257] Job losses and gains described in this analysis refer to those tied specifically to transition-related changes (for example, the shift from fossil fuel energy production to solar, wind, and other renewables). Losses and gains due to macroeconomic forces such as income, population, and productivity growth have also been excluded. A job is counted as a loss or a gain if it involves a shift in sector or subsector for a worker, indicating a changing job function, or a change in the geography of an existing job. O&M jobs consist of those related to the operations and maintenance activities in the sector and their supply chains, and include direct and indirect jobs. Indirect jobs are those created in the supply chain of the sector. In calculating indirect jobs, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. We do this to avoid double counting our job impacts. The indirect jobs shifts would be about 15 to 25 percent higher if all upstream sectors are considered, without netting out the job changes from other modeled sectors. See technical appendix for details.

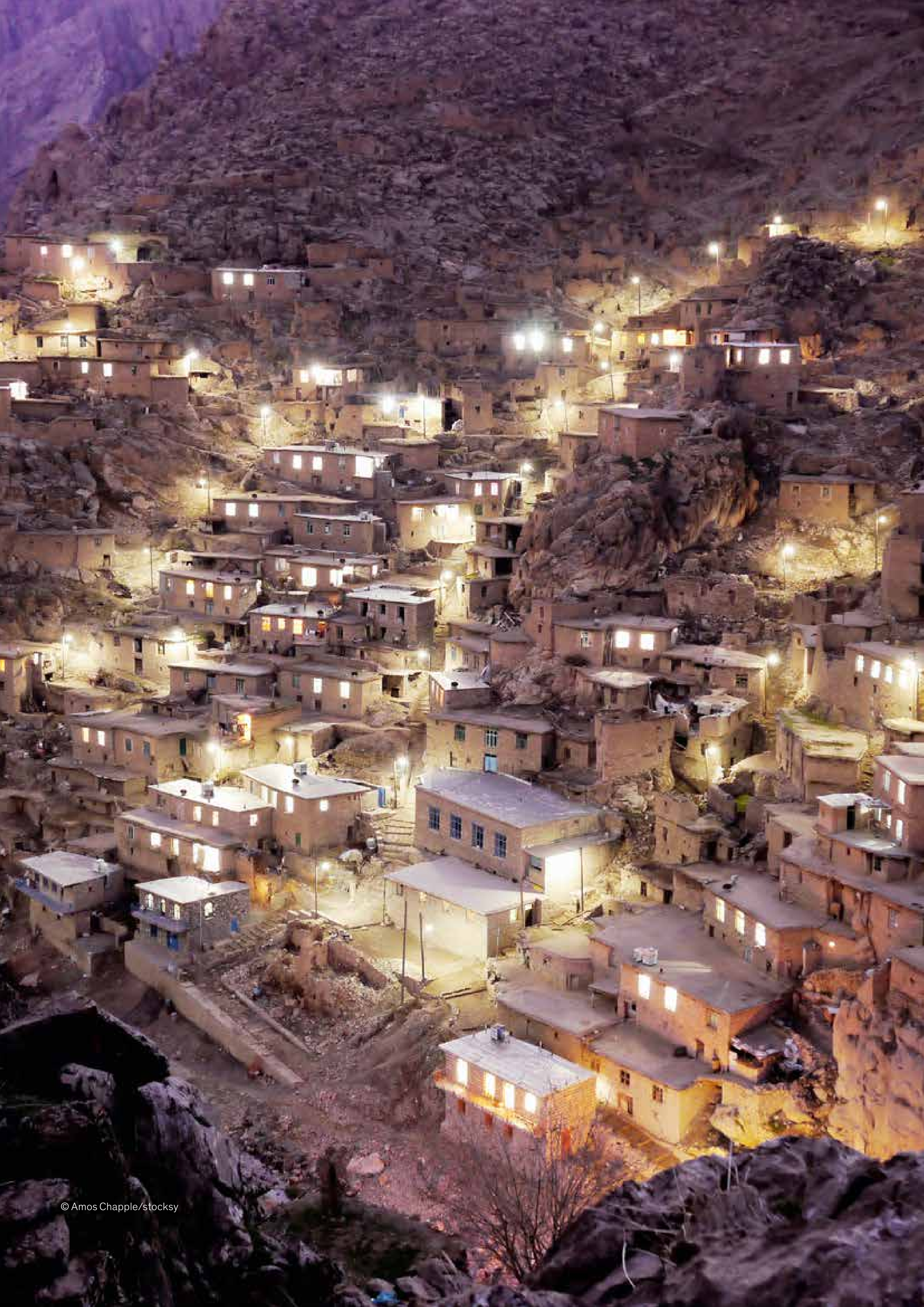
[258] Bruce Lippke et al., "Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns," *Carbon Management,* volume 2, number 3, 2011; P. Leskinen et al., *Substitution effects of wood-based products in climate change mitigation: From science to policy,* European Forest Institute, 2018.

[259] The market for carbon credits could be worth more than $50 billion a year by 2030. See *Final report,* Taskforce on Scaling Voluntary Carbon Markets, January 2021.

[260] Biomass is already part of the carbon cycle, and it stores carbon until it is burned. Areas where biomass is sustainably harvested can be reforested to sequester additional carbon; however, it is important to remember that new trees take more than 30 years to sequester the carbon released from harvested trees. In the meantime, emissions are net positive.

[261] "Valuing nature conservation," McKinsey & Company, September 2020.

[262] See, for example, *Sierra Leone economic diversification project,* World Bank, 2020.



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4. The transition in countries and regions

Viewed by geography, the challenges of the net-zero transition by 2050 are universal: all regions would need to decarbonize, all would have some exposure of their economies to the transition, all would face some degree of physical risk, and all would have growth potential resulting from the transition. But the exposure and its effects will be uneven. Our analysis suggests that regions with lower GDP per capita and those with greater fossil fuel resources would need to invest more than other regions, relative to GDP, to reduce emissions, build a low-emissions economy, and support economic development. They would also see a larger proportion of their economies exposed to the shifts under a net-zero transition. Lower-income households everywhere will be most affected, as discussed in chapter 2.

In this chapter, we consider four aspects of how the economic transformation could affect countries and regions. We look at the capital they would need to spend to decarbonize, the extent of their economic exposure, their exposure to rising physical climate risk, and the growth potential in their natural-capital endowments and their stores of technological and human capital.

One of the key challenges of a net-zero transition is that it could potentially set back progress on economic development goals in developing regions, bolstering the case for global cooperation. In these regions, national economies are more dependent today on sectors that would be exposed to the transition and would therefore be more exposed to shifts in jobs, GDP, and capital stock. And some of them will face a double burden—being exposed to both the transition adjustments and rising physical risks. At the same time, the transition could create potential for economic growth in many geographies.

To provide further understanding of the economic and societal adjustments that countries may need to make, we group 69 countries into six archetypes, based on their exposure to the socioeconomic shifts that will characterize the transition. They are fossil fuel resource producers, emissions-intensive producers, agriculture-based economies, land-use-intensive countries, downstream-emissions manufacturers, and services-based economies.[263] We also describe the varying growth potential that the transition could create for countries in these archetypes and, where noteworthy, the spending on physical assets they would need to make during the transition and the physical risks they could face if emissions continued to increase (see Box 8, “Methodology to assess countries’ current exposure to the transition and potential opportunities”).

To manage exposure, each country can consider taking actions of its own, such as investing in assets, funding worker-retraining programs, and supporting the growth of low-emissions sectors. But some countries are likely to face more substantial exposure, and making economic and societal adjustments may also be more challenging for them. Addressing economic and societal adjustments will thus only be possible with collective action and global solidarity at an unprecedented scale, as we discuss in chapter 5. The country and regional implications of the net-zero transition could also potentially affect trade flows, as we noted in Box E6 in the executive summary.

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[263] Countries were selected based on data availability across all the indicators in our analysis, as well as to ensure broad geographic coverage. Although we have placed each country within a single archetype, any given country—especially those with large and diversified economies—could also face some of the same issues we have highlighted for other archetypes. The archetypes thus indicate key issues a country may face but do not exclude the possibility that stakeholders in particular countries may need to reckon with issues that may be more closely associated with other archetypes.

Box 8

Methodology to assess countries' current exposure to the transition and potential opportunities

The analysis here examines the nature and magnitude of the exposure of countries to the transition as well as their potential to benefit from opportunities.

We first examine the overall spending on physical assets for energy and land-use systems that will be needed in different regions; we do this using activity levels for different sectors and regions from the NGFS Net Zero 2050 scenario and unit capital costs for different technologies.

Second, we examine the exposure of the economies of different countries to transition shifts more broadly by focusing on 69 countries that make about 95 percent of global GDP and about 80 percent of global emissions. Our approach to assessing countries' exposure to the net-zero transition involves measuring how much of their economy relates to sectors that, in turn, have high exposure to the transition and assessing the scale of change consumers may need to undertake.

To measure the exposure in each area of the economy, we considered the share of a country's GDP, capital stock, and jobs in sectors most exposed to the transition. We chose these areas because they collectively represent production activity and stocks of human and physical capital. To identify the sectors most exposed to the net-zero transition, we calculated the full life cycle of emissions of the sector (scope 1, 2, and 3) divided by the sector's output. Through this, we identified the most exposed sectors—namely, those with high emissions intensity in their own operations; those whose products, in turn, emit while being used; or those that have high emissions embedded in their supply chains (for further details, see also chapter 3). Each economy's transition-exposure score is the average of the shares of GDP, capital stock, and jobs in these exposed sectors. Thus, a zero score would indicate that none of the country's GDP, capital stock, or jobs are in these sectors, while 100 would indicate that all of the country's GDP, capital stock, and jobs are in these sectors.

Separately, we also look at consumer activity in the form of per capita household emissions (from driving, heating, and cooking) to assess the materiality of exposure for consumers and the extent to which they may need to shift practices as a result of the transition. For our consumer metric, we look at the amount of emissions consumers are directly responsible for by examining the consumer shares of road and buildings emissions.

Third, in addition to spending on physical assets and assessment of economies' exposure to the transition, we have evaluated each country's current position with respect to the opportunities that could arise in a net-zero transition. We primarily assess endowments of natural capital and the availability of technological and human capital as the basis for the comparative advantages that countries possess or could build over time.

Other aspects of a country's activities could be exposed, but we have not included those here. For example, we have not included tax revenue and exports, given the strong relationship of these two to GDP. As another example, countries with high exposure today may eventually benefit from the transition—for instance, by establishing economical sources of renewable power or building future assets in a way that reduces their future exposure. We instead describe these opportunities through our assessment of natural, technological, and human capital endowments, and consider this independent of our assessment of how countries' economies are exposed today. This is because such opportunities would be captured over time. They are also independent of the extent of exposure of countries today, and the associated economic and societal adjustments they would need to undertake.

For a list of sources for this section and other details, see the technical appendix.

Developing countries and fossil fuel–producing regions have relatively large exposure to the transition, raising concerns about growth and inequality

In a net-zero transition, every country and region would need to spend on physical assets to reduce greenhouse gas emissions and secure low-emissions energy to power future economic growth. We find that the relative size of the required spending on physical assets would be different across countries and regions.

In conducting this analysis, we sized the spending using trajectories provided by the NGFS for the Net Zero 2050 scenario. Some of these trajectories are provided at the regional level and others at the national level, influencing the granularity of our analysis.[264] We consider spending needed across our key energy and land-use systems to replace and build low-carbon physical capital stock and enabling infrastructure.[265]

The world's largest economies, the United States, Europe, and China, alongside other developed regions, account for more than half of total spending in the NGFS Net Zero 2050 scenario. This represents about 6 percent of their combined national GDP in the period 2021 to 2050 (Exhibit 24). These regions would invest more than half of their total net-zero spending to switch away from the use of fossil fuels in mobility, buildings, and industrial applications. They would also make substantial capital spending in power to increase low-emissions electricity penetration, deploy storage technologies, and upgrade grids.

While the absolute value of spending would be lower for developing regions, the amount is much larger when measured as a share of GDP. In sub-Saharan Africa, Latin America, India, and some other Asian countries, spending on physical assets could amount to about 10 percent of GDP or more. These regions already spend more as a share of GDP on physical assets for energy and land-use systems today compared with developed economies, and this is expected to continue—irrespective of future transition actions—given their stage of development and their goal to spur higher rates of economic growth and development.[266] For example, in our analysis of the NGFS Current Policies scenario, investment in India would still total more than 9 percent of GDP. Spending would increase to some extent from these levels in the net-zero scenario analyzed here. It would moreover be spent differently. Sixty percent of annual average investments would be on low-emissions assets under current policies compared to 80 percent in the NGFS Net Zero 2050 scenario. Similarly in sub-Saharan Africa, spending on low-emissions assets would increase from about 50 percent under Current Policies to 70 percent in a net-zero transition. In the future, as incomes increase and the build-out of low-carbon assets peaks, developing regions would invest a declining fraction of their income in energy and land systems, relative to today.

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[264] All analyses here are based on the 2021 NGFS scenarios. The Net Zero scenario is based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE. In the scenario net zero is reached by 2050 on a global basis but there are some regional differences. China, India, the Middle East and North Africa, Russia, Ukraine, and Commonwealth of Independent States, and other Asia are assumed to still have some positive emissions that are offset by net negative emissions in the rest of the world. For further details, see the technical appendix and "Technical documentation version 2.2," NGFS Climate Scenario Database.

[265] This analysis is focused on the spending needed to build physical assets. We do not consider spending needed, for example, to reskill workers, for the economic diversification of affected communities, or for the write-offs associated with stranded assets. The estimation here includes spend for physical assets across various forms of energy supply, energy demand, and land use. This includes both what is typically considered investment in national accounts and, in some cases, spending on consumer durables such as personal cars. We typically consider spending to replace physical assets at the point of emissions (for example, cars for mobility); additional spending would also occur through the value chain. We have not sized this, to minimize double counting. For a detailed view of the spending on physical assets sized in this research, see chapter 2 and the technical appendix.

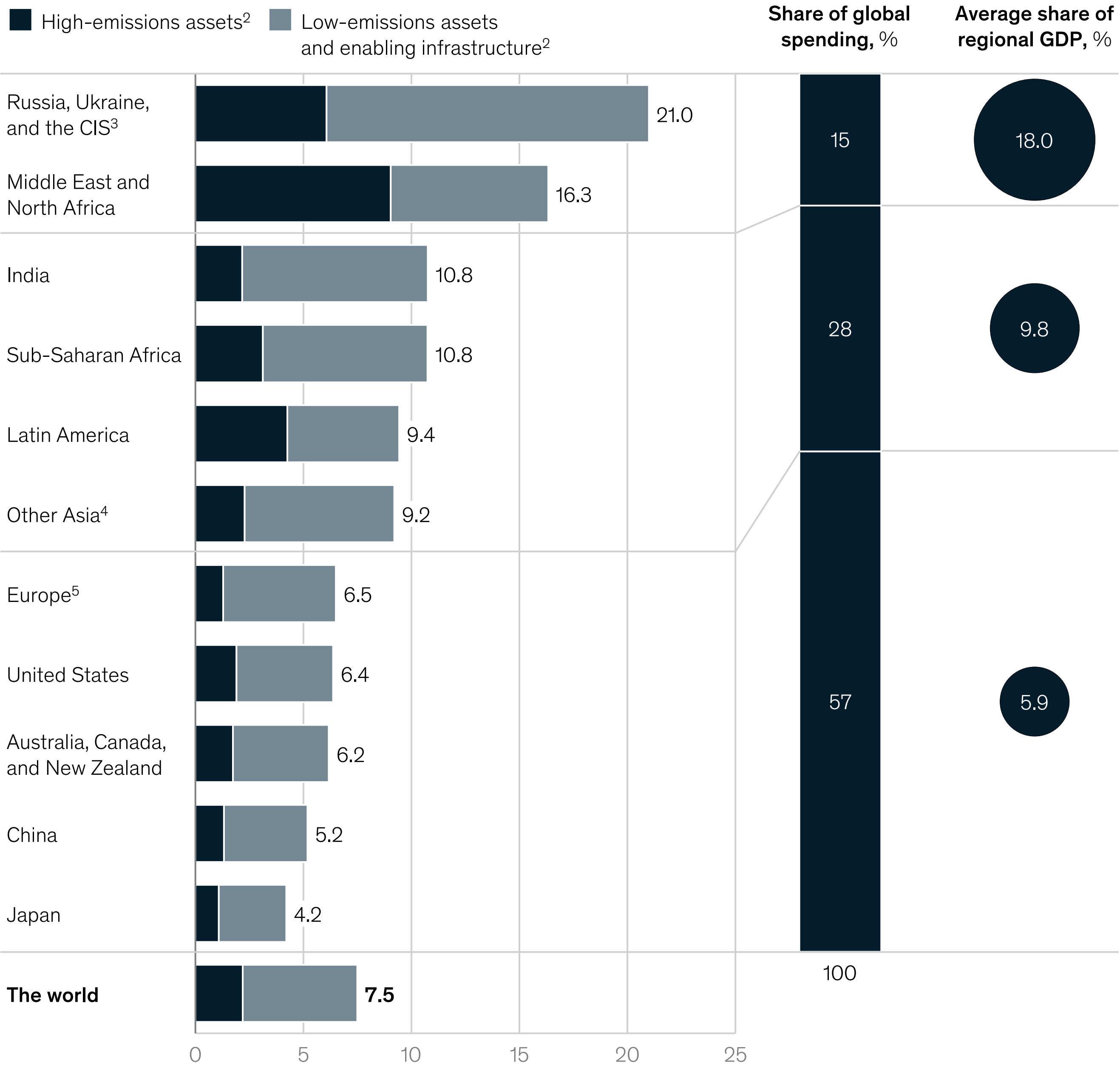
[266] In the NGFS scenario examined here, sub-Saharan Africa and India are expected to see real GDP growth of about 4 to 5 percent per year on average over the next 30 years, compared with 3 percent growth for China and 1 to 2 percent growth for developed regions.

Exhibit 24

As a percentage of GDP, fossil fuel–producing regions and developing countries would spend more than others on physical assets for energy and land-use systems. (1 of 2)

Spending on physical assets for energy and land-use systems under NGFS Net Zero 2050 scenario,[1]

% of 2021–50 GDP



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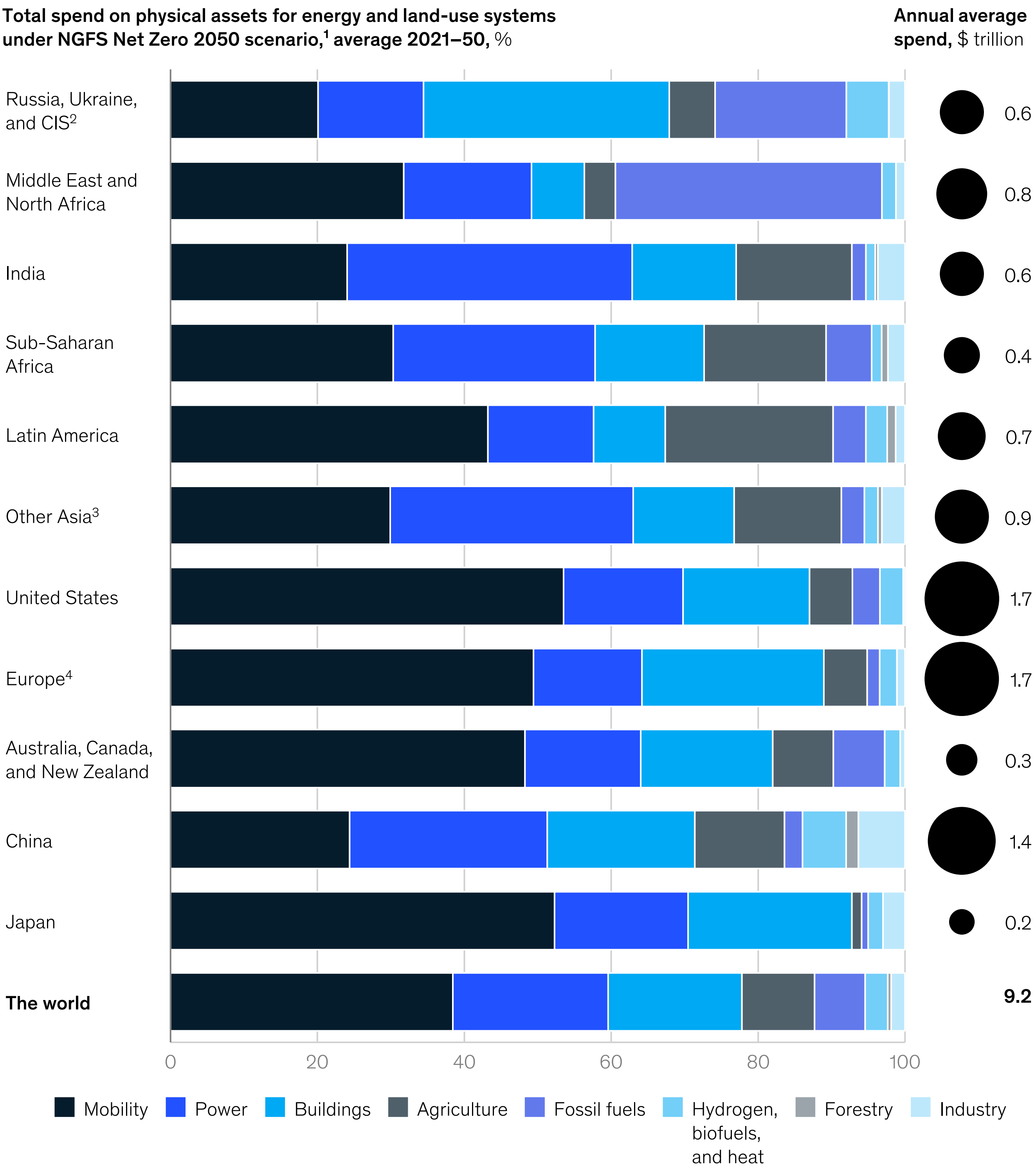
1. Estimation includes spend for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (eg, for vehicles), and land use. This includes both what are typically considered "investments" in national accounts and spend, in some cases, on consumer durables such as personal cars. Scenario based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall carbon dioxide equivalent (CO_2e) emissions today. Our analysis includes a more comprehensive view of spending by households and businesses on assets that use energy, capital expenditures in agriculture and forestry, and some continued spend in high-emissions physical assets like fossil fuel–based vehicles and power assets. For further details, see technical appendix.
2. Our analysis divides high-emissions assets from low-emissions assets. High-emissions assets include assets for fossil fuel extraction and refining, as well as fossil fuel power production assets without CCS; fossil fuel heat production, gray-hydrogen production; steel BOF; cement fossil fuel kilns; ICE vehicles; fossil fuel heating and cooking equipment; dairy, monogastric, and ruminant meat production. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, geothermal, biomass, gas with CCS, and nuclear power along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using EAF, DRI with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or fossil fuel kilns with CCS; low-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass, including heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; and land restoration. See technical appendix.
3. CIS refers to the Commonwealth of Independent States.
4. Includes, among others, South Korea and Southeast Asia.
5. Includes, among others, the 27 European Union countries, Norway, Switzerland, Turkey, and the United Kingdom.

Note: Figures may not sum to 100% because of rounding.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

Exhibit 24 (continued)

As a percentage of GDP, fossil fuel–producing regions and developing countries would spend more than others on physical assets for energy and land-use systems. (2 of 2)



1. Estimation includes spend for physical assets across various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (for example, for vehicles, alternate methods of steel and cement production), and various forms of land use (for example, GHG-efficient farming practices). This includes both what are typically considered "investments" in national accounts and spend, in some cases, on consumer durables such as personal cars. Scenario based on the NGFS Net Zero 2050 scenario using REMIND-MAgPIE (phase 2). Based on analysis of systems that account for ~85% of overall CO_2e emissions today. Spend estimates are higher than others in the literature because we have included spend on high-carbon technologies, agriculture and land-use, and taken a more expansive view of the spending required in end-use sectors.
2. CIS refers to the Commonwealth of Independent States.
3. Includes, among others, South Korea and Southeast Asia.
4. Includes, among others, the 27 European Union countries, Norway, Switzerland, Turkey, and the United Kingdom.

