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Climate math: What a 1.5-degree pathway would take

Decarbonizing global business at scale is achievable, but the math is daunting.

Amid the coronavirus pandemic, everyone is rightly focused on protecting lives and livelihoods. Can we simultaneously strive to avoid the next crisis? The answer is yes—if we make greater environmental resilience core to our planning for the recovery ahead, by focusing on the economic and employment opportunities associated with investing in both climate-resilient infrastructure and the transition to a lower-carbon future.

Adapting to climate change is critical because, as a recent McKinsey Global Institute report shows, with further warming unavoidable over the next decade, the risk of physical hazards and nonlinear, socioeconomic jolts is rising.[1] *Mitigating* climate change through decarbonization represents the other half of the challenge. Scientists estimate that limiting warming to 1.5 degrees Celsius would reduce the odds of initiating the most dangerous and irreversible effects of climate change.

While a number of analytic perspectives explain how greenhouse-gas (GHG) emissions would need to evolve to achieve a 1.5-degree pathway, few paint a clear and comprehensive picture of the actions global business could take to get there. And little wonder: the range of variables and their complex interaction make any modeling difficult. As part of an ongoing research effort, we sought to cut through the complexity by examining, analytically, the degree of change that would be required in each sector of the global economy to reach a 1.5-degree pathway. What technically feasible carbon-mitigation opportunities—in what combinations and to what degree—could potentially get us there?

[1] See "