Source: Network for Greening the Financial System 2021 (Net Zero 2050 scenarios) REMIND-MAgPIE model; Vivid Economics; McKinsey Center for Future Mobility Electrification Model (2020); McKinsey Hydrogen Insights; McKinsey Power Solutions; McKinsey–Mission Possible Partnership collaboration; McKinsey Sustainability Insights; McKinsey Agriculture Practice; McKinsey Nature Analytics; McKinsey Global Institute analysis

This is most evident in China, where spending on these systems accounts for about 8.1 percent of GDP today, a proportion that would fall to 3 percent by 2050 in the NGFS Net Zero 2050 scenario.

The nature of spending would vary substantially in developed and developing countries. First, the transition in the scenario examined here could take place at a slower pace in developing countries. As a consequence, spending on high-emissions assets would persist for longer and hence make up more than one-quarter of annual average spending. Second, the sectoral mix of their spending would look quite different. A much larger share of the spending on physical assets would go to power and agriculture in developing countries than in developed regions. In India, for example, 30 to 40 percent of spending would be in power. Similar levels of spending would be observed in other countries in developing Asia and Africa. Agriculture is the other area where the share of spending would be much higher than in developed regions. In Latin America, for example, it would increase by more than 50 percent over the course of the NGFS Net Zero 2050 scenario, particularly for low-carbon crops, emissions mitigation measures, and reforestation.

Fossil fuel–based economies would continue to have the highest spending on physical assets for energy and land-use systems as a share of their GDP, about 15 percent or higher in the Middle East and North Africa, Russia, Ukraine, and Commonwealth of Independent States such as Kazakhstan. These regions would continue to spend the largest share on fossil fuel production and distribution in the world in the NGFS Net Zero 2050 scenario given their competitive cost position. The Middle East and North Africa in particular would account for more than 50 percent of the total spending on fossil fuels in 2050 in this scenario, up from 30 percent today, even as demand declines by as much as 65 percent. However, even these economies would allocate about half of their spending to low-emissions assets or more under a net-zero transition.

Importantly, while the relative scale of the spending on physical assets is substantially higher for developing and fossil fuel–based economies, this alone is not an indicator of how difficult it will be for developing and fossil fuel–reliant regions to reach a low-emissions economy. Indeed, as mentioned previously, many of these geographies already spend more as a share of GDP on physical assets for energy and land-use systems and are expected to continue to do so as they grow their economies. However, specific aspects of their net-zero transition could make deploying capital challenging for these regions.

First, developing regions might face challenges in accessing capital markets. This may be particularly acute as they look to invest in low-emissions technologies, which may be harder to finance and come with different risk-return expectations. Second, as mentioned above, existing high-emissions assets in these economies are still relatively young; thus there may be less incentive to undertake low-carbon capital spending amid concerns about stranded assets. Third, there may not always be sufficient know-how and capacity on the ground to implement projects. Fourth, concerns of other socioeconomic consequences from a net-zero transition, for example, job dislocations, could exist. Finally, because the economies of these countries rely on emissions-intensive sectors, government tax revenues and public spending may be more constrained under a net-zero transition.[267]

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[267] Similar conclusions were also reached by the IEA. See for example *Financing clean energy transitions in emerging and developing economies,* International Energy Agency, June 2021.

Larger shares of the economies of lower-income and fossil fuel resource-producing countries are exposed to the transition today

Beyond the spending on physical assets that regions would need to undertake, we also assessed how countries' economies would be exposed to the net-zero transition, and thus need to transform. A country's exposure to the transition increases with the share of its economy that comes from sectors that would experience outsize effects under a net-zero transition. Our analysis of economic systems and sectors, discussed in chapter 3, showed that sectors with the highest exposure would be those with emissions-intensive operations (for example, steelmaking), products (for example, automobile manufacturing), and supply chains (for example, construction). To gauge the transition exposure of national economies, we looked at the proportions of employment (jobs), economic production (GDP), and existing physical capital stock in these exposed sectors. We chose these variables to capture a broad range of economic exposures a country may experience. With these economic measures, we calculated a transition-exposure score ranging from zero for a country whose employment, economic production, and capital stock have no exposure to 100 for a country with full exposure.[268]

Four general points about this analytical method are worth emphasizing. First, it accounts for the possibility that countries that directly emit the most carbon may not necessarily have the highest levels of exposure. Exposure to the transition could result from either direct scope 1 emissions (such as those resulting from domestic energy use) or from indirect emissions upstream and downstream in value chains. For example, a country with a large but relatively low-emissions automotive value chain could nevertheless be exposed to the transition.

Second, country exposure varies with the share of jobs, output, or capital stock in sectors exposed to the transition rather than the absolute level. Assessing the exposed share of jobs or capital or output, rather than the absolute quantity of the exposed jobs or capital or output, provides a way of gauging the materiality of the transition for each country.

Third, for this country-level analysis, we chose to measure economic exposure (share exposed) rather than quantify actual socioeconomic outcomes (realized gain or loss, for example in jobs, GDP, or value of physical capital stock) because such outcomes are not predetermined. They could be mitigated by the scale and nature of actions taken to manage the transition. Measuring the exposure therefore allows decision makers to understand where to focus attention and effort on managing the transition.

Finally, it is important to note that countries' current efforts (for example, spending to transform power assets or to diversify economies) could reduce their exposure going forward. However, this analysis focuses on exposure today in order to create a fact base for countries to inform their decision making.

Based on our analysis, we can make the following observations:

— **All countries' economies would be exposed to the net-zero transition to some extent.** On our transition-exposure scorecard, no country scores a zero, emphasizing the universality of the shifts required to achieve net zero by 2050. Some portion of jobs, GDP, or capital stock in every country is tied to sectors that are most exposed to the transition's impacts: those that emit greenhouse gases directly, produce goods that emit GHGs, or use emissions-intensive inputs. These sectors make up about 40 percent of a country's jobs on average, about 35 percent of a country's GDP on average, and about 40 percent of a country's capital stock on average (and in countries including India and Saudi Arabia, these percentages can rise to 50 to 70 percent).

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[268] Our transition exposure of economies score consists of average exposure in three categories: employment (jobs), production activity (GDP), and capital stock. In each case, we consider the share of overall activity or stock that is in sectors most exposed to the transition—that is, those with high emissions in their operations, in the use of their products, or in their supply chains. These sectors include mining and extraction of energy-producing products, manufacture of coke and refined petroleum products, manufacture of motor vehicles, manufacture of other transportation equipment, manufacture of machinery and equipment, manufacture of fabricated metal products, manufacture of electrical equipment, fossil fuel–based electricity, manufacture of basic metals, manufacture of other nonmetallic minerals, manufacture of chemicals, air transportation, water transportation, land transportation, agriculture and forestry, sewerage, food products, water supply, wood products, paper products, textiles, pharmaceutical products, construction, rubber and plastic products, and mining of nonenergy products and mining support. For further details, see the technical appendix.

- **Countries with lower GDP per capita generally have higher exposure to the transition today.** This is because relatively higher shares of their jobs, GDP, and capital stock are in more exposed sectors, such as emissions-intensive manufacturing, agriculture, and fossil fuel–based power, while a smaller share of their economies is in service sectors, which are relatively less exposed to the transition (Exhibit 25). Examples of the most exposed countries include Bangladesh, India, Kenya, and Nigeria. By contrast, our analysis shows that countries with higher GDP per capita would be less exposed because much of their economy is in service sectors, which have relatively lower exposure to the transition. France, Spain, the United Kingdom, and the United States are examples of such countries.
- **Significant fossil fuel resource production creates relatively high exposure for some countries.** Examples include countries in the Middle East such as Saudi Arabia and Qatar, as well as Australia, Canada, Nigeria, Norway, and Russia, which have significant deposits of oil, gas, or coal. About one-third of Qatar's GDP and capital stock is in the extraction and refinement of fossil fuels. In Norway, the fossil fuel sector represents about one-fifth of GDP and approximately 15 percent of capital stock. As a result, significant portions of these economies would be exposed to the transition, and could experience some degree of transformation in a net-zero economy.
- **Several countries that would have high exposure to the transition also face elevated physical risks from rising heat and humidity.** Drawing on our previous research on physical climate risks, we find that countries like Ghana, India, Nigeria, and Vietnam, which would be more exposed to the transition, also have high exposure to the physical risks associated with a hotter and more humid climate. These countries are exposed to physical risks specifically to human livability and workability from lethal heat waves or chronic increases in heat and humidity.[269] Our prior analysis of India, for example, showed that some 160 million to 200 million people could be living in urban areas with a nonzero annual probability of experiencing a lethal heat wave by as early as 2030, under a scenario in which no adaptation or mitigation measures are implemented.[270]

Thus, for many lower-income and fossil fuel–producing countries, challenges associated with climate change could compound. These countries would need to balance multiple imperatives: decarbonizing their economies and funding associated capital expenditures, managing exposure of large parts of their economies to a net-zero transition and to rising physical risks, and enabling economic development and growth, particularly by expanding access to affordable, secure energy. Secondary effects from direct exposure could also extend to government tax revenues and exports, which are often linked with exposed sectors like fossil fuel extraction or steel. Inequity concerns may grow as an issue, particularly as developing economies argue that they have contributed less than others to emissions and yet are being asked to shoulder a large burden in the net-zero transition that could slow their efforts to make energy more accessible and affordable to lower-income households.

As discussed in chapter 2, low-income households everywhere would also be most exposed to any cost increases that feed through to consumers. This is particularly true for energy prices, and any up-front capital costs that households may need to bear (for example, related to autos). At the same time, while the net-zero transition will mean countries are exposed differentially, they also have opportunities to benefit from the economic adjustment.

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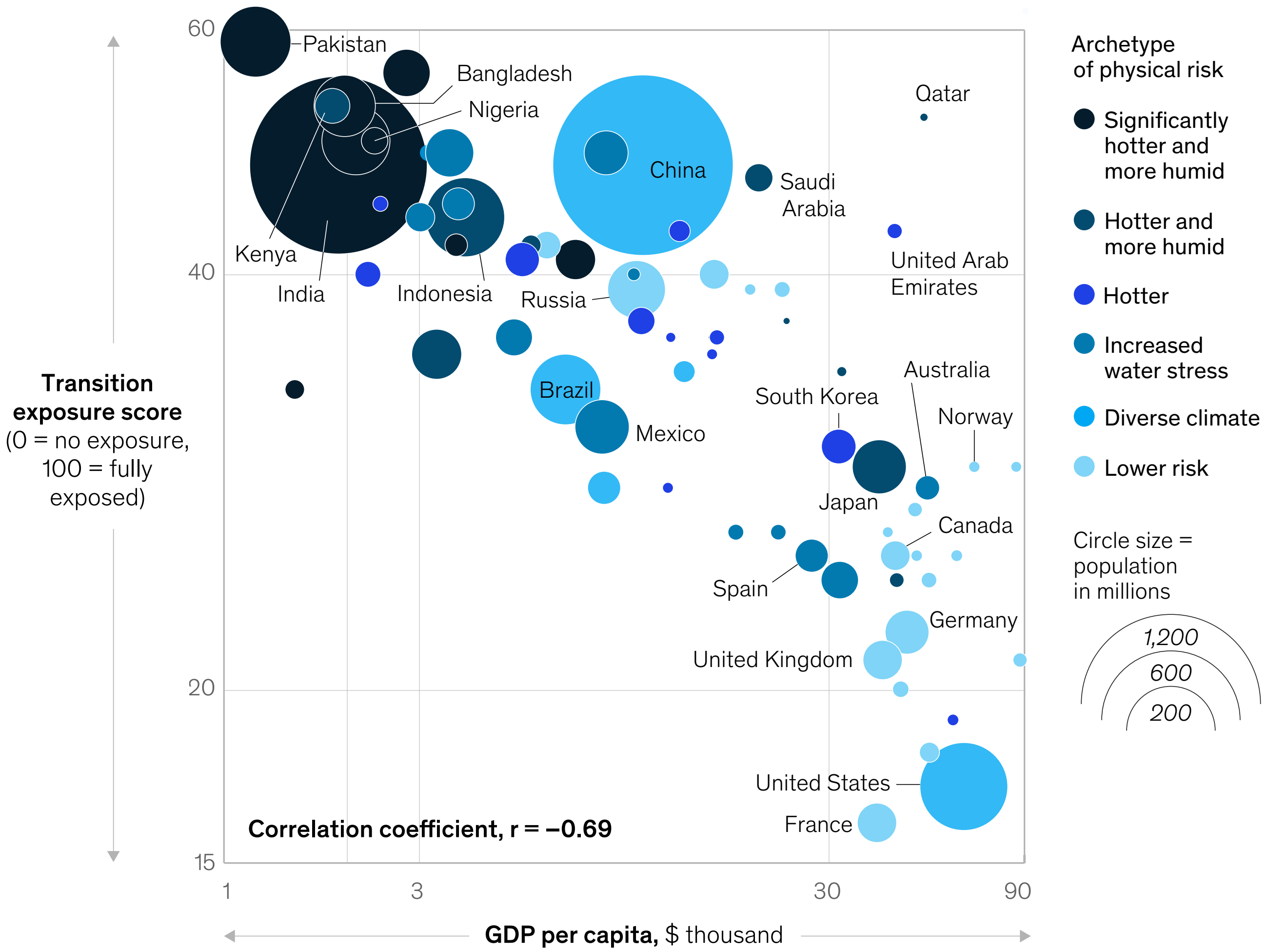
[269] Information on physical risks in this chapter comes from *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

[270] See *Will India get too hot to work?* McKinsey Global Institute, November 2020.

Exhibit 25

Countries with lower GDP per capita and fossil-fuel resource producers have higher transition exposures.

Archetype of physical risk[1] through transition exposure vs GDP per capita by country[2] (logarithmic scale)



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1. For further details, see *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.
2. Based on average share of jobs, GDP, and capital stock in exposed sectors. These sectors are identified based on their scope 1, 2, and 3 emissions intensity. For further details, see technical appendix.

Source: Oxford Economics; OECD; ILO; World Input-Output Database; IHS Connect; World Bank; International Energy Agency; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; UN; International Renewable Energy Agency (IRENA); MINSTAT; INDSTAT; Global Solar Atlas; Global Wind Atlas; US Geological Survey; WEF; McKinsey Nature Analytics; McKinsey Global Institute analysis

Countries could use natural endowments or technological and human capital to achieve the potential growth the transition would enable

Just as countries are exposed to the transition's shifts, they also have the potential to gain from opportunities that arise from a net-zero transition. A country could prosper during and after the transition for many reasons. Here, we focus on their endowments of natural capital (such as sunshine and wind) and the availability of technological and human capital, that could help them capture opportunities from the transition. Whereas natural-capital endowments are fixed, other forms of capital can be developed. While the following list of factors is not exhaustive, it is meant to provide an initial overview of considerations for decision makers:

Natural-capital endowments. Growth potential could be available to countries with rich stocks of natural capital, such as ample sunlight and wind, forestland, mineral resources, and CO_2 storage potential. Natural geological features that enable less energy-intensive extraction of fossil fuels could also be a useful endowment. Our analysis of countries' natural-capital endowments includes the following types (Exhibits 26a–d):

— *Solar potential.* High solar irradiance (that is, power received from the sun per unit area) provides an opportunity to generate renewable solar power.[271] It also provides other opportunities—for example, the potential to produce green hydrogen for domestic consumption and for export, as huge amounts of low-emissions energy are needed for green hydrogen. Example countries with high availability of solar resources include Australia, Egypt, Kenya, Oman, Qatar, Saudi Arabia, Senegal, and the United Arab Emirates. Many countries with high solar potential rely substantially on fossil fuel assets today.

— *Wind potential.* High wind power density allows countries to generate renewable wind power and, as above, avail of other opportunities such as green hydrogen.[272] Argentina, Chile, New Zealand, Norway, and the United Kingdom have the highest wind power potential of the countries we analyzed.

— *Reforestation potential.* The potential for reforestation of land also creates opportunities for CO_2 sequestration.[273] This, in turn, could help countries produce carbon credits that might be sold on voluntary or compliance markets.[274] We measured countries' potential by assessing the extent of land that is technically suitable for reforestation. We narrowed this area down to a realistic reforestation potential using biophysical filters.

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[271] *Global photovoltaic power potential by country,* World Bank, April 2020. Average theoretical solar potential, global horizontal irradiance, kWh/m2 per day. It is important to note that solar endowments alone do not determine the ability of the grid to transition because of issues of grid storage and managing daily and seasonal intermittency.

[272] Global Wind Atlas 3.0, a web-based application developed, owned, and operated by the Technical University of Denmark. The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program. Mean wind power density of the 10 percent windiest areas at 100m height, W/m2. Calculated by downscaling large-scale forecasting data from the European Centre for Medium-Range Weather Forecasts. It is important to note that wind endowments alone do not determine the ability of the grid to transition, because of issues of grid storage and managing daily and seasonal intermittency.

[273] McKinsey Nature Analytics. Countries' reforestation potential was calculated by assessing the extent of land that is technically suitable for reforestation, then narrowing this area down to a realistic reforestation potential using biophysical filters. The resulting area is then converted into carbon sequestration potential. Three specific filters were used. First, a biome filter, to exclude biomes where reforestation is nonnatural or could have negative effects on ecosystems and climate, for instance boreal forests/taiga; grasslands, tropical savannas, and shrublands; and deserts and xeric shrublands biomes. Second, a water stress filter, to exclude areas where water stress is projected to be extremely high (greater than 80 percent) or the area is forecast to be arid in 2040, based on the RCP 8.5 scenario. Third, a human footprint filter to exclude current cropland and urban areas, as well as areas where urban expansion is projected with a probability greater than 50 percent by 2050. Spatially explicit carbon-sequestration rates were then applied to each area with reforestation potential to estimate the total abatement potential. See Jean-Francois Bastin et al., "The global tree restoration potential," *Science,* volume 365, number 6448, July 2019; and Susan Cook-Patton et al., "Mapping carbon accumulation potential from global natural forest regrowth," *Nature,* issue 585, September 2020.

[274] *Final report,* Taskforce on Scaling Voluntary Carbon Markets, January 2021.

We then converted the resulting area into carbon sequestration potential. Based on this measure, Costa Rica, Honduras, and Panama have the highest reforestation potential relative to land area of the countries we analyzed, and Brazil has the highest potential in absolute terms.

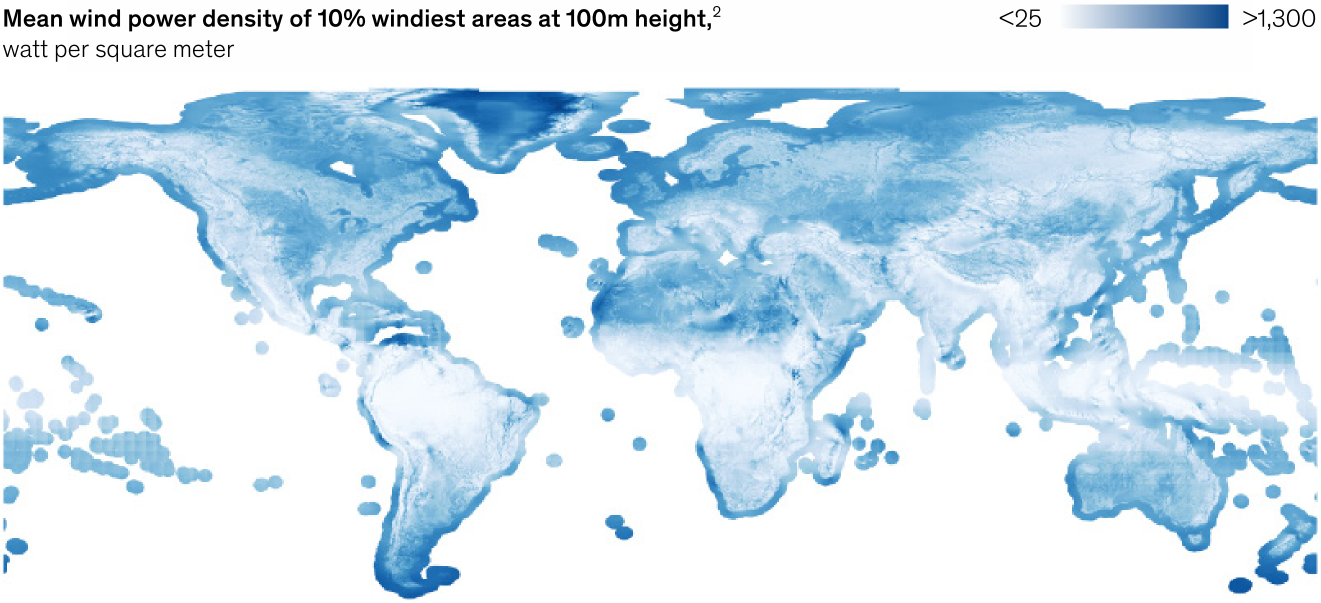
— *Minerals' availability.* Minerals needed to make low-carbon goods such as solar panels and electric-vehicle batteries include cobalt, copper, lithium, nickel, zinc, and rare earths.[275] These can be used domestically or exported. Of the countries analyzed, Brazil, Chile, China, and Vietnam have the highest average reserves of these minerals relative to their respective current annual production.

Exhibit 26a

Countries could capture potential growth opportunities from the transition to net-zero emissions: Renewable power example.

Average theoretical solar potential,[1]
kilowatt-hour per square meter per day

Mean wind power density of 10% windiest areas at 100m height,[2]
watt per square meter



1. Calculated as the power output achievable by a typical configuration of the utility scale PV system, taking into account GHI (global horizontal irradiation, or the total solar radiation that reaches a horizontal surface), the air temperature affecting the system performance, the system configuration, shading and soiling, and topographic and land-use constraints.
2. Calculated by downscaling large-scale forecasting data from the European Centre for Medium-Range Weather Forecasts. These data are then entered into the DTU Wind Energy modeling system to model local wind climates for a 250m grid across the globe.

Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.
Source: Global Solar Atlas; Global Wind Atlas; McKinsey Global Institute analysis

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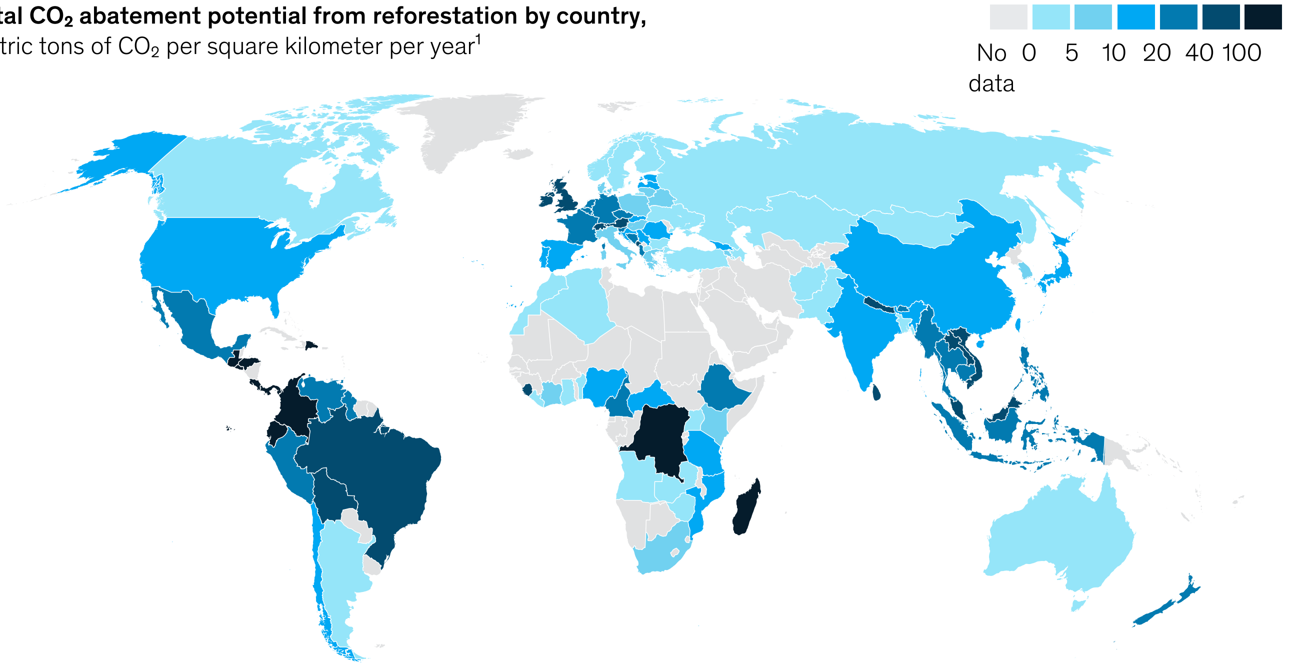
[275] *Mineral commodity summaries 2020,* US Geological Survey, January 2020. Ratio of proven reserves to global production for each mineral is calculated as the total proven reserves of the mineral divided by the total current annual global production. This was done in order to account for the varying values of the absolute levels of different minerals (that is, one ton of copper is not the same as one ton of cobalt). We therefore normalize the reserves available of each mineral with their respective current annual production (acknowledging that usage may increase during and after the net-zero transition, as well as the fact that reserves include only currently discovered deposits). This is not an exhaustive list of all materials critical for the net-zero transition, and is meant to be illustrative.

Exhibit 26b

Countries could capture potential growth opportunities from the transition to net-zero emissions: Reforestation example.

Total CO_2 abatement potential from reforestation by country,
metric tons of CO_2 per square kilometer per year[1]



1. Abatement potential is calculated using biophysical filters to identify reforestation opportunities on all land areas suitable for reforestation. Specific carbon-sequestration rates that correspond to different opportunities are then applied to estimate the total abatement potential.

Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.

Source: McKinsey Nature Analytics; Bastin et al., 2019; McKinsey Global Institute analysis

— *Carbon-sequestration capacity.* Capture and storage of CO_2 may enable a country's carbon-intensive industries to continue operating while avoiding the associated emissions. It may also facilitate the creation of a blue-hydrogen industry (where emissions from hydrogen production via natural gas are economically captured and stored). Countries such as Canada, Norway, and the United States have extensive potential to store captured carbon geologically, based on the measure analyzed here. They have identified many high-potential basins and are beginning to develop pilot CO_2 storage projects.[276]

Other forms of natural capital that we did not assess for data availability reasons could also prove useful. For example, the carbon intensity of a country's fossil fuel extraction could affect its competitiveness if a price is placed on carbon. Heavy oils (such as those in the Canadian oil sands) require large energy inputs (for instance, steam flooding) or the use of light hydrocarbon diluents for transportation, so they have much higher carbon intensities than light crude oils.[277] Saudi Arabia's crude oil production, by comparison, has some of the lowest carbon intensity regionally and globally.

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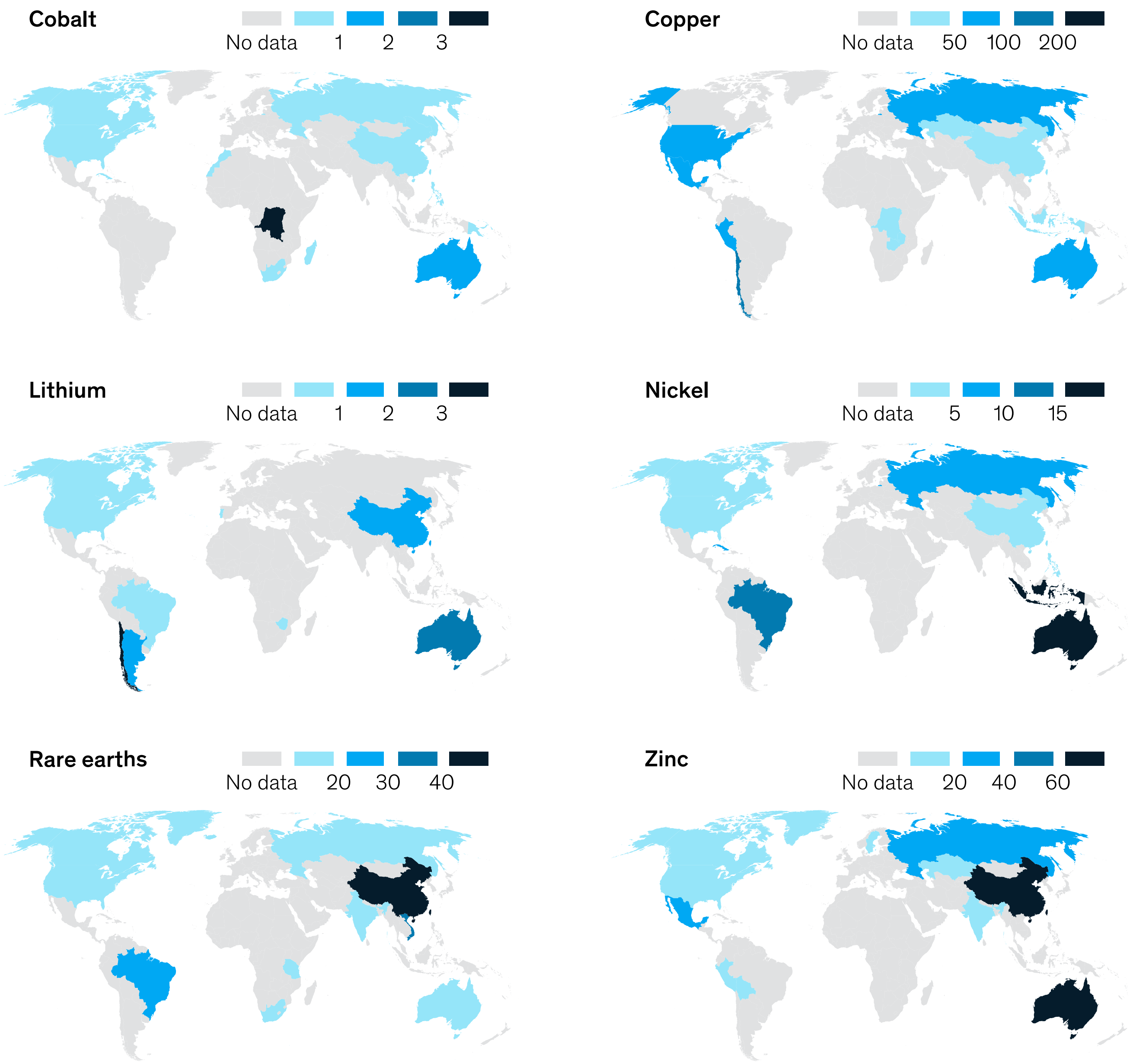
[276] Christopher Consoli, *CCS storage indicator (CCS-SI),* Global CCS Institute, 2018. The CCS-SI uses a defined methodology to undertake critical analysis of a nation's storage resource development and record the progress in national and global storage development. The metric is calculated based on three factors: natural geological storage potential, maturity and confidence of storage resource assessments, and experience in CO_2 storage project development to date. The result is a score out of 100, with higher scores indicating a greater state of readiness of storage resources to support wide-scale deployment of CCS.

[277] McKinsey Energy Insights; Stanford Oil Production Greenhouse Gas Emissions Estimator (OPGEE); and IEA Methane Tracker.

Exhibit 26c

Countries could capture potential growth opportunities from the transition to net-zero emissions: Minerals example.

Reserves of minerals that are used in low-emissions technologies,
average ratio of mineral reserves to global production[1]



1. Each ratio expresses a country's total proven reserves of the mineral, divided by total current annual global production of the mineral. This is to normalize for different levels of usage of each mineral, acknowledging that usage may change during or after the transition.

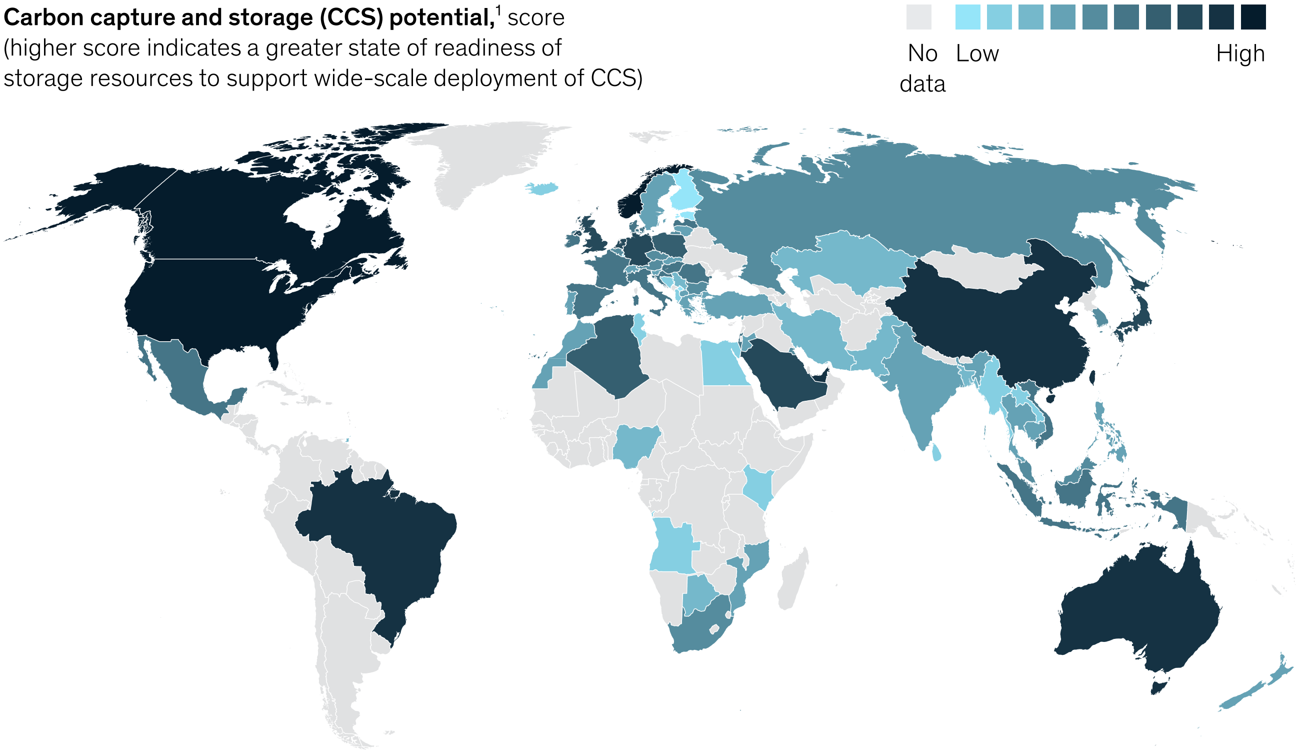
Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.

Source: US Geological Survey; McKinsey Global Institute analysis

Exhibit 26d

Countries could capture potential growth opportunities from the transition to net-zero emissions: Carbon capture and storage example.

Carbon capture and storage (CCS) potential,[1] score
(higher score indicates a greater state of readiness of
storage resources to support wide-scale deployment of CCS)



1. The score out of 100 is calculated based on three factors: (1) Natural geological storage potential, (2) Maturity and confidence of storage resource assessments, (3) Experience in CO_2 storage project development to date. Higher scores indicate a greater readiness of storage resources to support wide-scale deployment of CCS.

Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.

Source: Global CCS Institute, 2018 CCS-SI update

Technological and human capital: Some countries have already gained strong positions in the markets for sophisticated low-carbon goods, such as solar panels and EVs. These markets could have further growth potential under a net-zero transition, and the opportunities would thus continue and potentially increase. Countries could more easily serve these markets if they possess suitable technological and human capital. Countries that now lack these forms of capital could develop them by creating favorable conditions for investors, supporting R&D and industrial development, upskilling or reskilling workers, or training students to work in low-carbon industries, among other initiatives.

We evaluate a country's technological capital based on R&D spending as a percentage of GDP and on the number of patents related to climate-change mitigation.[278] These metrics help measure the extent of a country's innovative capacity in relation to climate transition. For example, the United States spends 2.8 percent of its GDP on R&D and has approximately 11,000 patents in technologies such as renewable-energy generation and low-emissions transportation that would likely be needed in a net-zero transition. Similarly, South Korea spends 4.8 percent of its GDP on R&D and has approximately 6,600 patents in similar areas.

We measure the potential for a country to benefit from human capital needs in a net-zero transition based on the share of STEM graduates in the population.[279] This provides an indication of the workforce's technical skill, which, in turn, might be applied to developing solutions for the climate transition. The highest-scoring countries in this respect include China, Finland, Israel, Malaysia, Morocco, Oman, and Singapore (for further details, see also discussion in the next section).

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[278] "Research and development expenditure % of GDP," World Bank; *Patents by technology: Patents in environment-related technologies,* Organisation for Economic Co-operation and Development.

[279] We used data from the International Labour Organization ILOSTAT database. While we focused on STEM skills for our analysis in this report, we acknowledge that many other skills will also be needed in a net-zero transition.

Various forms of physical capital could also support a country's transition to a low-carbon economy, although we have not measured them in quantitative terms for this analysis, due to data availability. Existing industrial processes and infrastructure that have low emissions intensity could prove advantageous, for example, if consumers shift their preferences or carbon border taxes are applied. Even currently high-emissions infrastructure could be a benefit if it can readily be retrofitted, for example, with alternate low-emissions fuel sources.

Six archetypes of countries based on their transition exposure highlight the unevenness of the economic shifts needed

To help decision makers understand how the net-zero transition might play out across countries, we grouped 69 countries into six distinct archetypes based on the nature and magnitude of their exposure to the economic transformation we analyze in this report (Exhibit 27). This exercise highlights the distinct and uneven economic and societal adjustments that countries will need to make as the world transitions to net-zero emissions.

Sector exposures reflect the average shares of GDP, jobs, and existing physical capital stock in groups of sectors that are most exposed to the transition.[280] In addition, we assessed per capita household scope 1 emissions to measure exposure at the household level. This measure provides an indication of the extent to which households may need to change their behaviors (for example, adopting new diets) and invest (for example, in EVs) as the transition progresses.[281] We also describe how countries in each archetype could benefit from transition opportunities.

Countries in the same archetype have exposure in similar parts of the economy, although their overall exposure scores can vary. Although we have placed each country within a single archetype, any given country—especially those with large and diversified economies—could also face some of the same issues we have highlighted for other archetypes. The archetypes thus indicate key issues a country may face but do not exclude the possibility that stakeholders in particular countries may need to reckon with issues that may be more closely associated with other archetypes.

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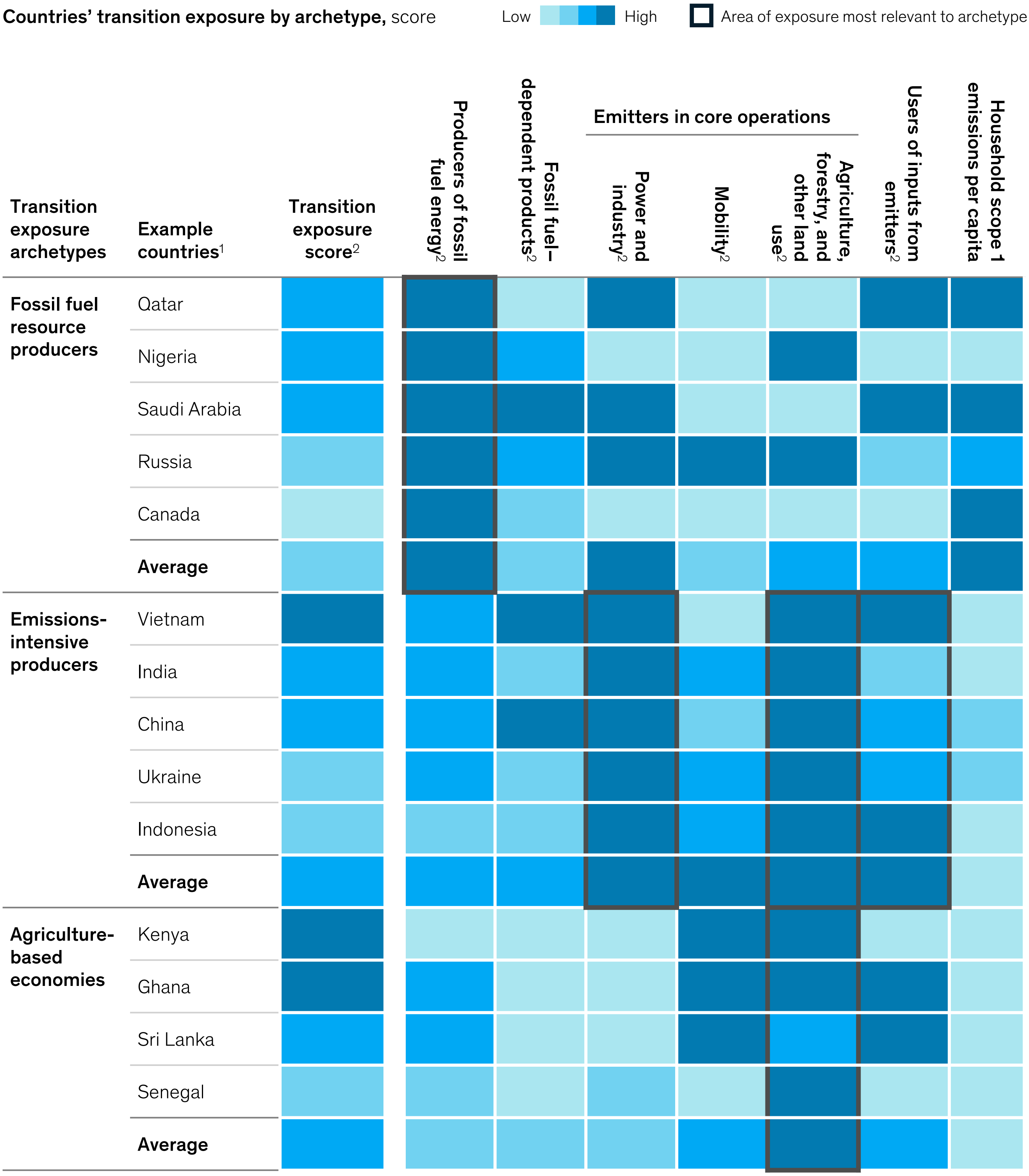
[280] These groups of exposed sectors are described in more detail in chapter 3. They include sectors such as fossil-fuel extraction and automotive manufacturing whose products are exposed to the transition (producers of fossil fuel energy and producers of fossil fuel–dependent products), sectors with high levels of emissions from their operations (emitters in core operations), and sectors that make products with high levels of embedded emissions because of the nature of their inputs (users of inputs from emitters).

[281] We include per capita household scope 1 emissions in our analysis of country exposure here but do not include it in the earlier scoring of overall transition exposure across countries. This is to allow us to focus our analysis there on production activities and to limit any potential overlap with consumption activities. We also omit spending on physical assets from the archetype analysis here because of data limitations. Because NGFS scenarios provide some decarbonization trajectories at a regional rather than country level, we were unable to estimate the individual spending requirements of the 69 countries covered by our analysis. Unless otherwise cited, the emissions data cited in this chapter come from the European Commission's Emissions Database for Global Atmospheric Research (EDGAR).

Exhibit 27

Based on the nature of their exposure to the net-zero transition, countries can be grouped into six archetypes. (1 of 2)

Countries' transition exposure by archetype, score



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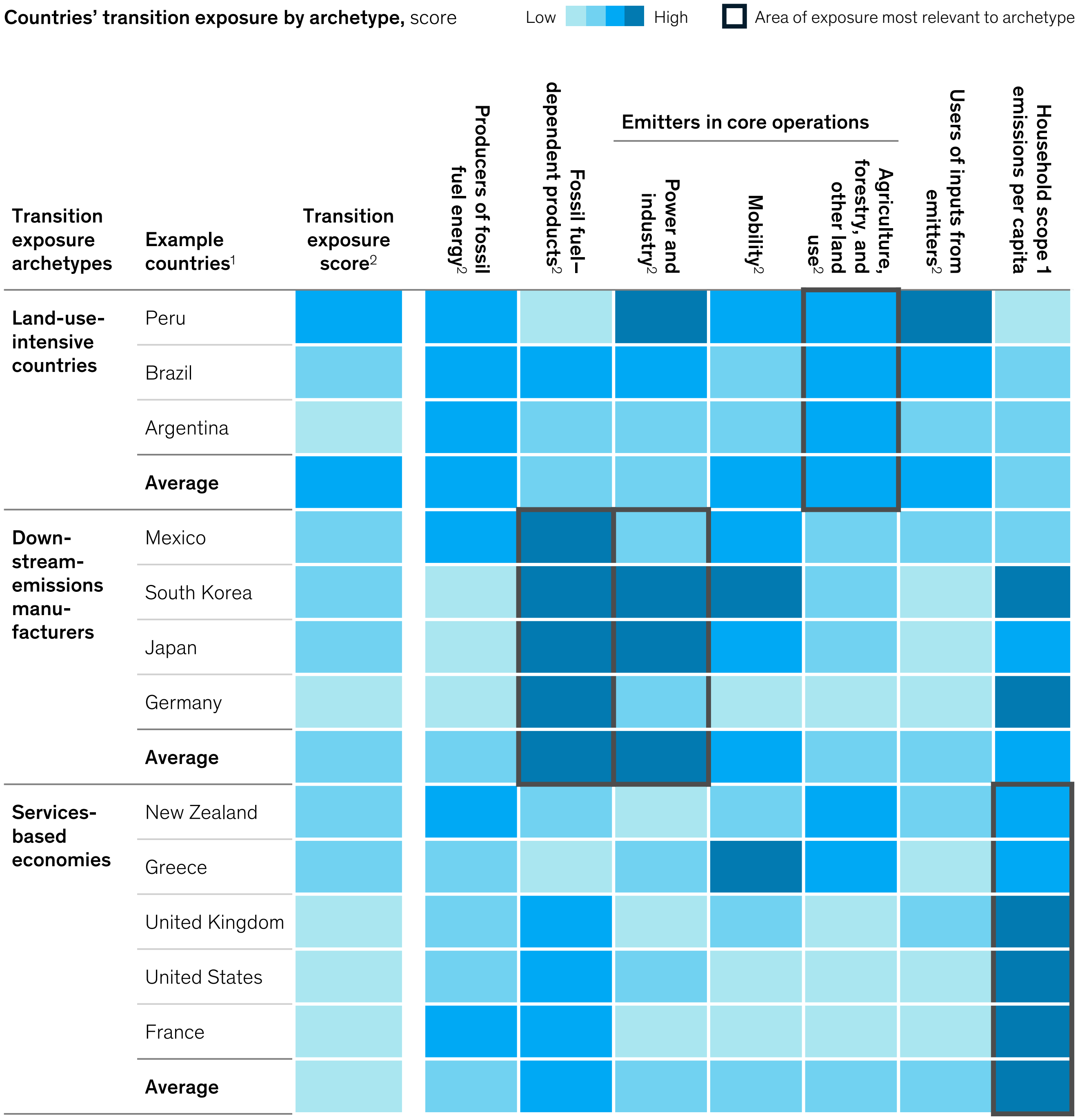
1. Averages rows within each archetype are based on a simple average of every country within that archetype, both those shown in rows and other countries in the archetype. For fossil-fuel producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, and Uruguay; for downstream emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland.
2. Simple average of the share of GDP, jobs, and capital stock in the sectors with highest exposure to the net-zero transition.

Note: Colors in each column based on relative quartiles within each column rather than across columns. Countries are allocated to an archetype to illustrate specific transition exposures they may experience. However, any given country—especially those with large diversified economies—could face some of the exposures highlighted for other archetypes. Low = below 1st quartile; high = above 3rd quartile. For exposed sectors included, see technical appendix.

Source: Oxford Economics; OECD; ILO; World Input-Output Database; IHS Connect; World Bank; International Energy Agency; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; MINSTAT; INDSTAT; McKinsey Global Institute analysis

Exhibit 27 (continued)

Based on the nature of their exposure to the net-zero transition, countries can be grouped into six archetypes. (2 of 2)



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1. Averages rows within each archetype are based on a simple average of every country within that archetype, both those shown in rows and other countries in the archetype. For fossil-fuel producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, and Uruguay; for downstream emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland.
2. Simple average of the share of GDP, jobs, and capital stock in the sectors with highest exposure to the net-zero transition.

Note: Colors in each column based on relative quartiles within each column rather than across columns. Countries are allocated to an archetype to illustrate specific transition exposures they may experience. However, any given country—especially those with large diversified economies—could face some of the exposures highlighted for other archetypes. Low = below 1st quartile; high = above 3rd quartile. For exposed sectors included, see technical appendix.

Source: Oxford Economics; OECD; ILO; World Input-Output Database; IHS Connect; World Bank; International Energy Agency; US Bureau of Labor Statistics; India NSS-Employment survey; China National Bureau of Statistics; MINSTAT; INDSTAT; McKinsey Global Institute analysis

We also examine the potential of each country to seize transition opportunities by assessing their endowments of natural capital and their stocks of technological and human capital. Exhibit 28 highlights a range of endowments for countries in different archetypes. It is also important to note that our discussion of country opportunities and transition exposure is illustrative and not exhaustive; for example, there may be other opportunities from which countries have the potential to benefit.

Finally, we also measure countries' exposure to physical risk based on six indicators described in our previous physical risk research (Exhibit 29).[282] Below, we describe the six archetypes and the attributes that define them.

Fossil fuel resource producers

Countries in this archetype include Australia, Bahrain, Canada, Egypt, Kuwait, Nigeria, Norway, Oman, Qatar, Russia, Saudi Arabia, the United Arab Emirates, and Venezuela. These economies have large fossil fuel resource–producing sectors, which include oil, gas, and coal extraction, along with the manufacturing of coke and refined petroleum products. As described in chapters 2 and 3, our analysis suggests that these sectors have high exposure to the transition because demand for their existing products could decline in a net-zero transition, potentially also stranding physical assets.

The magnitude of exposure varies among countries. For example, about 25 percent of Saudi Arabia's GDP is in fossil fuel–producing sectors, and about one-third of Qatar's GDP and capital stock is in those sectors. That compares with about 6 percent of GDP in Canada and 3 percent in Australia. A key adjustment for fossil fuel resource producers to consider under a net-zero transition would be diversifying their economies. Exposed sectors in these countries are often not the most significant employers; in most cases, these sectors account for less than 2 percent of jobs. However, the potential effect on national income could be significant. According to the International Energy Agency, annual per capita income from oil and natural gas in producer economies could fall by about 75 percent by the 2030s, with knock-on societal impacts.[283]

Replacing the economic output from exposed sectors could involve action to support growth in new industries needed for a net-zero economy, as we discuss below. Since fossil fuel resource sectors are also capital intensive, a relatively large share of capital stock in these countries (an average of about 17 percent versus about 3 percent in the rest of the countries) is also in sectors exposed to the net-zero transition. Some of this capital stock could be preserved if it is retrofitted to reduce emissions in the near term. One avenue would be spending to decarbonize the hydrocarbon value chain, for example, via CCS. Other assets may need to be retired prematurely (see chapter 2). Spending on physical assets is already high in these countries, for example about 15 percent in the Middle East and North Africa, and would continue at around these levels in a net-zero transition. However the allocation of this spending would be different: 45 percent would be spent on low-emissions assets, up from only around 10 percent today. Additional spending may also be needed to protect assets and people from rising physical climate risks. The level of physical risk varies among countries in this archetype, though our analysis suggests that countries toward the equator are likely to become hotter and more humid with increasing physical climate change.[284] Other countries, such as Canada, may be less exposed and even see some benefit from a changing climate, for example, the potential for improved agricultural yields.

Thus, for the countries with higher shares of exposure in particular, various challenges could exist: the potential loss of government revenue from exposed sectors, the reallocation of capital spending, and the potential need to diversify their economies while managing physical risks.

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[282] *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.
[283] *Net zero by 2050: A roadmap for the global energy sector,* IEA, July 2021.
[284] *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

At the same time, these countries have opportunities to tap into under a net-zero transition, though capturing them and sufficiently compensating for loss in revenues and exports will come with challenges. Many of these countries possess ample solar and wind resources, which are a prerequisite for developing renewable-energy capacity. Most countries rank in the top quartile of economies we examined for either solar or wind potential. For example, Egypt, Saudi Arabia, and the United Arab Emirates have high solar potential, while Canada, Norway, and Russia have high wind potential. These countries could use their renewables capacity to develop new projects, such as the production of green hydrogen. Saudi Arabia, for example, has started moving in this direction, unveiling plans for one of the world's largest green-hydrogen projects in 2020.[285] Relatively low levels of carbon intensity and relatively lower costs are associated with the oil and gas extraction of some fossil fuel producers, for example those in the Middle East; thus, those countries could be the last standing providers of the remaining fossil fuels needed in a net-zero economy, in the scenario modeled here.

Emissions-intensive producers

Countries in this archetype include Bangladesh, China, India, Indonesia, Pakistan, South Africa, Thailand, Turkey, Ukraine, and Vietnam. These economies center on producing industrial goods and agricultural commodities for domestic and world markets. They have high transition-exposure scores because their employment, GDP, and physical capital stock are concentrated in emissions-intensive manufacturing sectors like steel and cement, in fossil fuel–based power, and in agriculture.[286] On average, exposed sectors account for almost half of jobs, GDP, and capital stock across these economies.

Our analysis suggests that a key challenge for these countries under a net-zero transition is asset stranding. Their capital stock (coal-fired power plants, for example) is often newer than that of advanced economies. In the Net Zero 2050 scenario, owners of industrial assets would likely face a difficult choice between retrofitting assets and retiring them (see chapter 2). The average age of coal power plants in India and China is less than 15 years, compared with more than 30 years in the United States.[287] Lower-income countries may also find that some low-carbon technologies (for example, electric-arc furnaces for steel production and CCS equipment for steel or cement factories) remain too expensive to deploy or, in some cases, may not yet be ready for large-scale deployment. This puts these countries in a bind: the costs of low-emissions assets would likely need to come down before these emerging economies will invest in them rather than in high-emissions assets. Without careful planning, however, they run the risk that continued spending on lower-cost, high-emissions assets could result in the need to prematurely retire or reduce utilization of these assets after only a few years as the world transitions to a net-zero path.

Another area of exposure for these countries comes from the large share of their economic activity in hard-to-abate sectors like steel and cement; the costs of lower-carbon manufacturing processes (such as DRI-EAF steel) may be higher than those of existing processes, which may affect the profitability of these sectors. More broadly, while economic growth in these countries is expected to come with more construction activity, this could be more expensive in the NGFS Net Zero 2050 scenario because of the rising costs of steel and cement. Higher construction costs could also affect consumers.

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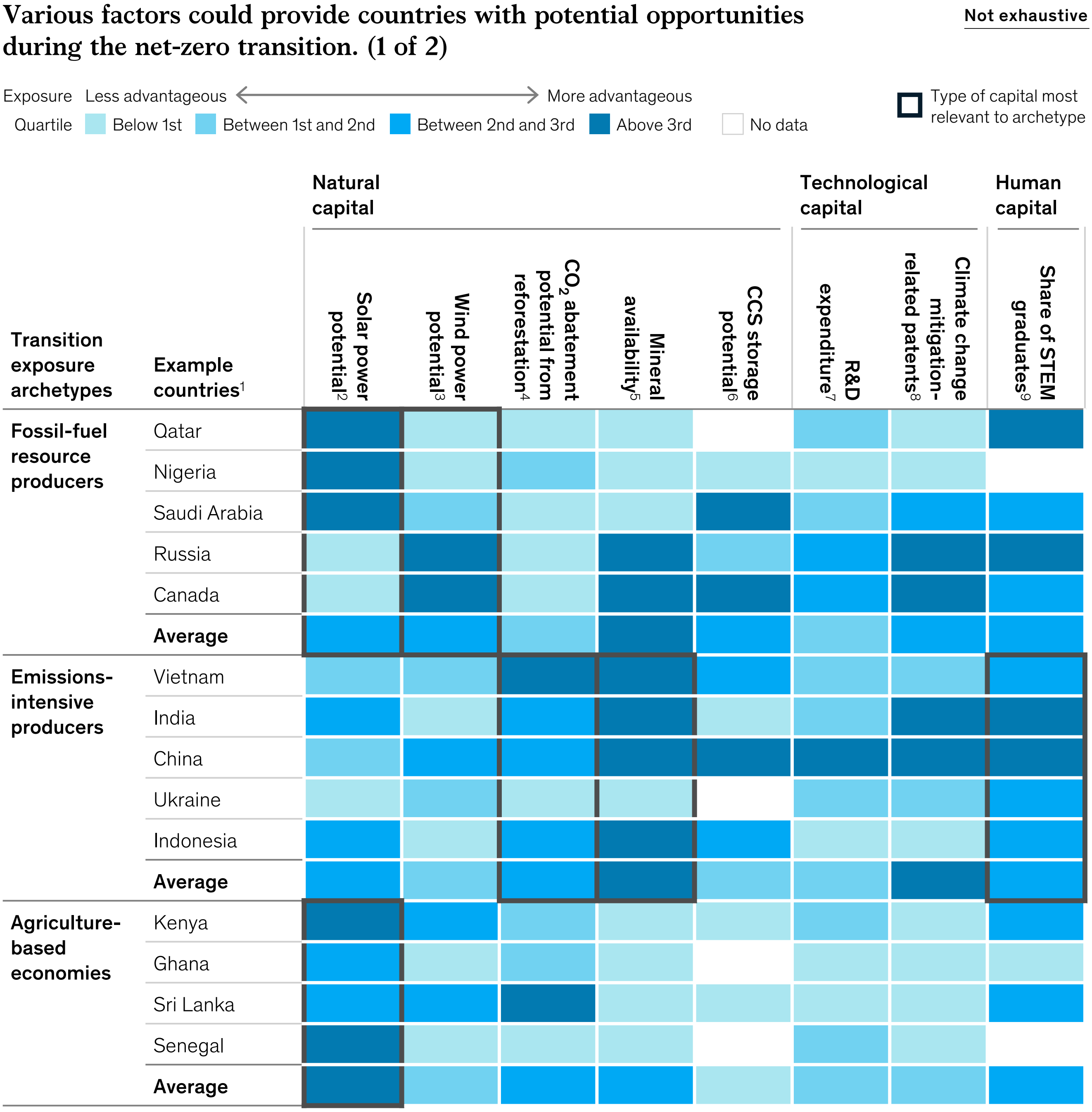
[285] John Parnell, "World's largest green hydrogen project unveiled in Saudi Arabia," Green Tech Media, July 7, 2020.

[286] These are industrial sectors that have a high level of emissions intensity in their own operations (high scope 1 emissions intensity), for example, steel and cement manufacturing. For further details, see the sector-exposure analysis in chapter 3.

[287] Steel and coal power data from IEA.

Exhibit 28

Various factors could provide countries with potential opportunities during the net-zero transition. (1 of 2)



Transition exposure archetypes	Example countries[1]	Solar power potential[2]	Wind power potential[3]	CO_2 abatement potential from reforestation[4]	Mineral availability[5]	CCS storage potential[6]	R&D expenditure[7]	Climate change mitigation-related patents[8]	Share of STEM graduates[9]
Fossil-fuel resource producers	Qatar	Above 3rd	Below 1st	Below 1st	Below 1st		Between 1st and 2nd	Below 1st	Above 3rd
	Nigeria	Above 3rd	Below 1st	Between 1st and 2nd	Below 1st	Below 1st	Below 1st	Below 1st	
	Saudi Arabia	Above 3rd	Between 1st and 2nd	Below 1st	Below 1st	Above 3rd	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd
	Russia	Below 1st	Above 3rd	Below 1st	Above 3rd	Between 1st and 2nd	Between 2nd and 3rd	Above 3rd	Above 3rd
	Canada	Below 1st	Above 3rd	Below 1st	Above 3rd	Above 3rd	Between 2nd and 3rd	Above 3rd	Between 2nd and 3rd
	Average	Between 2nd and 3rd	Between 2nd and 3rd	Between 1st and 2nd	Above 3rd	Between 2nd and 3rd	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd
Emissions-intensive producers	Vietnam	Between 1st and 2nd	Between 1st and 2nd	Above 3rd	Above 3rd	Between 2nd and 3rd	Between 1st and 2nd	Between 1st and 2nd	Between 2nd and 3rd
	India	Between 2nd and 3rd	Below 1st	Between 2nd and 3rd	Above 3rd	Below 1st	Between 1st and 2nd	Above 3rd	Above 3rd
	China	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd	Above 3rd	Above 3rd	Above 3rd	Above 3rd	Above 3rd
	Ukraine	Below 1st	Between 1st and 2nd	Below 1st	Below 1st		Between 1st and 2nd	Between 1st and 2nd	Between 2nd and 3rd
	Indonesia	Between 2nd and 3rd	Below 1st	Between 2nd and 3rd	Above 3rd	Between 2nd and 3rd	Below 1st	Below 1st	Between 2nd and 3rd
	Average	Between 2nd and 3rd	Between 1st and 2nd	Between 2nd and 3rd	Above 3rd	Between 1st and 2nd	Between 1st and 2nd	Above 3rd	Between 2nd and 3rd
Agriculture-based economies	Kenya	Above 3rd	Between 2nd and 3rd	Between 1st and 2nd	Below 1st	Below 1st	Between 1st and 2nd	Below 1st	Between 2nd and 3rd
	Ghana	Between 2nd and 3rd	Below 1st	Between 1st and 2nd	Below 1st		Below 1st	Below 1st	Below 1st
	Sri Lanka	Between 2nd and 3rd	Between 2nd and 3rd	Above 3rd	Below 1st	Below 1st	Below 1st	Below 1st	Between 2nd and 3rd
	Senegal	Above 3rd	Below 1st	Below 1st	Below 1st		Between 1st and 2nd	Below 1st	
	Average	Above 3rd	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd	Below 1st	Between 1st and 2nd	Between 1st and 2nd	Between 2nd and 3rd

1. Average rows within each archetype are based on a simple average of every country within that archetype, both those shown in rows and other countries in the archetype. For fossil-fuel resource producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, and Uruguay; for downstream-emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland.
2. Power output achievable by a typical utility-scale PV system, taking into account global horizontal irradiation (or the total solar radiation that reaches a horizontal surface), the air temperature affecting the system performance, the system configuration, shading and soiling, and topographic and land-use constraints.
3. Mean wind power density of 10% windiest areas at a height of 100m. Calculated by downscaling large-scale forecasting data from the European Centre for Medium-Range Weather Forecasts. These data are then entered into the DTU Wind Energy modeling system to model local wind climates for a 250m grid across the globe measured as watt per square meter.
4. Abatement potential is calculated using biophysical filters to identify reforestation opportunities on all land areas suitable for reforestation. Specific carbon-sequestration rates that correspond to different opportunities are then applied to estimate the total abatement potential measured as tonnes of CO_2 per kilometer squared per year.
5. Average of the ratios of proven reserves in a country to global production across 6 minerals. Includes cobalt, copper, lithium, nickel, zinc, and rare earths.
6. CCS (carbon capture and storage) Storage Indicator, a metric based on three factors: natural geological storage potential, maturity and confidence of storage resource assessments, and experience in CO_2 storage project development to date.
7. Primary government expenditures as a proportion of original approved budget.
8. Number of patents filed in a country for technologies related to climate-change mitigation.
9. Tertiary-level graduates in a country that graduates in natural sciences, mathematics, and statistics, as a share of all graduates.

Note: Colors in each column based on relative quartiles within each column rather than across columns. Countries are allocated to an archetype to illustrate specific types of capital that they possess. However, any given country could also have access to some of the forms of capital highlighted for other archetypes.

Source: Global Solar Atlas; Global Wind Atlas; US Geological Survey; McKinsey Nature Analytics; Bastin et al., 2019; Cook-Patton et al., 2020; Global CCS Institute, 2018 CCS-SI update; World Bank; OECD; ILOSTAT; McKinsey Global Institute analysis

Exhibit 28 (continued)

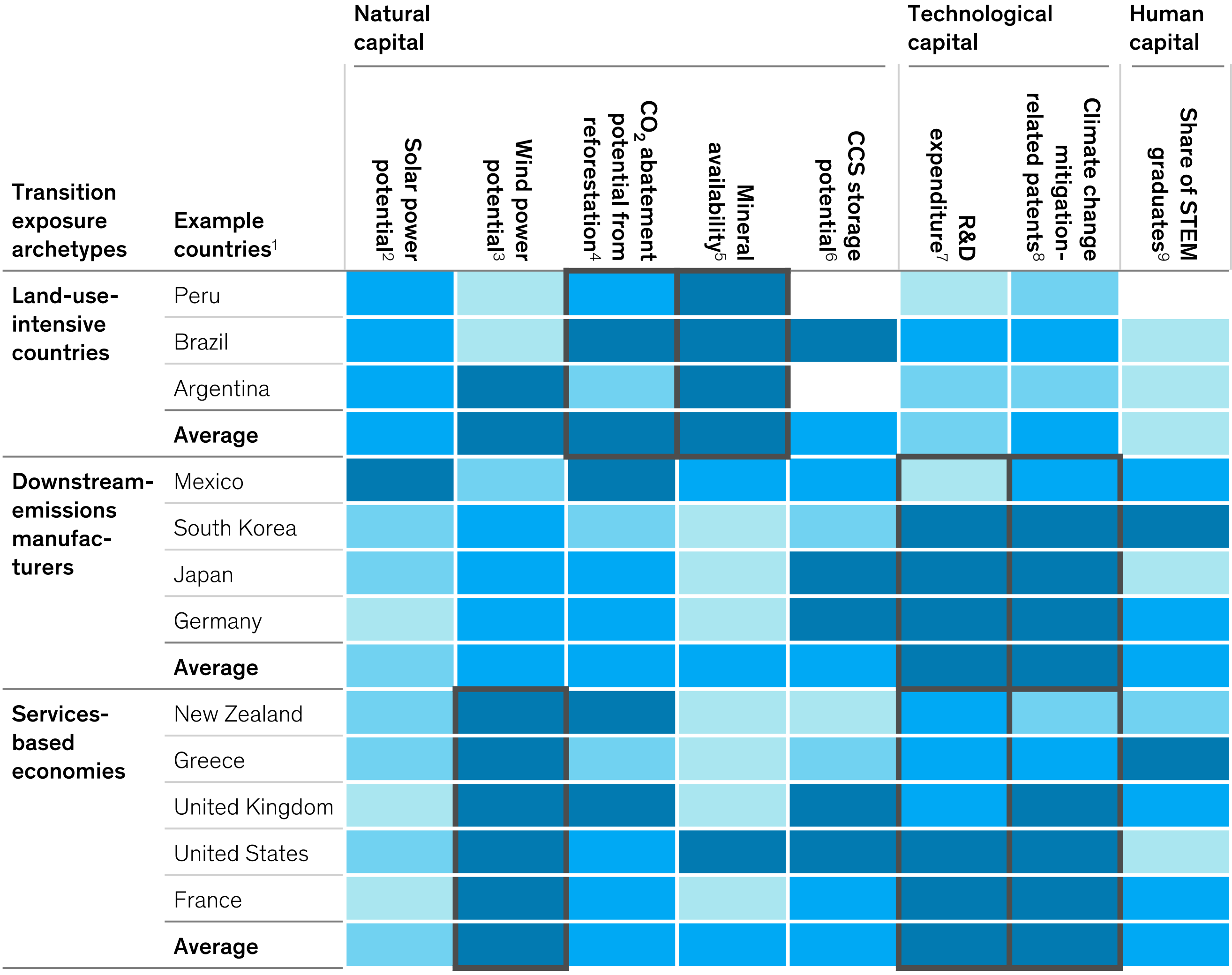
Various factors could provide countries with potential opportunities during the net-zero transition. (2 of 2)

Not exhaustive

Exposure Less advantageous ⟷ More advantageous

Quartile ▢ Below 1st ▢ Between 1st and 2nd ▢ Between 2nd and 3rd ■ Above 3rd ☐ No data

☐ Type of capital most relevant to archetype



		Natural capital					Technological capital		Human capital
Transition exposure archetypes	**Example countries**[1]	**Solar power potential**[2]	**Wind power potential**[3]	**CO_2 abatement potential from reforestation**[4]	**Mineral availability**[5]	**CCS storage potential**[6]	**R&D expenditure**[7]	**Climate change mitigation-related patents**[8]	**Share of STEM graduates**[9]
Land-use-intensive countries	Peru	Between 2nd and 3rd	Below 1st	Between 2nd and 3rd	Above 3rd	No data	Below 1st	Between 1st and 2nd	No data
	Brazil	Between 2nd and 3rd	Below 1st	Above 3rd	Above 3rd	Above 3rd	Between 2nd and 3rd	Between 2nd and 3rd	Below 1st
	Argentina	Between 2nd and 3rd	Above 3rd	Between 1st and 2nd	Above 3rd	No data	Between 1st and 2nd	Between 1st and 2nd	Below 1st
	Average	Between 2nd and 3rd	Above 3rd	Above 3rd	Above 3rd	Between 2nd and 3rd	Between 1st and 2nd	Between 2nd and 3rd	Below 1st
Downstream-emissions manufac-turers	Mexico	Above 3rd	Between 1st and 2nd	Above 3rd	Between 2nd and 3rd	Between 2nd and 3rd	Below 1st	Between 2nd and 3rd	Between 2nd and 3rd
	South Korea	Between 1st and 2nd	Between 2nd and 3rd	Between 1st and 2nd	Below 1st	Between 1st and 2nd	Above 3rd	Above 3rd	Above 3rd
	Japan	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd	Below 1st	Above 3rd	Above 3rd	Above 3rd	Below 1st
	Germany	Below 1st	Between 2nd and 3rd	Between 2nd and 3rd	Below 1st	Above 3rd	Above 3rd	Above 3rd	Between 2nd and 3rd
	Average	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd	Between 2nd and 3rd	Between 2nd and 3rd	Above 3rd	Above 3rd	Between 2nd and 3rd
Services-based economies	New Zealand	Between 1st and 2nd	Above 3rd	Above 3rd	Below 1st	Below 1st	Between 2nd and 3rd	Between 1st and 2nd	Between 1st and 2nd
	Greece	Between 1st and 2nd	Above 3rd	Between 1st and 2nd	Below 1st	Between 1st and 2nd	Between 2nd and 3rd	Between 2nd and 3rd	Above 3rd
	United Kingdom	Below 1st	Above 3rd	Above 3rd	Below 1st	Above 3rd	Between 2nd and 3rd	Above 3rd	Between 2nd and 3rd
	United States	Between 1st and 2nd	Above 3rd	Between 2nd and 3rd	Above 3rd	Above 3rd	Above 3rd	Above 3rd	Below 1st
	France	Below 1st	Above 3rd	Between 2nd and 3rd	Below 1st	Between 2nd and 3rd	Above 3rd	Above 3rd	Between 2nd and 3rd
	Average	Between 1st and 2nd	Above 3rd	Between 2nd and 3rd	Between 2nd and 3rd	Between 2nd and 3rd	Above 3rd	Above 3rd	Between 2nd and 3rd

1. Average rows within each archetype are based on a simple average of every country within that archetype, both those shown in rows and other countries in the archetype. For fossil-fuel resource producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, and Uruguay; for downstream-emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland.
2. Power output achievable by a typical utility-scale PV system, taking into account global horizontal irradiation (or the total solar radiation that reaches a horizontal surface), the air temperature affecting the system performance, the system configuration, shading and soiling, and topographic and land-use constraints.
3. Mean wind power density of 10% windiest areas at a height of 100m. Calculated by downscaling large-scale forecasting data from the European Centre for Medium-Range Weather Forecasts. These data are then entered into the DTU Wind Energy modeling system to model local wind climates for a 250m grid across the globe measured as watt per square meter.
4. Abatement potential is calculated using biophysical filters to identify reforestation opportunities on all land areas suitable for reforestation. Specific carbon-sequestration rates that correspond to different opportunities are then applied to estimate the total abatement potential measured as tonnes of CO_2 per kilometer squared per year.
5. Average of the ratios of proven reserves in a country to global production across 6 minerals. Includes cobalt, copper, lithium, nickel, zinc, and rare earths.
6. CCS (carbon capture and storage) Storage Indicator, a metric based on three factors: natural geological storage potential, maturity and confidence of storage resource assessments, and experience in CO_2 storage project development to date.
7. Primary government expenditures as a proportion of original approved budget.
8. Number of patents filed in a country for technologies related to climate-change mitigation.
9. Tertiary-level graduates in a country that graduates in natural sciences, mathematics, and statistics, as a share of all graduates.

Note: Colors in each column based on relative quartiles within each column rather than across columns. Countries are allocated to an archetype to illustrate specific types of capital that they possess. However, any given country could also have access to some of the forms of capital highlighted for other archetypes.

Source: Global Solar Atlas; Global Wind Atlas; US Geological Survey; McKinsey Nature Analytics; Bastin et al., 2019; Cook-Patton et al., 2020; Global CCS Institute, 2018 CCS-SI update; World Bank; OECD; ILOSTAT; McKinsey Global Institute analysis

Exhibit 29

Countries are exposed to physical climate risks, in addition to the effects of the net-zero transition. (1 of 2)

Based on RCP 8.5[1]

■ High risk increase
◧ Moderate risk increase
□ No or slight risk increase
░ Risk decrease/no data

				Livability and workability			Food systems	Physical assets/ infrastructure services	Natural capital
Transition exposure archetypes	**Example countries**[1]	**Physical risk archetype**[1]	**Change in… (2018–50, pp)**	Share of population that lives in areas experiencing a nonzero annual probability of lethal heat waves[2]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate- exposed regions	Water stress[3]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[4]	Share of land surface changing climate classification
Fossil fuel resource producers	Qatar	Hotter and more humid		░	░	░	░	░	░
	Nigeria	Significantly hotter and more humid		■	■	░	□	□	□
	Saudi Arabia	Hotter and more humid		□	■	░	░	□	□
	Russia	Lower risk		□	◧	□	░	◧	■
	Canada	Lower risk		□	◧	░	░	■	■
Emissions-intensive producers	Vietnam	Significantly hotter and more humid		■	■	░	□	◧	■
	India	Significantly hotter and more humid		■	■	░	░	◧	■
	China	Diverse climate		■	◧		□	■	■
	Ukraine	Increased water stress		□	◧	■	■	■	■
	Indonesia	Hotter and more humid		□	■	░	□	■	□
Agriculture-based economies	Kenya	Hotter and more humid		□	◧	░	░	◧	■
	Ghana	Significantly hotter and more humid		◧	■	░	□	◧	◧
	Sri Lanka	Significantly hotter and more humid		░	░	░	░	░	░
	Senegal	Significantly hotter and more humid		◧	■	□	□	□	□

1. RCP 8.5 = Representative Concentration Pathway 8.5. Our research on physical climate risk uses the RCP 8.5 scenario of greenhouse gas concentration because the higher-emissions scenario it portrays enables us to assess the inherent physical risk from climate change in the absence of adaptation and decarbonization actions. For fossil fuel resource producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Malaysia, Panama, and Uruguay; for downstream-emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland. For details on physical risk archetypes, see *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.
2. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
3. Water stress is measured as annual demand for water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
4. Risk values are calculated based on expected values, ie, probability-weighted value at risk.

Source: Woodwell Climate Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020; McKinsey Global Institute analysis

Exhibit 29 (continued)

Countries are exposed to physical climate risks, in addition to the effects of the net-zero transition. (2 of 2)

Based on RCP 8.5[1]

■ High risk increase
▩ Moderate risk increase
▨ No or slight risk increase
□ Risk decrease/no data

			Livability and workability			Food systems	Physical assets/infrastructure services	Natural capital
Transition exposure archetypes	**Example countries[1]**	**Physical risk archetype[1]**	**Change in… (2018–50, pp)** Share of population that lives in areas experiencing a nonzero annual probability of lethal heat waves[2]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions	Water stress[3]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[4]	Share of land surface changing climate classification
Land-use-intensive countries	Honduras	Hotter	▨	■	▨	▨	▨	▨
	Peru	Lower risk	▨	▨	□	▨	▨	■
	Brazil	Diverse climate	▨	■	▨	▩	▩	▩
	Argentina	Diverse climate	▨	▩	□	▨	■	■
Downstream-emissions manufacturers	Mexico	Increased water stress	▨	▩	■	▨	■	■
	South Korea	Hotter	▨	▩	▩	▨	▩	■
	Japan	Hotter and more humid	▨	▩	□	▨	■	■
	Germany	Lower risk	▨	▩	▨	▨	▩	■
Service-based economies	New Zealand	Lower risk	▨	▨	□	▨	▩	▩
	Greece	Increased water stress	▨	▩	■	▨	▨	■
	United Kingdom	Lower risk	▨	▨	□	▨	■	▩
	United States	Diverse climate	▨	▩	■	▨	■	■
	France	Lower risk	▨	▩	▨	▨	■	■

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1. RCP 8.5 = Representative Concentration Pathway 8.5. Our research on physical climate risk uses the RCP 8.5 scenario of greenhouse gas concentration because the higher-emissions scenario it portrays enables us to assess the inherent physical risk from climate change in the absence of adaptation and decarbonization actions. For fossil fuel resource producers, other countries include Australia, Bahrain, Egypt, Kuwait, Norway, Oman, UAE, and Venezuela; for emissions-intensive producers, Bangladesh, Pakistan, South Africa, Thailand, and Turkey; for agriculture-based economies, Morocco and the Philippines; for land-use-intensive countries, Bolivia, Chile, Colombia, Costa Rica, Ecuador, Malaysia, Panama, and Uruguay; for downstream-emissions manufacturers, Austria, Bulgaria, Czech Republic, Hungary, Italy, Poland, Romania, Slovakia, and Sweden; and for services-based economies, Belgium, Denmark, Finland, Ireland, Israel, Netherlands, Portugal, Singapore, Spain, and Switzerland. For details on physical risk archetypes, see *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.
2. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
3. Water stress is measured as annual demand for water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
4. Risk values are calculated based on expected values, ie, probability-weighted value at risk.

Source: Woodwell Climate Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020; McKinsey Global Institute analysis

Workers face exposure, too. Agriculture workers make up a large share of the workforce in these countries. They would be affected in the net-zero scenario as agriculture practices shift toward low-emissions farming and production shifts from livestock and feed to other goods. These changes would be particularly challenging for small subsistence farmers who are likely to lack access to the information, technical know-how, working capital (such as short-term loans), and investment capital (long-term loans) that could help them during the transition. Finally, many countries in this archetype could be substantially affected by rising physical risks. India, for example, could become hotter, more humid, and more flood-prone in a scenario where emissions are not abated.

Countries in this archetype could also benefit from the growth potential of a net-zero transition, according to our analysis. Overall, many are expected to experience faster economic growth than more developed economies and would invest in capital stock, such as power capacity. For example, as discussed above, spending to decarbonize and support growth in India could be as high as 11 percent of GDP over the next three decades. While the scale of spending is high, choosing to install low-emissions assets, such as renewables-based power, could help minimize stranded-asset risk and offer opportunities to leapfrog to new technologies that can come with lower operating costs. More broadly, such spending would also create near-term job opportunities, for example associated with the construction sector.

Innovation opportunities could be available to some emissions-intensive producers; for example, some 39 percent of graduates in China are STEM specialists. Asian countries—many of which are included in this archetype—more broadly possess technological resources that could be conducive to low-emissions innovation. The region accounts for almost half of global R&D spending and over the last decade has produced the largest share of global growth in technology metrics such as patents filed, tech company revenue, and venture capital funding.[288]

Many of these countries possess rich mineral deposits. For example, countries like China and Vietnam have reserves more than ten times larger than current annual global production of certain rare-earth metals that will be important for manufacturing low-emission technologies. Some countries in this group have high reforestation- and afforestation-abatement potential, which gives them a chance to attract the capital spending necessary, through carbon-offset markets, to produce negative emissions. Indonesia, for example, could abate 34 tCO_2 per square kilometer of land.

Agriculture-based economies

For the countries in this group, including Ghana, Kenya, Morocco, the Philippines, Senegal, and Sri Lanka, agriculture is the primary source of employment and income for much of the population. The agriculture and forestry sectors together account for as much as 54 percent of jobs, 29 percent of GDP, and 24 percent of capital stock for countries in this archetype. The result is fairly high transition-exposure scores, given the need to reduce the agriculture sector's significant emissions, through both low-emissions farming practices and potentially adapting the sector's production mix to fulfill changing local and global demands for food and crop-based fuel. Almost all countries in this group are also exposed to physical climate risk, which would subject their agricultural workforce to increased heat and humidity under warming scenarios. In addition, physical climate changes affect agricultural output, because higher temperatures and shifts in precipitation patterns cause increasingly variable crop yields.[289] Total emissions for these countries tend to be relatively low, on average 1.3 tCO_2 per capita versus a global average of 5.8 tCO_2 per capita.[290] Consumer emissions from driving, heating, and cooking are also relatively low, at 0.2 tCO_2 per capita on average versus 1.1 tCO_2 per capita for the other countries in our analysis. While relatively low today, it is important to ensure that future economic growth can be secured through a low-emissions footprint, if the world is to achieve net-zero emissions.

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[288] *Climate risk and response in Asia,* McKinsey Global Institute, November 2020.

[289] *How will African farmers adjust to changing patterns of precipitation?* McKinsey Global Institute, May 2020.

[290] International aviation and shipping emissions are included in the global per capita emission calculation; data from EDGAR v5.0; population data for the per capita calculation from *World Population Prospects,* United Nations, Department of Economic and Social Affairs, Population Division, 2019.

Our analysis suggests that for countries with significant agriculture sectors, a net-zero transition would require a broad shift to low-GHG farming practices. Prior McKinsey research has identified a set of proven technologies and practices, which are already being deployed. They include electrification of farm equipment, manure management, the use of animal feed that cuts methane emissions, and reduced fertilizer usage.[291] Many of these interventions that reduce emissions and increase carbon sequestration have the additional benefit of lower operating costs (for further details, see chapter 3), and improving resilience to physical climate changes, in turn leading to other benefits. For example, interventions such as agroforestry and improving the quality of inputs like seeds and fertilizers can help increase productivity and can lead to a sharp decline in deforestation and raise incomes.[292]

Scaling these practices across countries in this archetype will require significant capital spending and a concerted effort to reach millions of smallholder farmers. This capital spending will be needed to improve farmer access to high-quality inputs and improved farm technologies (such as electric farm equipment). Providing farmers with relevant skills and training will also be required to sustainably increase yields while simultaneously reducing emissions.[293] For countries in this archetype, capital constraints may make it challenging to fund interventions that increase resilience to physical climate change, decarbonize the agriculture sector, and boost economic growth at the same time.

The net-zero transition presents other opportunities for countries in this archetype. When compared to the Current Policies scenario, the NGFS Net Zero 2050 scenario sees increased global demand for lower-emissions food sources, such as poultry, legumes, soybeans, and nuts, leading to new jobs and opportunities for farmers. Other sources of growth may be outside the agricultural sector altogether. For example, all countries belonging to this archetype are located in areas with high levels of solar irradiance: on average, they have a theoretical solar potential of more than five kWh per square meter of land per day. Scaling up solar energy generation capacity therefore represents a significant opportunity.[294] Some countries also have relatively high abatement potential from reforestation and afforestation. Sri Lanka, for example, has abatement potential of 42 tCO_2 per square kilometer of land, per year.

As with some other archetypes, these countries are expected to invest substantially in new assets as they grow their economies; this offers the potential to leapfrog and build out low-emissions assets. Countries in sub-Saharan Africa, for example, would need to spend slightly more than 10 percent of GDP over the next decade in the NGFS Net Zero 2050 scenario.

Land-use-intensive countries

This group includes Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Honduras, Malaysia, Panama, Peru, and Uruguay, the economies of which depend, in large part, on their natural capital.[295] Agriculture and forestry account for significant shares of their GDP (8 percent on average), jobs (15 percent on average, and almost 30 percent in countries such as Bolivia, Ecuador, and Honduras), and capital stock (6 percent). The contribution of other sectors such as fossil fuel production, power, and industry to GDP, jobs, and capital stock is also sizable in some countries in the archetype. The agriculture and forestry sectors also present opportunities, as mentioned below.

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[291] Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, “Agriculture and climate change: Reducing emissions through improved farming practices,” McKinsey & Company, April 2020.

[292] *Socio-technical innovation bundles for agri-food systems transformation,* Cornell Atkinson Center for Sustainability, 2020.

[293] See, for example, *World Resources Report: Creating a sustainable food future,* World Resources Institute, 2019; and *Growing better: Ten critical transitions to transform food and land use,* Food and Land Use Coalition, 2019.

[294] Lynn Bouchene, Ziyad Cassim, Hauke Engel, Kartik Jayaran, and Adam Kendall, “Green Africa: A growth and resilience agenda for the continent,” McKinsey & Company, October 28, 2021.

[295] Large and diversified economies like Brazil could also face some of the transition exposure we have highlighted for other archetypes, as previously noted.

Changes to land use would have a key effect on these countries under the Net Zero 2050 scenario, as these countries would need to curb deforestation or regulate the use of their existing forest area to lessen their CO_2 emissions. Reducing deforestation and practicing reforestation and afforestation could produce valuable carbon credits for sale in international markets. Forest protection and restoration would also affect forest-border communities, where livelihoods depend on the use of forestland. Options to consider for lessening the socioeconomic effects include supporting economic diversification, which could encompass developing activities associated with sustaining forests (see chapter 3 for further details).

The agriculture sectors and workforces of these countries would also be affected. As with agriculture-based economies, a net-zero transition would involve mass adoption of low-emissions agricultural practices, along with associated capital investments. Farmers could benefit as demand increases under a net-zero transition for low-emissions crops, such as cassava and sweet potato, some of which are cultivated extensively in these countries. Countries like Brazil, with a relatively large fossil resource sector, would also be affected by some of the issues described for that archetype.[296]

Countries in this archetype have options beyond forestry and other land use for deriving value from their natural capital in the Net Zero 2050 scenario. Most have significant solar potential, and some including Argentina have wind potential. Many of these countries are also endowed with the minerals that would be in demand under the net-zero scenario; Argentina, Brazil, Chile, and Peru, for example, each have reserves greater than the current annual global production for certain minerals or rare-earth metals that will be important for manufacturing low-emission technologies.

Downstream-emissions manufacturers

Countries in this archetype include Austria, Bulgaria, the Czech Republic, Germany, Hungary, Italy, Japan, Mexico, Poland, Romania, Slovakia, South Korea, and Sweden. The phrase “downstream emissions” refers to the quantities of CO_2 that are emitted during the use of the goods these countries specialize in making. These goods include transportation equipment (for example, vehicles, vehicle components, and airplanes), industrial machinery (for example, kilns used in steelmaking and industrial boilers used in coal power), and household appliances (for example, gas stoves and gas boilers).

For the average country in this group, the manufacturing of high-emissions products accounts for about 7 percent of jobs, 9 percent of GDP, and 8 percent of capital stock, and it also supports wider economic activity and exports. Our analysis shows that most countries in this group have transition-exposure scores in the middle of the overall range.

In the Net Zero 2050 scenario, demand would shift toward products that emit less carbon when used. As a result, the manufacturing sectors in these countries could be exposed. Some automakers in these countries have begun preparing for this type of shift. A major transitional task for these countries in the net-zero scenario would likely be moving toward the manufacture of low-emissions products, reconfiguring supply chains, and reskilling the labor force. The effects could extend beyond the sectors directly touched by the transition. For example, Germany’s motor vehicle manufacturing sector provides approximately two indirect jobs for every direct job. Motor vehicles account for about 16 percent of Germany’s export value.[297]

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[296] Brazil is an example of a country for which the net-zero transition will have broader implications beyond its categorization in the land-use-intensive archetype. Its economy is one of the ten largest in the world. It also has a well-developed and diversified industrial sector, and its agricultural sector is a top global producer of some commodities, including soybeans and beef. Land-use change and agriculture account for about 50 percent of its emissions, while transportation represents about 20 percent and industry about 20 percent. For further details, see, for example, *Ensuring greener economic growth for Brazil,* Climate Policy Initiative, December 2018.

[297] Federal Statistical Office of Germany.

Some countries in this group also face another sort of exposure: a substantial share of their manufacturing activity is in sectors with high-emissions operations, such as steel and cement. Their emissions-intensive manufacturers would need to adopt low-emissions processes or retrofit existing machinery and equipment during the net-zero transition.

Most of the growth potential for countries in this archetype would likely come from their technological capital, our analysis shows. They generally have high levels of R&D expenditure (an average of about 2 percent of GDP—almost double that of countries in other archetypes) and intellectual property associated with climate-change mitigation (an average of about 1,700 relevant patents per country versus an average of about 450 for other countries). Their technical resources could allow these countries to redesign products and reengineer industrial operations for a net-zero future.

Services-based economies

Countries including Belgium, Denmark, Finland, France, Greece, Ireland, Israel, the Netherlands, New Zealand, Portugal, Singapore, Spain, Switzerland, the United Kingdom, and the United States have diversified economies oriented toward services sectors. Since these sectors have relatively low exposure to the net-zero transition, the overall transition exposure of these countries is also low. For the countries in this group, exposed sectors, on average, account for just 22 percent of jobs (versus 42 percent for the rest), 24 percent of GDP (versus 38 percent for the rest), and 21 percent of capital stock (versus 38 percent for the rest). Some countries in this category, such as the United States, also have midsize fossil fuel resource sectors and downstream-emissions manufacturing sectors (about 2 to 3 percent of GDP).

While the aggregate economic exposure of these countries may be less than in other archetypes, communities that depend on exposed sectors could be disproportionately exposed under a net-zero transition. As previously noted, more than 10 percent of jobs in 44 US counties are in the coal, oil and gas, fossil fuel power, and automotive sectors.[298]

According to our analysis, services-based economies are likely to experience shifts at the consumer level in the Net Zero 2050 scenario because they have high consumer emissions per capita (on average, around 12 tCO_2 per capita versus about 6 tCO_2 per capita for the rest). For households, this could mean adopting behavioral changes and spending more up-front on low-emissions goods including EVs.

These countries could have promising opportunities related to low-emissions energy, especially wind. Their top-decile land areas for windiness have an average potential of 850 W/m2, compared with an average of about 580 W/m2 for top-decile areas in other countries. Some countries within the group that do not have as high wind potential, such as Israel, nevertheless have high solar potential. Services-based economies also have rich stocks of technological capital—their average R&D spend is about 2.3 percent of GDP, compared with about 1 percent for other countries, and their average number of patents related to climate-change mitigation is about 1,100, compared with about 550 for the rest. They can also provide services, such as financial or information services, in support of the transition.

Countries are exposed to the net-zero transition in highly uneven ways, in both the challenges they face and the opportunities they could seek to capture. Mapping these differences can help stakeholders understand where they may need to intervene to minimize risks and maximize their advantages. As we describe in the next chapter, global action, resolve, and unity would likely be needed to support economic and societal adjustments.

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[298] "Quarterly census of employment and wages," US Bureau of Labor Statistics.

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5. Managing the transition

As this report has shown, the economic transformation required to reach the goal of net-zero emissions by 2050 is both universal and significant in scale, and it will be felt unevenly across sectors and countries. These characteristics of the transformation in turn raise major challenges for public- and private-sector leaders as they look to support an orderly transition, capture opportunities, and mitigate risks.

Many of these adjustments can be best supported through coordinated action involving governments, businesses, and enabling institutions, and extending planning and investment horizons. This action would need to be taken in a spirit of unity for two key reasons: first, the universal nature of the transition means that all stakeholders will need to play a role. Every country and sector contributes to emissions either directly or indirectly through its role in global production and consumption systems. Second, the burdens of the transition will not be evenly felt, and the costs will be much more difficult for some stakeholders to bear than others. This is all the more challenging because contributions to emissions have not been even across stakeholder groups. Thus stakeholders would need to approach the transition with singular unity, resolve, and ingenuity.

In this final chapter, we review potential actions to manage the transition that leaders may want to consider. We first highlight broad areas of action to support adjustments to the transition. While these may not be exhaustive, they provide stakeholders with an overview of the range of actions which could be considered to enable the economic and societal adjustments that will be needed. We then examine how these broad actions could be undertaken by specific groups of stakeholders: companies, financial institutions, governments, enabling institutions, and individuals. In undertaking these and other actions, they will need to consider both risks and opportunities to their organizations and their stakeholders and determine the role they can play in supporting the necessary adjustments for all.[299]

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[299] The actions described in this section specifically relate to the economic and societal adjustments needed for the transition, given the scope of this research. An effective response to climate change more broadly, we believe, will involve not only making economic and societal adjustments to deal with the effects of the net-zero transition, but also meeting the other fundamental requirements described in previous chapters. We identify seven categories of actions. Leaders can understand and commit to the transition, including understanding the fundamentals of climate science and the transition and making personal and professional commitments; assess and plan their actions, including through building risk assessment capabilities and establishing decarbonization plans; reduce and remove emissions in accordance with these plans; conserve and regenerate natural capital to support decarbonization; adapt and build resilience to manage the physical risk that is already locked in; reconfigure and grow, for example by reallocating capital and ramping down high-carbon businesses while scaling low-carbon ones; and seek to engage and influence their communities, across their investors, customers, suppliers, peers, and regulators. While the actions described in this chapter are specific to the economic and societal adjustments needed for the transition, they fall into the various categories listed above. For further details, see Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.

Three broad economic and societal adjustments will be needed to support the net-zero transformation

We describe potential actions with respect to the three types of economic and societal adjustments discussed in this report: effective capital reallocation and new financing structures, management of demand shifts and near-term unit cost increases, and compensating mechanisms to address socioeconomic impacts.

Catalyzing effective capital reallocation and new financing structures. As discussed, the net-zero transition will require both an increase in capital spending on low-emissions assets and the reallocation of capital from high-emissions assets to low-emissions assets. Several measures could help accelerate capital allocation, as follows:

— *Scaling up climate finance.* Many public and private financial institutions have committed to net-zero emissions and to funding activities that are integral to the net-zero transition. Significantly more financing will be needed. This could come from both traditional financial instruments and more specialized instruments such as green bonds, as discussed below. Partnerships between financial institutions and real-economy stakeholders can help marshal financing as well.

— *Developing new financial instruments and products.* New financial products and structures can help companies wind down legacy assets and scale up new low-emissions assets. Among the possible solutions are special-purpose vehicles which enable companies to ring-fence legacy assets with high emissions and retire them in line with a net-zero pathway. They could also develop financing structures such as long-term purchase agreements from low-emissions plants, which have lower total life-cycle costs, to replace coal-generation assets, as well as new financial instruments, for example, for negative emissions or for nature-based solutions.

— *Cultivating voluntary carbon markets.* Developing and scaling voluntary carbon markets in the near term and compliance markets in the longer term could play a role in financing the transition. Carbon credits could become an important vehicle for financing the net-zero transition, to complement company efforts to decarbonize their operations. They could, for example, help channel capital to forest-rich developing countries where there is potential to prevent deforestation or plant new forests. Voluntary carbon markets would include markets both for avoidance credits (for example, to prevent forests from being cut down) and for removal credits (for example, from afforestation or direct air capture). For this to happen at scale, the world will need to build voluntary carbon markets that are large, transparent, verifiable, and environmentally robust.[300] The Taskforce on Scaling Voluntary Carbon Markets has estimated that demand for carbon credits could increase by a factor of 15 or more by 2030 and by a factor of up to 100 by 2050, and that the market for carbon credits could be worth upward of $50 billion in 2030.[301]

— *Pricing externalities to rebalance incentives.* Governments might consider how various policies where organizations pay for their emissions could encourage capital spending in emissions-reduction projects. Carbon pricing could also generate revenue that governments might use to support the transition.

— *Backstopping low-carbon investment and scaling up public finance.* Public authorities or private companies could consider assuming some of the risk of investing in low-carbon projects so that investors will be more likely to finance them, through public guarantees or other risk hedges. This can help support capital flows to sectors and geographies with large financing gaps. Public finance on a national and global scale could be used to fund

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[300] *Final report,* Taskforce on Scaling Voluntary Carbon Markets, January 2021.

[301] Ibid.

key infrastructure investment that provides positive impacts but may be more difficult to finance through markets (for example, EV charging stations, hydrogen fueling stations, and carbon sequestration).

- *Funding the repurposing or decommissioning of redundant assets.* Various options are available to organizations that wish to hasten the retirement of redundant assets. One proposed mechanism to accelerate the decommissioning of coal-fired power plants would involve purchasing plants so that they can be retired ahead of schedule, and then having the owners invest the proceeds in low-emissions energy projects.[302] Multilateral or government funds could be used to manage the ramping down of emitting assets and minimize the value at risk from stranded assets.

Managing demand shifts and near-term unit cost increases. Our analysis suggests that demand for certain goods will change during the transition, along with companies' capital and operating expenditures. Interventions on both the supply side and the demand side could help mitigate these effects.

- *Building awareness and transparency around climate risks and opportunities.* As organizations navigate the net-zero transition, they stand to benefit from identifying the risks and opportunities associated with physical climate hazards and transition impacts. Formal efforts to gauge climate risks are expanding. Among others, financial regulators including the Bank of England and the European Central Bank are mandating climate-risk stress tests for financial institutions.[303]
- *Anticipating future competitive dynamics and making adjustments.* As the basis of competition is altered, companies may need to overhaul their portfolios and business models and to identify new areas of opportunity from a net-zero economy. Governments would similarly need to consider exposure of their economies to the transition, as well as opportunities to benefit.
- *Lowering technology costs with R&D.* Some existing technologies that will be needed to achieve a net-zero economy by 2050 are not yet cost competitive with entrenched high-carbon technologies. Technology gaps remain. Investment in R&D can help bring down technology costs, and various support models exist. In the United States, for example, the Department of Energy's National Laboratories partner with private companies to drive R&D.[304]
- *Nurturing industrial ecosystems.* To produce low-carbon technologies at a cost that permits their broad uptake, companies may need to develop capabilities through partnerships that are not part of existing value chains or through new business ecosystems. Governments can consider the role they might play in creating policy environments that are conducive to the formation and functioning of such ecosystems.
- *Identifying measures to manage cost increases.* Organizations can identify a range of compensating mechanisms in cases where decarbonization actions increase costs and can understand which measures work best under different sets of circumstances and constraints. Examples include identifying opportunities to distribute the impact of cost increases along the value chain, partnering with suppliers to lower costs, and, where feasible, charging consumers a "green premium" or otherwise including this as part of the value proposition.
- *Sending demand signals and creating incentives.* Markets for emerging and still-expensive low-emissions technologies are often too small and unpredictable for manufacturers to achieve economies of scale. Interventions to lift demand can lessen market risk and create the long-term certainty that encourages manufacturers to add production capacity.

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[302] See, for example, Donald P. Kanak, *For health and climate: Retiring coal-fired electricity and promoting sustainable energy transition in developing countries,* Program on International Financial Systems, August 2020.

[303] See *The 2021 biennial exploratory scenario on the financial risks from climate change,* Bank of England discussion paper, December 2019; and Luis de Guindos, "Shining a light on climate risks: The ECB's economy-wide climate stress test," European Central Bank blog, March 18, 2021.

[304] See Hal Harvey, *Designing climate solutions: A policy guide for low-carbon energy,* Island Press, 2018.

Establishing compensating mechanisms to address socioeconomic impacts. The uneven impacts of the net-zero transition could be substantial and prove to be a major stumbling block if stakeholders feel that they are not protected from risk or given support in pursuing opportunities. The public and private sectors could consider taking the following measures to help enable adjustment to uneven impacts.

— *Supporting economic development and diversification.* Geographies could develop new low-emissions industries as demand wanes for fossil fuels and carbon-intensive industries. Some countries possess the natural capital to do so, for example, forest-rich countries that can promote reforestation to sequester carbon, create jobs, and secure financial inflows.[305] Others will want to consider options for developing the technological, human, and physical capital to create these new sectors.

— *Enabling reskilling and redeployment of workers.* Retraining workers for new tasks and ensuring that new entrants into the workforce have the right skills for the jobs needed in a low-carbon economy can help promote an inclusive transition.

— *Instituting support schemes (including insurance) for workers and consumers.* Options for aiding displaced workers include income-support measures like unemployment protection and cash transfers, which can provide support while workers retrain and find jobs. Subsidies and other programs could also help consumers, especially low-income households, if the transition brings higher up-front capital expenditures or higher energy prices.

Stakeholders can play unique roles in supporting transition adjustments

To meet the challenges of the net-zero transformation, both the public and the private sectors would need to accelerate fundamental shifts in capabilities, cooperative models, and enabling institutions that span sectors and nations. Below, we summarize some of the roles that stakeholders in various groups can play to help foster a more orderly transition.

Companies can consider integrating climate considerations into their strategies and decision-making frameworks

Companies have begun to develop comprehensive plans for achieving net-zero emissions and to integrate those plans into their strategies, combining elements of what might be called “offense” (such as entering new markets, funding R&D, or participating in innovation ecosystems) and “defense” (divesting businesses or retrofitting high-emissions assets to lower their emissions). Here are some practices that companies can consider in order to help drive their organizations toward net-zero goals while also supporting broader economic and societal adjustments.

Articulating and communicating a coherent case for change, and upskilling employees. This will require a clear message from upper and middle management, with the CEO taking visible ownership and accountability for the sustainability agenda and the chief sustainability officer assuming an ever-broader mandate. Leaders will need to internalize the fundamentals of climate science and economics so they can understand both the imperative for the net-zero transition and its effect on their constituencies.

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[305] McKinsey & Company and the World Economic Forum estimate that this reforestation solution could potentially generate emission reductions of about 7 $GtCO_2$ per year by 2030. See Daniel Aminetzah, Emily Birch, Julien Claes, Joshua Katz, Peter Mannion, Sebastien Marlier, and Dickon Pinner, “Why investing in nature is key to climate mitigation,” McKinsey & Company, January 2021.

Developing ongoing capabilities to make granular, holistic, and dynamic assessments of transition-related risks and opportunities. Companies in every industry will be exposed, to some degree, to risks and opportunities resulting from the net-zero transition. To stay abreast of developments related to climate change, organizations will likely need new and lasting capabilities to quantify their exposure and consider opportunities, data, infrastructure, and talent. Companies will benefit from developing the ability to conduct scenario-based modeling exercises that offer a probabilistic view of potential outcomes and their variations across sectors and geographies. Analytical models will need to encompass physical risks, the transition's socioeconomic impacts, and competitive shifts. Companies may also want to benchmark exposure and opportunities in their direct operations as well as their supply chains, distribution channels, and broader business ecosystems relative to peers. Momentum has been growing toward public disclosures of information about climate risk, which could support both benchmarking efforts and effective capital allocation. In 2017, for example, the Task Force on Climate-Related Financial Disclosures published detailed recommendations to help companies provide better climate-related information on four topics central to their operations: governance, strategy, risk management, and metrics.[306] A key part of this will also be better tracking of scope 1, 2, and 3 emissions, including through the use of digital tools to increase transparency of emissions in companies' own operations and in their supply chains.

Defining and evolving decarbonization plans as the competitive, financial, and regulatory landscape moves. This would include scope 1 and 2 emissions (with priority given to "no regret" actions such as improving energy efficiency and investing in decarbonization with positive returns). Where feasible, material, and needed, and depending on the nature of their operations, businesses can expand these plans to include scope 3 emissions. Such plans would encompass both operational transformations, including supported by digital technologies, and the decommissioning or repurposing of assets. Numerous steel producers, for example, are planning green-hydrogen and carbon-capture projects in line with goals to achieve net-zero emissions by 2050 or earlier.[307]

Creating a portfolio of agile business strategies consistent with these decarbonization plans and with the risks and opportunities emerging in a net-zero economy. Companies can then put these plans in place as conditions change and opportunities arise. Repositioning for the net-zero economy could involve transformative changes such as investing in new physical assets, redesigning products, building new low-emissions businesses, revamping production processes, adjusting supply chains, reskilling workforces, and forming new partnerships. For example, some traditional automotive OEMs have announced plans to scale up production of electric vehicles.[308] Companies will need to be agile as they reposition themselves, to plan for the future based on imperfect information while retaining the ability to dynamically adjust as conditions evolve. Some decarbonization actions, such as installing carbon capture, utilization, and storage equipment, increase operating costs, and affected companies may need to find opportunities to offset these cost increases elsewhere in their value chains.

Integrating climate-related factors into all key business decisions. More broadly, executive teams may need to revisit their day-to-day business decisions and examine how the climate transition will affect decisions about strategy, risk management, finance and capital planning, R&D, product management, operations (including supplier management and procurement), organizational structure and talent management, pricing and marketing, and investor and government relations (Exhibit 30).

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[306] More than 2,600 organizations have expressed support for the task force's framework. Task Force on Climate-Related Financial Disclosures, *2021 status report,* September 2021.

[307] Tim Buckley, "World's biggest steel manufacturers are committing to hydrogen and CCS," *Energy Post,* January 11, 2021; and Dan Gearino, "Inside clean energy: A steel giant joins a growing list of companies aiming for net-zero by 2050," *Inside Climate News,* October 8, 2020.

[308] See, for example, "Volkswagen is accelerating transformation into software-driven mobility provider," Volkswagen, March 5, 2021; and "GM boosts investment, grows electric portfolio to lead in EV race," General Motors, November 2020.

Exhibit 30

A decision-making framework for companies. (1 of 2)

	Business decision	Potential implications of a net-zero transition
Strategy	How should the company achieve growth?	• Growth plans would need to be consistent with a net-zero economy and the organization's own net-zero plans • New opportunities may appear (eg, markets, products, or processes) • Some opportunities may look more risky (eg, products whose use is emissions-intensive, or products with high-emissions manufacturing processes)
	What should the corporate portfolio consist of?	• May become necessary to divest from some businesses, and build or acquire new low- or zero-carbon businesses
	How should the company engage with sector peers?	• Engagement with peers may be necessary to solve shared problems (eg, joint investments, make common commitments, create industry-wide technology road maps)
Risk management	What are the main risks that the company measures and manages?	• New risks may emerge that need to be managed, including – Exposure to physical risks (eg, flooding, storms, heatwaves) may increase across own operations, supply chains, and distribution channels – Transition risks may arise (eg, demand shifts, cost increases), creating new strategic and operational pressures
	How should the company manage major risks?	• Climate risk management requires new processes, analytical tools, and data sources • Risk framework incorporates these new risks and "edge case" scenarios
Finance and capital planning	What should the company's annual capital expenditure budget be (short and long term)?	• Higher capital outlays may be needed in the near term to decarbonize operations or create new products • Pay-off periods for decarbonization investments may be longer in some cases than for other capital expenditures, especially if investments cause operating costs to increase (eg, in hard-to-abate sectors)
	How should the company manage and maintain existing assets?	• High-emissions assets may need to be written off prematurely or written down on an accelerated timeline • Additional capital spending is needed to pay for retrofits of plants and equipment (eg, replacing natural gas as a fuel with hydrogen)
	How should the company obtain financing?	• Capital availability may become contingent on credible net-zero targets and strategies • Cost of capital for high-carbon operations could increase
R&D, product design	How much should the company spend on R&D, and where should it focus this spending to address new opportunities?	• Additional spending on R&D may be required to develop decarbonization solutions, from early-stage discovery through commercialization, in line with the company's growth aspirations
	How should the company measure the effectiveness of its R&D expenditures?	• New metrics are needed to track the effect of R&D spending on emissions reductions, in addition to financial returns from R&D spend
	How can the company design products to increase their appeal, while managing costs?	• Design requirements may need to be expanded to prioritize emissions reductions across the product life cycle and value chain (ie, building a "zero carbon" product)

Source: McKinsey Global Institute analysis

Exhibit 30 continued)

A decision-making framework for companies. (2 of 2)

	Business decision	Potential implications of a net-zero transition
Operations (own and suppliers)	What performance indicators should the company use to track and manage operations?	• Emissions indicators may need to be established as operating metrics, in addition to traditional metrics (eg, cost, productivity, safety) • New data sources and measurement techniques may need to be instituted to track emissions across all operational activities (scopes 1, 2, and 3)
	How can the company achieve efficient and cost-effective operations?	• Own operations may need to be transformed to reduce emissions • Operating costs, including input costs, may change as a result of decarbonization efforts by the company and its suppliers
	How can the company make its own operations and supply chain more resilient?	• Business operation and supply-chain volatility may increase as a result of physical climate risks, and from the climate transition (eg, shortages of key mineral resources, production capacity that may be insufficient to meet rising demand) • Investments may be needed to make own operations and supply chains more resilient to these shocks (eg, raising inventory levels, diversifying suppliers)
	What should the company's sourcing strategy be? How should it interact with suppliers?	• Manufacturing low-emissions products may create a need to work with new suppliers • Closer collaboration with suppliers may become necessary to lower the company's supply-chain emissions
Organizational structure and talent management	How should the company be organized?	• New strategic and operational requirements may call for organizational changes to create accountability, manage trade-offs, should they occur (eg, increased costs vs lower emissions in some cases), and minimize duplicative efforts
	How can the company ensure that it has the right talent to manage the transition ?	• Some hiring decisions would need to include climate-related expertise • Training programs may need to be set up to ensure that people at all levels, including the executive team, can integrate climate considerations into their work
	How should the company align workforce incentives with business priorities?	• As the company puts more climate-related performance indicators in place, achievement of climate priorities may become an integral factor in compensation
Pricing and marketing	How should the company align its product portfolio with customers' needs and preferences?	• Customers may expect more information about emissions associated with products • Customers' preferences may shift toward low- and zero-emissions products
	How should the company price products?	• In some product categories, customers may become willing to pay a "green premium" • Marketing leaders may need to develop a more nuanced understanding of customer segments and willingness to pay for low-emissions products
Investor relations	How should the company engage in dialogue with investors?	• Investors may request disclosures of business plans and targets to reduce emissions and pursue low-emissions growth, along with progress updates • Need to build investor narrative to appropriately engage with them
Government relations	How should the company engage with regulators and policy makers?	• Changing landscape of climate-related regulations would require regular monitoring • Engagement with policy makers can help companies shape effective regulation

Source: McKinsey Global Institute analysis

Considering if and when to take a leadership position in the company's industry and its ecosystem of investors, supply chains, customers, and regulators. In some instances, companies might find it easier to take the actions described above if they work with private- and public-sector organizations that have similar goals. Industry-level groups can help support voluntary commitments and appropriate policy and regulatory changes related to the transition. Businesses can also join forces to help countries, regions, and cities think about the potential impacts of a net-zero transition and how they will manage them. In Houston, Texas, the Greater Houston Partnership business coalition led a study examining approaches to possible shifts in primary-energy sectors, which are at the center of the city's economy.[309]

Financial institutions can support large-scale capital reallocation even as they manage individual risks and opportunities

In the near term, financial institutions will need to consider assessing and disclosing their risks as well as measuring and committing to reduce their financed emissions. Over time, they will need to translate these commitments into actions that lower emissions. Many banks, asset managers, insurers, private-equity firms, and other financial institutions have begun deploying capital in a way that supports the transition. Estimates from the Climate Policy Initiative suggest that public and private actors increased their climate investments in the last decade and global climate finance flows reached about $630 billion in 2019–20, a 70 percent increase since 2011–12.[310] The scale of capital deployment to date, however, falls short of the spending need on physical assets suggested by our analysis of the NGFS Net Zero 2050 scenario. Financial institutions could accelerate capital allocation by more widely adopting the following practices:

Rethinking conventions for risks and returns. Some decarbonization projects are likely to have longer payback periods than the projects that financial institutions and companies are accustomed to funding. This may compel financial institutions to adjust their criteria for which projects they finance—or, as discussed below, partner with other organizations to finance projects in new ways. Banks are also revisiting assumptions about risk as a result of climate change.[311]

Assessing and disclosing climate risks. As noted earlier in this chapter, some regulators now require banks to conduct climate-risk assessments. Based on these assessments, financial institutions could begin to incorporate climate factors into capital allocation, loan approvals, portfolio monitoring, and reporting. Ratings agencies are also incorporating climate factors into their assessments. Expectations from investors and the public are also spurring financial institutions to make more extensive disclosures of their climate risks and their responses to climate change and the net-zero transition.

Measuring and reducing financed emissions. Banks and asset managers are increasingly making pledges to align their portfolios with 1.5°C or 2.0°C warming targets or to achieve net-zero financed emissions by a certain date. The Glasgow Financial Alliance for Net Zero (GFANZ), for example, a global coalition in the United Nations' Race to Zero, has brought together more than 450 financial institutions across 45 countries controlling assets of more than $130 trillion. These institutions have committed to manage investment, lending, underwriting, and financial service activities to net zero by 2050, along with other nearer-term targets.[312] They have started translating these commitments into targets for sectors and geographies. Given that emissions ultimately are from counterparties, financial institutions may find it helpful to support the transition plans of those counterparties—for instance, by offering new financial solutions, advising them on emissions-abatement methods, and introducing partnership opportunities.

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[309] *Houston: Leading the transition to a low-carbon world,* Greater Houston Partnership, June 2021.

[310] *Preview: Global landscape of climate finance 2021,* Climate Policy Initiative, December 2020.

[311] Joseba Eceiza, Holger Harreis, Daniel Härtl, and Simona Viscardi, "Banking imperatives for managing climate risk," McKinsey & Company, June 2020.

[312] As of November 2021. See *Amount of finance committed to achieving 1.5°C now at scale needed to deliver the transition,* Glasgow Financial Alliance for Net Zero, November 3, 2021.

Translating commitments into actions that lower emissions. Over time, to meet their commitments and take advantage of opportunities, financial institutions could consider the scale-up of climate finance and expand the range of climate-finance products and services, such as funding for low-emissions power projects, new financial instruments to support negative emissions or nature-based solutions, and well-governed voluntary carbon markets.[313] For example, Temasek and BlackRock teamed up to launch Decarbonization Partners, which is designed to launch late-stage venture capital funds and private-equity growth funds focused on decarbonization solutions.[314] Some financial institutions are enabling customers to support climate action, for example through offering depositors the option of earmarking their money to fund green projects.

Governments and multilateral institutions could establish incentives, support vulnerable stakeholders, and foster collective action

Public-sector organizations have a unique role in managing uneven impacts on sectors and communities, in part by balancing numerous economic, environmental, and social considerations. Leaders could respond effectively by considering the following options, often in partnership with the private sector.

Assessing exposure to risks and opportunities, developing decarbonization plans, and creating net-zero strategies. This would include building some of the capabilities described previously for businesses. Governments might consider bringing climate considerations into decisions about urban planning, infrastructure development, and tax and subsidy regimes, among others. To support such activity, for example, the UK government in 2008 established the Climate Change Committee, a statutory body that advises the government on emissions targets, helps it adapt to the impact of climate change (including transition risks), and reports to Parliament on the progress of the climate transition.[315] One major adjustment will be developing new low-emissions industries to capture opportunities from a net-zero economy. As described in chapter 4, some countries and regions possess natural capital and could develop technological, human, and physical capital to create these new sectors.

Using policy measures, regulation, and other measures to support decarbonization actions across sectors. Potential mechanisms to consider include subsidies, grants, guarantees, taxes and carbon prices, demand signals, standards, and accreditation.[316] One example is a carbon price which could be set with a tax on the distribution, sale, or use of fossil fuels based on their carbon content, or with quotas in cap-and-trade systems that set an overall limit on emissions and create tradable emissions permits. Governments can also play a role in accelerating research and development that would lower technology costs.

Establishing multilateral and government funds to support low-carbon investment and manage stranded-asset risk. For large institutional investors such as pension funds, investing in low-carbon projects involves complex risks. Blended-finance mechanisms can help mitigate investment risk and “crowd in” private finance to a variety of projects. Development banks use these mechanisms to inject their own capital into projects and attract other investors. According to a 2019 report, blended-finance deals have totaled $10 billion to $20 billion a year globally since 2010. Of this amount, 36 percent supports climate action, one of the UN’s Sustainable Development Goals.[317] The Green Climate Fund, created by the United Nations Framework Convention on Climate Change, is one of the largest blended-finance facilities, with $30 billion of funding divided equally between climate-change mitigation and adaptation, and 173 approved projects since 2015.[318]

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

[314] “Temasek and BlackRock launch decarbonization investment partnership,” Temasek, April 13, 2021.

[315] See Alina Averchenkova, Sam Fankhauser, and Jared Finnegan, *10 years of the UK Climate Change Act,* Centre for Climate Change Economics and Policy, March 2018.

[316] Hal Harvey, *Designing climate solutions: A policy guide for low-carbon energy,* Island Press, 2018.

[317] *State of blended finance 2019,* Convergence, September 2019.

[318] “US climate envoy supports ‘indispensable’ GCF role during climate forum,” Green Climate Fund, April 21, 2021.

European development finance institutions have also committed to align portfolios with the Paris Agreement.[319] For example, Norway's Norfund has invested nearly 50 percent of its portfolio in the clean-energy sector.[320]

Instituting reskilling, redeployment, and social support programs for workers and managing negative effects on lower-income consumers. Governments have various options when it comes to retraining workers for the jobs needed in a low-carbon economy, ensuring that new entrants into the workforce have appropriate skills, and supporting workers who are making job transitions. The Scottish government, for example, worked with the national skills agency to retrain and reskill oil and gas workers after the closure of a number of facilities in the sector—enabling 89 percent of participants to find new jobs.[321] Social support programs can also assist displaced workers. Similarly, governments can play a role in supporting lower-income consumers, for example via subsidies or managing energy price increases.

Collaborating with other stakeholders to drive collective action. Governments can create or influence enabling institutions in constructive ways. Governments can also take leading roles in coordinating industrial-development efforts among stakeholders. In 2019, for example, South Korea's government published the Hydrogen Economy Roadmap to establish a national hydrogen ecosystem spanning three segments: upstream hydrogen infrastructure, hydrogen-fueling stations, and hydrogen vehicles.[322]

Enabling institutions such as standard setters, industry groups, and civil-society coalitions will be critical in coordinating action

The pace and scale of the transition mean that existing institutions may need to be revamped and new institutions created to disseminate knowledge, support capital deployment, manage uneven impacts, and organize collective action. Here are some areas where enabling institutions are well positioned to play valuable roles; more will no doubt emerge as the transition progresses.

Developing and enforcing governing standards, tracking, and market mechanisms. Standards and regulations can promote uniformity and consistency for practices such as measuring emissions, disclosing physical and transition risks, reporting on climate finance flows, validating carbon credits, and trading on voluntary carbon markets. For example, standards would be needed to measure, track, and ensure the traceability of scope 1, 2, and 3 emissions, supported through digital tools. Governing standards can help stakeholders factor emissions information into pricing and investment decisions, consumer choices, and regulatory and global trade regimes. The Science Based Targets initiative, for example, seeks to provide global standards for corporate net-zero targets, and the Partnership for Carbon Accounting Financials works on standards for measuring the emissions generated by financial institutions' investment and lending portfolios.[323]

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[319] "Climate neutrality: Council adopts the Just Transition Fund," Council of the EU, June 7, 2021.

[320] "DFC commits to net zero by 2040, increases climate-focused investments," US International Development Finance Corporation, April 22, 2021; and "Energy and climate," Norfund, September 2021.

[321] *Case study: Oil & gas transition Training fund, Scotland,* Platform for Coal Regions in Transition, 2019.

[322] *Korea hydrogen economy roadmap 2040,* IEA, September 2020.

[323] *Enabling financial institutions to assess and disclose greenhouse gas emissions of loans and investments,* Partnership for Carbon Accounting Financials; *Financial sector science-based targets guidance,* Science Based Targets, April 2021.

Convening stakeholders and facilitating collaboration. Industry and geographic forums can help disseminate best practices, arrange collective investment, shift value chains, and organize the build-out of infrastructure. They can also help organizations synchronize their responses to transition risks, so that none is exposed to the first-mover risk of adopting practices or making investments that raise the prices of their goods or services while peer companies' prices remain stable. The Mission Possible Partnership, for example, brings more than 200 heavy-industry experts together with banks and governments to create investment-grade net-zero strategies for high-emissions sectors like aviation, shipping, steel, and cement.[324]

Elevating risks and opportunities for workers and communities. Civil-society institutions can help integrate the voices of affected communities into decision making. In Canada, union leaders participated in the Task Force on Just Transition for Canadian Coal Workers and Communities. The task force's recommendations helped spur the government to expand employment insurance, training and education vouchers, and grants to affected communities.[325]

Individuals can manage their own exposure to the transition and play powerful roles as consumers and citizens

Unless individuals support the economic and societal adjustments that a net-zero transition would require, the transition will be unlikely to take place. In the long run, people stand to benefit greatly from a successful effort to limit global warming to 1.5°C, because such an effort would ameliorate physical risks and give rise to a host of new technologies. But individuals will also need to play a role in the economic and societal adjustments needed for the transition.[326] The following are some of the ways that individuals can support those adjustments.

Understanding exposure to risks and opportunities. Households may experience cost decreases in some cases and cost increases in others. Given the scale of the job gains and losses we noted in this report, people in some exposed occupations may need to learn new skills and practices to find work in a net-zero society. More broadly, the communities where individuals live may need to adjust as regions look to navigate the net-zero transition.

Shifting consumption patterns to support a net-zero transition. Reaching net zero would require households to adopt new patterns of consumption, such as switching to electric vehicles, renovating or retrofitting homes for energy efficiency, or eating less meat like beef and lamb to reduce agricultural emissions. This will be easiest where substitutes at the same or lower price are readily available. Consumers may face higher up-front capital costs in some cases, such as buying electric vehicles or retrofitting buildings but will likely achieve some ongoing cost savings from these choices. Even so, higher up-front costs can prove to be more challenging for lower-income households.

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[324] *Supercharging industrial decarbonization,* Mission Possible Partnership.

[325] *A just and fair transition for Canadian coal power workers and communities,* Task Force on Just Transition for Canadian Coal Power Workers and Communities, December 2018.

[326] See also Mekala Krishnan, Tomas Nauclér, Daniel Pacthod, Dickon Pinner, Hamid Samandari, Sven Smit, and Humayun Tai, "Solving the net-zero equation: Nine requirements for a more orderly transition," McKinsey & Company, October 2021.

Engaging in civic discourse. An informed public that recognizes the imperative for a net-zero transition could spur more decisive and transformative action on the part of government and business leaders. This would require a greater recognition of the magnitude of the challenge, along with a greater willingness to make adjustments in daily life and to accept solutions that might have been unappealing in the past. It would also require people to support compensating mechanisms for those who are negatively affected and to hold leaders accountable for the effects of their actions on future generations.

As this report has outlined, a transition to net-zero emissions amounts to a huge and complex undertaking, given its universal and very significant nature, and the unevenness that is likely to characterize it, based on our analysis. The challenges for leaders in business and policy in seeing through such a transition, and ensuring that it is orderly, should not be understated. Yet, as we have endeavored to show, the transition itself would bring opportunities. And the end result of a successful transformation to a low-emissions world would be immense. This is not just in terms of the substantial dislocation that would be avoided by ending the buildup of physical climate risk, but also in terms of opening up the prospect of a fundamentally transformed global economy with lower energy costs, and numerous other benefits—for example, improved health outcomes and enhanced conservation of natural capital. Moreover, the level of global cooperation that such a transition will ultimately require could serve as both a model and a basis for solving a broader array of global challenges. The findings of this research serve as a clear call for more thoughtful and decisive action, taken with the utmost urgency, to secure a more orderly transition to net zero. Daunting as the task may seem, it is fair to assume that human ingenuity would ultimately rise to the challenge of achieving net zero, just as it has solved other seemingly intractable problems over the past 10,000 years. The key issue is whether the world can muster the requisite boldness and resolve to broaden its response during the next decade or so, which will in all likelihood decide the nature of the transition.

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Technical appendix

This appendix gives details of the methodology and sources used in this report. It is organized in four sections, as follows:

1. Overview of methodology and key uncertainties
2. Quantification of overall economic shifts:
    A. Demand
    B. Capital spending and stranded assets
    C. Costs
    D. Jobs
3. Analysis of exposure of sectors across the economy
4. Analysis of countries' exposure and opportunities

1. Overview of methodology and key uncertainties

We assess the transition along two dimensions: energy and land-use systems, and geographies. For the first, we examine energy and land-use systems that account for about 85 percent of global CO_2 emissions: power, mobility (in particular, road transportation), industry (steel and cement production), buildings, agriculture and food, and forestry and other land use. We also look at fossil fuels, hydrogen, and biofuels that supply energy to many of these systems. For the geographic dimension, we analyze effects in 69 countries, which make up about 95 percent of global GDP.

We performed the analysis as follows. First, we used climate scenarios to quantify changes in important activity level variables in each energy and land-use system (further details below). Based on the evolution of such variables—which include changes in production and production capacity—we then assessed the implications for capital stock and investment, producer and consumer costs, and employment based on information about decarbonization technologies and their capital and operating costs, labor intensity, and value chains. Where possible, we used region-specific costs and labor assumptions, as well as expected technology learning curves over time, based on McKinsey analysis.

We chose not to develop our own transition scenarios and rely instead on widely used scenarios created by other institutions. Specifically, we analyze potential effects under the Net Zero 2050 scenario defined by the Network for Greening the Financial System (NGFS). This hypothetical scenario mirrors global aspirations to cut emissions by about half by 2030 and to net zero by 2050 to give an even chance of limiting warming to 1.5°C by the end of the century. This is achieved on a global basis. This means some high-emissions activities in hard to abate sectors and particular regions do not fall to zero by the middle of the century. Residual CO_2 emissions from these activities are counterbalanced by removals such as through land restoration and the use of bioenergy with CCS in the scenario.

We chose to work with the NGFS scenarios because they cover all major energy and land-use systems in a coherent manner, provide regional granularity, are designed for use in risk and opportunity analysis, and are becoming the standard scenarios used by financial institutions, regulators, and supervisors.[327]

In some cases, as a counterfactual for comparison, we also use the NGFS Current Policies scenario. This scenario anticipates warming of a little over 3°C by 2100. The NGFS Current Policies scenario includes some degree of transformation of the economy toward lower emissions, based on today's mitigation policies (based on an NGFS assessment of policies as of the start of 2020), and expected cost reductions in key low-emissions technologies. The comparison allows us to account for how other factors such as GDP growth or population growth could affect the economy between now and 2050.

The NGFS scenarios are generated by three different detailed energy and land-use system integrated assessment models that have also been used to inform mitigation pathway research cited by the Intergovernmental Panel on Climate Change. We used the results from the REMIND MAgPIE 2.1/-4.2 model in this research; this is because of the granularity it provides for agriculture. These scenarios broadly cover 12 regions: Australia, Canada and New Zealand; China; India; Japan; "Other Asia," which includes, among others, South Korea and Southeast Asia; United States; Latin America; the 27 European Union members and the United Kingdom; "Other Europe," which includes, among others, Switzerland, Norway, and Turkey; Russia, Ukraine, and the Commonwealth of Independent States; Middle East and North Africa; and sub-Saharan Africa. The full list of countries can be found on the NGFS website.

The NGFS scenarios capture how different economic, energy, land-use, and climate variables may change under different climate policy responses. We relied on these variables, alongside further downscaling from Vivid Economics, as inputs into our quantification of overall economic shifts, as described below.

Limitations of our approach and uncertainties. We recognize the limitations of the NGFS scenarios, as with any transition scenario, given that this is an emerging field of research. First, while some variables are explored at the sector level, the scenarios sometimes do not provide enough detail to explore how different types of activities will be affected. Second, the models underpinning the NGFS scenarios may not capture important dynamics or constraints within a sector. For example, the model we used favors more economy-wide use of biomass in energy and industry (for example, hydrogen production) than may be considered feasible in other sector-specific decarbonization pathways. Third, although the models do capture ongoing learning and technological innovation, they may fail to sufficiently anticipate the emergence of disruptive technologies that may change decarbonization pathways and of cost trajectories that fall faster than anticipated. Fourth, while some NGFS scenarios have begun to incorporate damages from physical risks in the economic modeling, further work is needed to fully integrate physical risks into the decarbonization pathways. As a result, we have focused here on scenarios that do not incorporate physical risk. This approach also allows us to focus our analysis on the effects of the transition alone. Finally, the scenarios reflect existing climate policies and technological trends in place before the COVID-19 pandemic and climate negotiations and pledges at COP26 in Glasgow in November 2021.

Our analysis concentrates largely on first-order effects. Various uncertainties could influence the magnitude of the outcomes highlighted here. While some of these factors could result in lower outcomes than those sized in this research, most factors suggest that additional costs and effects will likely occur as the transition unfolds. By the same token, the costs of physical climate risks could prove higher than those described in this research.

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[327] See *NGFS Climate Scenarios for central banks and supervisors,* Network for Greening the Financial System, June 2021. Some jurisdictions such as the European Union, Japan, and the United States reach net zero for all greenhouse gases by 2050 under this scenario.

Key uncertainties include the following:

- *Warming scenario and emissions pathway.* A higher warming scenario (for example, 2.0°C above preindustrial levels) may lead to smaller transition effects than a 1.5°C warming scenario, given the lower degree of emissions reduction and thus deviation from today's production and consumption patterns it entails (though physical risks would naturally be higher).
- *Sectors' decarbonization actions and activity levels.* Because the focus of our work is assessing the nature and magnitude of economic shifts and not identifying decarbonization actions, we used a prespecified net-zero scenario from NGFS. It is feasible that an alternate technology mix could result in lower costs and lesser shifts than those described here, and that further technological innovation could result in a different pathway with lower costs. For instance, an alternate scenario may incorporate substantially more use of carbon capture and storage (CCS) technologies and a focus on decarbonizing the hydrocarbon value chain. For example, this could happen if capture costs fall, regulatory frameworks are put in place to incentivize CCS use, and markets mature for recycled CO_2 as a material feedstock. Indeed CCS may play an increasingly important role if the scale-up of renewables proves slower or more disorderly than many anticipate.
- *Magnitude of direct and indirect socioeconomic effects.* Some effects could be larger than described here, for example, if executing the transition is more complex than the scenario here suggests, and additional capital spending is needed to maintain flexibility and redundancy in energy systems. Similarly, higher-order effects could substantially increase risks, particularly in the short term. For example, depending on how the transition is financed, the effects on the overall economy could be substantially higher than sized here. Finally, effects could also be larger under an abrupt or delayed transition.
- *Economic and societal adjustments needed for the transition.* Costs and investments could be higher than sized here, for example to implement social support schemes to aid economic and societal adjustments. Similarly, additional costs may arise from delays, setbacks, and urgently needed adaptation measures, particularly if restricting warming to 1.5°C proves not to be possible. For our analysis, we quantify the scale of first-order effects and describe qualitatively the adjustments needed.

Aspects we did not cover. Topics we did not cover include the likelihood, validity, and comparative costs associated with various decarbonization scenarios; the comparative merits of different emissions-reduction technologies; constraints on implementing and deploying decarbonization technologies (for example, scaling up supply chains); actions needed to drive and incentivize decarbonization; higher-order economic effects of the transition, including on output, growth, and human well-being; relative costs and merits of decarbonization and adaptation; and impacts that could result from physical climate hazards. We use benchmarks from the external literature and our past research to describe these latter possibilities.

As discussed above, our analysis here represents first-order estimates. Fully quantifying the costs of rising physical risks and the transition is complex. It would require estimating impacts from rising physical risks and the cost of adaptation actions, building robust estimates of the impact of the net-zero transition on the economy that take into account the higher-order effects described above, and doing so over time and while grappling with the various uncertainties described previously.

2. Quantification of overall economic shifts

A. Demand

Where possible, we take detailed activity-level demand data directly from the NGFS scenarios, for instance power capacity by production route (including coal, wind, and solar). NGFS provides these variables in five-year intervals, for example 2020 and 2025. For years in between, where needed, we interpolated linearly between data points.

Where the level of granularity is not sufficient or different activity-level measures are required, Vivid Economics downscaled the NGFS variables to provide additional insights. The downscaling was based on the relationship between NGFS and required variables from Vivid's proprietary models and open source models (for example VESM), as well as other industry benchmarks, as relevant. For example, Vivid estimates new vehicle sales, stocks, and kilometers by vehicle type from NGFS final energy use for transportation. This is done for a number of different vehicle types (for example, cars, light and heavy-duty trucks, buses, two- and three-wheelers) and power trains (for example, battery-electric vehicles, internal combustion engines, fuel cell electric vehicles). A similar approach was taken for buildings and industry using relevant proxies for activity levels in those systems. For agriculture, Vivid Economics estimated agriculture production from internal runs of the MAgPIE model. In such cases where downscaled variables were developed, we still refer to the specific sector variable as being based on the relevant NGFS scenario.

B. Capital spending

We estimated capital spending using activity levels in six energy and land-use systems in US dollars at 2020 market exchange rates. The general approach was to calculate spending on physical assets for each of the 12 regions in the NGFS data set and then aggregate total spending to the global level. In some parts of the report, this is represented as a fraction of GDP by dividing spending in the NGFS Net Zero 2050 scenario by GDP levels in each year. In all cases, total capital spending is estimated by multiplying the relevant activity-level production or capacity metrics (for example, capacity additions) by unit capital costs. In most cases, unit capital costs are broken out across the NGFS regions described previously.

This estimation includes spending on physical assets on various forms of energy supply (for example, power systems, hydrogen, and biofuel supply), energy demand (for example, for vehicles and alternate methods of steel and cement production), and various forms of land use (for example, GHG-efficient farming practices). This includes what is typically considered as investment in national accounts as well as spending, in some cases, on consumer durables such as personal cars. We typically consider spending to replace physical assets at the point of emissions (for example, cars for mobility); additional spending would also occur through the value chain. We have not sized this, to minimize double counting.

Others have estimated spending needs for the net-zero transition, and typically find ranges of \$3.0 trillion–\$4.5 trillion.[328] These evaluations often include an assessment of the spending needed in primary energy, power, hydrogen, biofuels, and energy efficiency, and the cost of electrifying components in end-use sectors such as buildings, transportation, and mobility. We broadened our scope relative to what is typically sized to include a more comprehensive view of spending by households and businesses on assets that use energy (for example, the full cost of passenger cars and heat pumps), capital expenditures in agriculture and forestry, and some continued spending on high-emissions physical assets like fossil fuel–based vehicles and power assets, as the economy transitions. Our estimates are thus higher than those in the literature.

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[328] See *Net Zero by 2050: A roadmap for the global energy sector,* IEA, 2021; *NGFS climate scenarios for central banks and supervisors,* NGFS, 2021; Christoph Bertram et al., "Energy system developments and investments in the decisive decade for the Paris Agreement goals," *Environmental Research Letters,* volume 16, number 7, June 2021; and David McCollum et al., "Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals," *Nature Energy,* volume 3, June 2018. The Energy Transitions Commission find incremental spending needs are \$1.5 trillion–\$1.8 trillion per year, which is also within the \$3 trillion–\$4.5 trillion range cited for total spending needs. See *Making mission possible: Delivering a net-zero economy,* Energy Transitions Commission, September 2020. In 2014 the Global Commission on the Economy and Climate with an expanded scope more similar to this report found investment needs of around \$6 trillion between 2015 and 2030 but much smaller incremental spending needs. See *Better growth, getter climate: The new climate economy report,* The Global Commission on the Economy and Climate, 2014.

Our analysis divides high-emissions assets from low-emissions assets. Low-emissions assets have a relatively small emissions footprint; the term does not always mean carbon neutral. This segmentation was done to allow us to size the scale of capital reallocation needed for the net-zero transition. In doing so, we recognize that the demarcation between high and low emissions is not always clear. Low-emissions assets and enabling infrastructure include assets for blue-hydrogen production with CCS; green-hydrogen production using electricity and biomass; biofuel production; generation of wind, solar, hydro-, biomass, gas with CCS, and nuclear power, along with transmission and distribution and storage infrastructure; heat production from low-emissions sources such as biomass; steel furnaces using the electric arc furnace (EAF) method of steel production, direct reduced iron (DRI) with hydrogen, basic oxygen furnaces with CCS; cement kilns with biomass or fossil-fuel kilns with CCS; low-emissions vehicles and supporting infrastructure; heating equipment for buildings run on electricity or biomass such as heat pumps; district heating connections; cooking technology not based on fossil fuels; building insulation; GHG-efficient farming practices; food crops, poultry and egg production; and land restoration.

We perform the following specific calculations for individual areas:

Fossil fuels, hydrogen, and biofuels
We take capital investment for fossil fuels at the worldwide level for extraction and conversion of coal, gas, and oil directly from the NGFS REMIND MAgPIE 2.1/-4.2 model (shortened to NGFS below). This includes investments in mining, shipping, ports, refining, and transmission and distribution as relevant.

Hydrogen demand was sized using the NGFS assumptions on secondary energy production on the regional and global levels. Production from NGFS is split into several pathways including from electricity, biofuels with and without CCS, natural gas with and without CCS, and coal with and without CCS. This does not include hydrogen production by industry for feedstock. We assume that the change in production levels is a good proxy for capacity additions in the future, given the size of market growth and asset life of facilities. We take costs for hydrogen production for each pathway from McKinsey Hydrogen Insights. This uses a representative average facility location for each production route as a proxy to assume global costs.

Biofuels demand was sized using the NGFS assumptions on future production levels and capital costs for biofuels with and without CCS on the regional and global level. We estimate biofuels capacity additions from production-level changes. As with hydrogen, we assume no renewal capacity given the young age of assets and size of market growth.

Power. We take capacity additions by production route directly from the NGFS, for instance coal, gas with and without CCS, solar and wind, and required storage capacity. We take capital costs for generation and storage technologies directly from McKinsey Power Solutions. Unit capital costs take into account costs of building, manufacturing, and maintaining power assets by country and production route. In addition, we take transmission and distribution investments directly from NGFS. This was benchmarked relative to transmission and distribution estimates from other sources, for example, the IEA.

For the power sector, we also conducted an assessment of stranded assets. Stranded value represents the cumulative value of prematurely retired and underutilized assets in 2020–50, undiscounted. We estimate it by first identifying the level of yearly depreciation that is expected given asset life and assumed economic life using data from the WRI Global Power Plant database as input. That figure was multiplied by the fraction of assets that are underutilized relative to past average utilization rates (between 2005 and 2020) and summed across years.

Industry (steel and cement)
For steel, Vivid Economics downscaled NGFS scenarios to create specific production routes, including blast oxygen furnaces with and without CCS, electric arc furnaces, and direct reduced irons (biogas and hydrogen). We take capital costs from McKinsey Basic Materials Insights. Capital costs include maintenance and growth capital expenditures.

For cement, Vivid Economics downscaled NGFS scenarios to create production routes, including coal, gas, biomass, coal with fly ash substitution, gas with fly ash substitution, coal with CCS, gas with CCS, coal with CCS, and fly ash substitution and gas with CCS, and fly ash substitution kilns. We take capital costs from McKinsey Sustainability Insights. Capital costs include maintenance and growth capital expenditures.

Road mobility

Vivid downscaled NGFS data to create estimates of new vehicle sales by type (including cars, light and heavy-duty trucks, buses, two- and three-wheelers) and powertrain (for example, battery-electric vehicles, internal combustion engine, fuel cell electric vehicles). We take up-front costs per vehicle and the cost of installing electric and hydrogen charging infrastructure from the McKinsey Center for Future Mobility Electrification Model.

Buildings

Vivid Economics provided sales data for each category. We take unit cost data from McKinsey Sustainability Insights that include the cost of buying unit, labor cost for installation, and construction. Up-front costs for heat pumps are assumed to be a weighted average of the costs for air-source, water-source, and ground-source heat pumps by sales. Fossil fuel boilers are assumed to be a weighted average of gas and oil boilers. District heating costs represent the costs of installing a new district heating connection in the property as well as centralized infrastructure costs for the connection from the property to heat source (for example, a heat plant or ground-source heat pump). Costs in developing regions are assumed to be half those of developed regions, due to limited availability of granular data across regions.

Agriculture, forestry, and other land use

Agriculture. We quantified the investment from implementing 25 GHG-efficient farming techniques and technologies outlined by other McKinsey research.[329] For agricultural production, Vivid Economics downscaled NGFS scenarios to create production variables. We take estimates for the capital costs for production and costs of implementing GHG efficient practices from McKinsey's Agricultural Practice. Capital costs capture spending on new farm equipment and infrastructure, as well as costs to maintain existing equipment.

Forestry and other land use. We estimate deforestation rates from the NGFS scenarios taking into account changes in NGFS forest cover, and afforestation rates and the wider literature on natural forest growth rates. The amount of avoided deforestation is the difference between deforested area in the NGFS Current Policies and Net Zero 2050 scenarios. To estimate capital spending we use projected costs (in US dollars per hectare) by country and type of project (for example, avoided deforestation and afforestation) from McKinsey Nature Analytics and multiply by area of land protected or restored. Investment costs consist mainly of land acquisition costs (both explicit costs to purchase land and implicit imputed rents of protecting land) and some one-off costs such as setting up offices and site preparation.

C. Costs

We sized the change in unit production costs to model the impact on producers in individual systems. We calculate unit cost of production as in-year operating expenditure plus in-year maintenance capital spending (the yearly expenses incurred to maintain equipment) plus capital charges and depreciation on the invested capital base of the sector. The unit cost of production is then computed by dividing cost of production by volume of production. This is done at the worldwide level and is meant to be an indicator of how costs of production may change for the average producer. Individual producers could see a different change to their cost of production based on many other factors. These include where they are located, what their main production routes are, and what regulation they face in their given jurisdiction(s). We used a weighted cost of capital of 8 percent to calculate capital charges for steel and cement and 6.5 percent for the power sector. This is in line with global averages in the power,

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[329] Justin Ahmed, Elaine Almeida, Daniel Aminetzah, Nicolas Denis, Kimberly Henderson, Joshua Katz, Hannah Kitchel, and Peter Mannion, “Agriculture and climate change: Reducing emissions through improved farming practices,” McKinsey & Company, April 2020.

steel, and cement sectors, but will vary from business to business. Shifts in costs were calculated relative to 2020 levels, which we sometimes refer to as "today."

For power, operating costs include the full in-year costs of energy (mainly electricity), operation and maintenance (including labor, spare parts, replacement of the technology), and water. We estimated the delivered cost of electricity. Data are sourced from McKinsey Power Solutions. For cement and steel, operating costs include those for feedstock, energy, and other operating costs. Data are sourced from McKinsey Sustainability Insights and McKinsey–Mission Possible Partnership collaboration.

We also examined the total cost of ownership data from McKinsey Center for Future Mobility. Total cost of ownership accounts for purchase price, operating costs, for instance fuel and maintenance costs, and resale value; based on three-year ownership of a new car.

In conducting these analyses, we largely focus on the impact of shifts in demand across different energy and land-use systems with different economics of production. We exclude any impact of shifting subsidies or carbon taxes, which result in transfers across different actors in the economy. We also excluded any effects of rising physical risks on costs.

D. Jobs

We measure the total direct and indirect operation and maintenance (O&M) and construction and manufacturing (capital expenditures) job impacts (losses and gains) from the net-zero transition. Our analysis captures potential effects of shift in demand for jobs across subsectors, sectors, and geographies; we refer to rising demand for jobs as "jobs gained," and diminishing demand for jobs as "jobs lost." In reality, this could manifest as a shift in job activity for individual workers. To do this, we only considered jobs in existing sectors that are directly affected by the climate transition, in new sectors that might emerge as a result of the net-zero transition, and in their upstream sectors. Job losses and gains are modeled for every five-year increment between 2020 and 2050.

The transition to net zero will not be the only global trend affecting employment between 2020 and 2050. Significant shifts are likely across all job sectors as a result of trends including population growth, sector-specific productivity enhancements, rising incomes, an aging population, and technological disruptions from automation and AI adoption.[330] Given these factors, we sought to disaggregate job gains and losses specifically associated with achieving net-zero emissions under the Net Zero 2050 scenario. When transition-related job changes are referred to in this report, figures include both technological and policy changes already planned or in the process of implementation as well as incremental changes required to achieve net zero by 2050. Figures exclude changes associated with the macroeconomic and within-sector productivity trends outlined above.

In an effort to describe a comprehensive view of job transitions tied to achieving net zero by 2050, calculations for gross job losses and gains include new jobs created (for example, CCS jobs that do not currently exist), current jobs lost (for example, coal mining jobs, which are likely to decline), jobs shifting between subsectors within a given sector (for example, a job that shifts from coal to solar power generation counts as both one job lost and one job gained), and jobs being lost or gained across regions. While many such job losses and gains will occur between now and 2050 across the economy as a whole, job losses and gains analyzed in this report are focused on sectors within the energy and land-use systems most closely tied to achieving the net-zero transition. Thus, for various reasons, this analysis does not capture broad labor market shifts expected over the next three decades, but narrowly focuses on the shifts from a net-zero transition alone.

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[330] See *The future of work after COVID-19,* McKinsey Global Institute, February 2021.

Our methodology does not account for any higher-order impacts and assumes an orderly transition, one in which high emissions assets are ramped down and low emissions assets are ramped up to the levels needed without constraints or challenges. We do not consider challenges associated with the reskilling or redeployment of workers, as this analysis captures the demand for employment in the economy. Finally, employment levels will also depend on fiscal and monetary policy that could be constrained by the aggregate financing requirement, which we do not model. This analysis has numerous uncertainties and we have needed to make assumptions, for example related to productivity growth within sectors and subsectors, and relative productivity levels across different technologies.

Throughout our discussion we account for both the jobs in our focus sectors (direct jobs) and the upstream jobs associated with final demand in our focus sectors (indirect jobs). The indirect jobs are calculated using multipliers derived from input-output tables that account for local and imported inputs to production in our focus sectors.

Operations and maintenance (O&M) jobs relate to the operations and maintenance activities in the sector (direct jobs), and their supply chains (indirect jobs). Direct O&M jobs are permanent, full-time positions in the affected sectors. Indirect O&M jobs are permanent, full-time jobs in all the sectors that provide inputs and services used in production in the directly affected sectors (for example, transportation, financial services).

Capital expenditures jobs are those arising from capital investment in the sector, are associated with manufacturing and construction (direct jobs), and their supply chains (indirect jobs), and are not included in either the baseline jobs figure for 2020 or the O&M losses and gains across sectors. Direct capital expenditures jobs are temporary, full-time jobs created in construction and manufacturing as a result of capital investment in the directly affected sectors (for example, to build low-emissions capacity in power). These jobs are calculated based on the amount of investment in a given year, and attributed fully to the year in which the capital investment occurs. Indirect capital expenditures jobs are temporary, full-time jobs created in all the sectors that provide inputs, supply services, and otherwise support construction and manufacturing resulting from capital investment in the directly affected sectors. These jobs are attributed fully to the year in which the capital investment occurs.

A comparison of job figures in this report to those outlined in other literature analyzing the effects of the net-zero transition would initially suggest that losses and gains described herein tend to be higher than other estimates.[331] This is driven by a series of differentiating factors specific to this analysis: 1) Compared to a range of other comparable publications, analysis in this report captures a more comprehensive view across 12 major sectors, whereas many reports focus either specifically on a single sector (for example, power) or a series of related sectors (for example, fossil fuels production and utilization, hydrogen, renewables); 2) analysis in this report captures direct and indirect (upstream), O&M and capital expenditure jobs, whereas other comparable reports focus primarily on direct jobs within the sector; 3) we consider job losses and gains, including shifts across granular subsectors to give a total number for reallocations (gross gains plus gross losses) as well as the net differences usually in focus. In addition, our numbers can differ from reports that count total jobs in relevant sectors under different scenarios. Our definition separates job shifts from the transition between today and 2050, including those associated with current policies and incremental policy and technology changes required to achieve net zero, from jobs linked to non-transition effects like income and population growth. Our transition numbers will thus tend to be lower than any total projections by sector for a future year but higher than any comparison between a 1.5 scenario and a counterfactual that only differs in the pace of transition-related policy and activity changes.

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[331] See, for example, IEA, *World energy outlook 2021;* IRENA, *Renewable energy and jobs: Annual review 2021;* and ILO, *Greening with jobs,* 2018.

Calculation approach

Job losses and gains analyzed in this report are focused on sectors within the energy and land-use systems most closely tied to achieving the net-zero transition and which are the focus of this research. We measure the jobs impact in the following existing sectors, which account for about 85 percent of total emissions: power, automobiles, steel, cement, agriculture, forestry, oil, gas, and coal extraction and production (OGC), and buildings. We also measure jobs in the following new sectors: CCS, hydrogen, minerals mining, and biofuels. We model some sectors at the subsector level (for example, in power, we model jobs by coal, gas, solar PV, wind, etc.; in steel, we model jobs by BOF, EAF, and DRI). For purposes of this analysis, we report job losses and gains at the aggregated global level but derive those global figures from a buildup of modeling sector-specific activity levels within the 12 regions in the NGFS REMIND-MAgPIE model.

We calculate direct O&M jobs by multiplying the job intensity (that is, the number of jobs per unit of production or installed capacity) of each sector and subsector in a given year and region with the activity level of that subsector in that year and region (that is, units of production or installed capacity), derived either directly from the NGFS scenario data or from downscaling of NGFS scenarios done in collaboration with Vivid Economics, as noted earlier.

We derive job intensity by applying annual productivity growth assumptions to baseline (2020) job intensity by region for each sector and subsector. These productivity growth assumptions are based on forward-looking productivity growth estimates where available, and historical productivity growth where forward-looking estimates are not available.

Indirect O&M jobs are calculated in each period by multiplying the direct O&M jobs in that period by the corresponding indirect jobs multiplier (that is, the number of indirect jobs per direct job) for the respective sector and region. Our indirect jobs multipliers are derived using regional input-output tables constructed from underlying OECD country tables. We then adjusted up these indirect jobs within the region to account for inputs provided through inter-regional trade, resulting in the total indirect jobs associated with direct jobs within the region.

Because the direct jobs of each sector we model are in some cases upstream jobs in another modeled sector (for example, an oil and gas job is an upstream job for the fossil-based power sector), we take a final step of netting out any double counting. To do so, we exclude a set of sectors for which we have done bottom-up calculations elsewhere, including agriculture, forestry and fishing; mining and extraction of energy; coke and refined petroleum, other nonmetallic mineral products, manufacture of basic metals, motor vehicles, trailers and semi-trailers; power; machinery, and equipment and construction. If all upstream sectors are considered, the indirect jobs shifts would be about 15 to 25 percent higher without netting out the job changes from other sectors already modeled.

We calculate direct capital expenditures jobs by multiplying capital expenditures investment numbers for each sector and subsector by region by year (described above in the investments section) with a combination of two sets of jobs multipliers (that is, number of jobs per million dollars) for the respective year and region: construction and machinery and equipment n. e. c. (referred to in this report as “manufacturing” unless otherwise specified). These multipliers by region and year are derived from the same input-output tables and multipliers as the indirect jobs multipliers described above, which we also use in calculating indirect capital expenditures jobs.

We assume capital expenditures investment to be split equally between construction and manufacturing for all sectors, except buildings, where we estimate the split as 20/80 between construction (that is, installation) and manufacturing.

3. Analysis of exposure of sectors across the economy

We measure sector exposure to the climate transition in terms of the life cycle emissions intensity of sectors. Life cycle emissions include sectors' emissions in their own operations (scope 1 emissions), in their supply chains (scope 2 and scope 3 [inputs] emissions), and in the use of their products (scope 3 [products] emissions).[332] We normalize sectors' emissions by their gross output to estimate emissions' intensity; normalizing by gross output allows us to assess the sectors' emissions relative to the magnitude of their activities. We thus measure emissions intensity in terms of kilotons of emissions per million dollars of gross output.

We consider all CO_2, CH_4, and N_2O emissions produced and consumed by economic sectors in our analysis. We use the GWP100 methodology to convert all gases to CO_2 equivalent. We define sectors based on the ISIC Rev. 4 sector classifications, and analyze sectors at the same level of granularity as available in the World Input-Output Database (WIOD). We use WIOD data for gross output by sector and to analyze the flow of goods and services between sectors.

We calculate emissions intensity by sector as follows:

Scope 1: We map each category of emissions (for example, power) to the sector that is the site of those emissions or whose operations result in those emissions (for example, electricity, gas, and utilities). For most categories of emissions, there is a clear one-to-one mapping to a sector whose operations result in those emissions, with the exceptions of commercial buildings heating, and road transport. This is because all sectors operate commercial buildings and vehicles that result in these emissions. We distribute these categories of emissions between all sectors proportionally, based on their stocks of total construction assets and total transportation equipment, respectively. We use these two measures as proxies for the levels of heating and driving needs of each sector. We then divide the total scope 1 emissions allocated to each sector by that sector's gross output to get to the scope 1 emissions intensity. We arrive at the gross outputs for each sector from an aggregated, global input-output table from WIOD.

Scope 2: We use the aggregated, global input-output table from WIOD to get the value of input that each sector buys from the electricity, gas, steam, and air conditioning supply sector. We multiply these values with the scope 1 emissions intensity of the electricity, gas, steam, and air conditioning supply sector (calculated in the prior step) to arrive at the total scope 2 emissions of each sector. We then divide the total scope 2 emissions of each sector by that sector's gross output to arrive at the scope 2 emissions intensity.

Scope 3 (inputs): We use the aggregated, global input-output table from WIOD to get the value of inputs that each sector buys from all the other sectors, except the electricity, gas, steam, and air conditioning supply sector (since that was covered under the previous step). We then multiply these values with the respective scope 1 emissions intensities of the sectors from which the inputs are being bought to arrive at the total scope 3 (inputs) emissions. We then divide the total scope 3 (inputs) emissions of each sector by that sector's gross output to get to the scope 3 (inputs) emissions intensity.

Scope 3 (products): We define scope 3 (products) emissions as emissions from the products of a sector that are reliant on fossil fuels to operate (for example, internal combustion engine cars, gas boilers, and blast oxygen furnaces). We map each category of emissions (for example, aviation) to the sector whose fossil fuel–reliant products create those emissions (for example, manufacture of other transport equipment, manufacturing of coke and refined petroleum products, and mining and extraction of energy-producing products). Here, each category of emissions can be mapped to more than one sector—that is, counted

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[332] For purposes of this research "scope 1" emissions are direct greenhouse emissions that occur from sources that are controlled or owned by an organization; "scope 2" emissions are associated with the purchase of electricity, steam, heat, or cooling. "Scope 3" emissions are the result of activities from assets not owned or controlled by the reporting organization but that the organization indirectly impacts in its value chain; thus scope 3 emissions result from emissions across an organization's value chain that are not within the organization's scope 1 and 2 boundary. See *Greenhouse gases at EPA,* United States Environmental Protection Agency. Similar definitions can also be applied when considering the scope 1, 2, and 3 emissions for a sector.

more than once—as the products of multiple sectors may be creating those emissions. For example, in the case of road transportation emissions, we would map these emissions once to the manufacture of motor vehicles sector, which produces the ICE cars that need oil to operate, once to the manufacturing of coke and refined petroleum products sector, which produces the refined crude oil used in ICE cars, and once to the mining and extraction of energy- producing products sector, which produces the unrefined crude oil. Some categories of emissions, such as waste, are not mapped to any sector because they are not caused by the products of any sector. We then divide the total scope 3 (products) emissions allocated to each sector by that sector's gross output to get to the scope 3 (products) emissions intensity.

Life cycle emissions intensity: We sum the scope 1, 2, 3 (inputs), and 3 (products) emissions intensities of each sector to get to the life cycle emissions intensity of that sector.

We use this analysis to classify sectors into archetypes. To do this, we first look at a sector's scope 3 (products) emissions intensity. If it is relatively high, we classify the sector into producers of fossil fuel energy or producers of fossil fuel–dependent products, based on whether they produce fossil fuel themselves or not. We look at this scope of emissions first because we believe that this represents the most material exposure to a sector. Together, these categories represent sectors with high emissions in their core products.

Then we look at a sector's scope 1 emissions intensity. If it is relatively high, we classify the sector into emitters in core operations. We look at this scope of emissions next because we believe that this represents the next most material exposure to a sector, since the sector would have to fundamentally change its own operations under a net-zero transition.

Next, we look at a sector's combined scope 2 and scope 3 (inputs) emissions intensities (as these are both driven by inputs). If they are relatively high, we classify the sector into users of inputs from emitters.

If none of the above is true (that is, if all scope of emissions intensities are low), we classify the sector in relatively low exposure.

4. Analysis of countries' exposure and opportunities

To analyze how countries and regions would be affected by a net-zero transition, we have conducted four broad sets of analyses.

First, we examine the overall spending on physical assets for energy and land-use systems that will be needed in different regions; we do this using activity levels for different sectors and regions from the NGFS Net Zero 2050 scenario and unit capital costs for different technologies. This is a similar approach to that described previously for capital spending.

Second, we examine the exposure of the economies of different countries to transition shifts more broadly. We focus on 69 countries that make up about 95 percent of global GDP and about 80 percent of global emissions. Countries were selected based on data availability across all the indicators in our analysis, as well as to ensure broad geographic coverage.
To measure the exposure in each area of the economy, we considered the share of a country's GDP, capital stock, and jobs in sectors most exposed to the transition. We chose these areas because they collectively represent production activity and stocks of human and physical capital. To identify the sectors most exposed, we considered the archetypes described previously that represent the most exposed sectors; namely those with high emissions intensity in their own operations; those whose products, in turn, emit while being used; and those that have high emissions embedded in their supply chains. Each economy's transition-exposure score is the average of the shares of GDP, capital stock, and jobs in these sectors. Thus, a zero score would indicate that none of the country's GDP, capital stock, or jobs are in these sectors, while 100 would indicate that all of the country's GDP, capital stock, and jobs are in these sectors.

Separately, we also look at consumer activity in the form of per capita household emissions (from driving, heating, and cooking) to assess the materiality of exposure for the consumers and the extent to which they may need to shift practices as a result of the transition. For our consumer metric, we look at the amount of emissions for which consumers are directly responsible by examining the consumer shares of road and buildings emissions.

This analysis accounts for the possibility that countries that directly emit the most carbon may not necessarily have the highest levels of exposure. Exposure to the transition could result from either direct scope 1 emissions (such as those resulting from domestic energy use) or from indirect emissions upstream and downstream in value chains. For example, a country with a large but relatively low-emissions automotive value chain could nevertheless be exposed to the transition.

Country exposure varies with the share of jobs, output, or capital stock in sectors exposed to the transition. Assessing the exposed share of jobs or capital or output, rather than the absolute quantity of the exposed jobs or capital or output, provides a way of gauging the materiality of the transition for each country.

For this country-level analysis, we chose to measure economic exposure (share exposed) rather than quantify actual socioeconomic outcomes (realized gain or loss, for example in jobs, GDP, or value of physical capital stock) because such outcomes are not predetermined. They could be mitigated by the scale and nature of actions taken to manage the transition. Measuring the exposure therefore allows decision makers to understand where to focus attention and effort on managing the transition.

It is important to note that countries' current efforts (for example, spending to transform power assets or to diversify economies toward hydrogen) could reduce their exposure going forward. However, this analysis focuses on exposure today in order to create a fact base for countries to inform their decision making. Similarly, countries with high exposure today may eventually benefit from the transition—for instance, by establishing economical sources of low-emissions power or building future assets in a way that reduces their future exposure. We describe these as we consider opportunities below, but do not quantify the impact on countries' economies and how this might reduce overall exposure.

Other aspects of a country's activities could be exposed, but we have not included those here. For example, we have not included tax revenue and exports, given their strong relationship to GDP.

Third, we have evaluated each country's current position with respect to the opportunities that could arise in the Net Zero 2050 scenario. We primarily assess endowments of natural capital and the availability of technological and human capital as the basis for the comparative advantages that countries possess or could build over time.

The presence of natural capital indicates a country's potential to develop sectors such as hydrogen production and minerals mining that would emerge during the transition, while technological and human capital indicate a country's capability to undertake innovations to enable the transitions.

Natural capital

Solar potential: We measure a country's solar potential based on its GHI (solar irradiance in kWh / m2 / day); that is, power received from the sun per unit area. This provides an indication of the density of solar resource in a country and its ability to capture that potential. Data are sourced from the World Bank database of global photovoltaic power potential by country, April 2020.

Wind potential: We measure a country's wind potential based on its mean wind power density in the 10 percent most windy areas at 100m height (W/m2). This provides an indication of the density of wind resource in a country and its ability to capture that potential. Data is sourced from the Global Wind Atlas 3.0, a web-based application developed, owned, and operated by the Technical University of Denmark. The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program. This is calculated by downscaling large-scale forecasting data from the European Centre for Medium-Range Weather Forecasts.

Reforestation potential: Countries' reforestation potential was calculated by assessing the extent of land that is technically suitable for reforestation, then narrowing this area down to a realistic reforestation potential using biophysical filters. The resulting area is then converted into carbon sequestration potential. Three specific filters were used. First, a biome filter, to exclude biomes where reforestation is nonnatural or could have negative effects on ecosystems and climate, for instance boreal forests/taiga; grasslands, tropical savannas, and shrublands; and deserts and xeric shrublands biomes. Second, a water stress filter, to exclude areas where water stress is projected to be extremely high (greater than 80 percent) or the area is forecast to be arid in 2040, based on the RCP 8.5 scenario. Third, a human footprint filter to exclude current cropland and urban areas, as well as areas where urban expansion is projected with a probability greater than 50 percent by 2050. Spatially explicit carbon-sequestration rates were then applied to each area with reforestation potential to estimate the total abatement potential.[333] Data is sourced from McKinsey Nature Analytics.

Minerals availability: The ratio of proven reserves to global production for each mineral is calculated as the total proven reserves of the mineral divided by the total current annual global production for each of six categories of minerals (cobalt, copper, lithium, nickel, zinc, rare earths). This was done in order to account for the varying values of the absolute levels of different minerals (that is, one ton of copper is not the same as one ton of cobalt). We therefore normalize the reserves available of each mineral with their respective current annual production (acknowledging that usage may increase during and after the net-zero transition, as well as the fact that reserves include only currently discovered deposits). Data is sourced from *Mineral commodity summaries 2020,* US Geological Survey, January 2020.

Carbon-sequestration capacity: Data are sourced from Christopher Consoli, *CCS storage indicator (CCS-SI),* Global CCS Institute, 2018. The CCS-SI uses a defined methodology to undertake critical analysis of a nation's storage resource development and record the progress in national and global storage development. The metric is calculated based on three factors: natural geological storage potential, maturity and confidence of storage resource assessments, and experience in CO_2 storage project development to date. The result is a score out of 100, with higher scores indicating a greater state of readiness of storage resources to support wide-scale deployment of CCS.

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[333] See Jean-Francois Bastin et al., "The global tree restoration potential," *Science,* July 2019, volume 365, number 6448, and Susan Cook-Patton et al., "Mapping carbon accumulation potential from global natural forest regrowth," *Nature,* September 2020, issue 585.

Technological and human capital

R&D: We measure a country's R&D capabilities based on its R&D spending as a share of its GDP. This provides an indication of the overall innovative capabilities of a country. Data is sourced from the World Bank's database on research and development expenditure as a percentage of GDP.

Climate-specific patents: We measure a country's climate-specific capabilities based on the number of its climate change mitigation–related patents. This provides an indication of the climate change mitigation–specific innovative capabilities of a country. Data is sourced from the Organisation for Economic Co-operation and Development statistics on patents in environment-related technologies.

Relevant skill availability: We measure the availability of skills relevant for the climate transition in a country based on its share of STEM graduates. This provides an indication of the innovative capabilities of the workforce of a country. Data are sourced from the International Labour Organization ILOSTAT database. While we focused on STEM skills for our analysis in this report, we acknowledge that many other skills will also be needed in a net-zero transition.

Fourth and finally, we consider the physical risk exposures of different countries, drawing on our past research on the topic. For further details, see *Climate risk and response: Physical hazards and socioeconomic impacts,* McKinsey Global Institute, January 2020.

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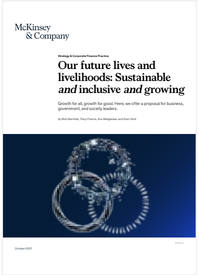

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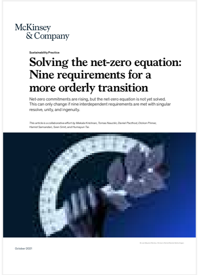

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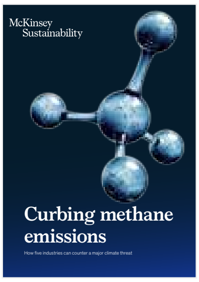

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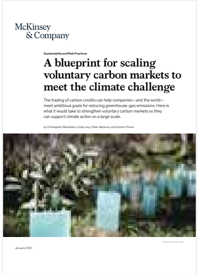

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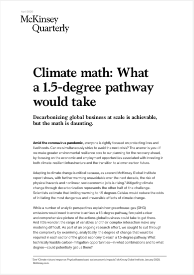

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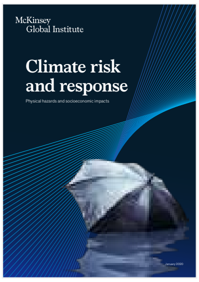

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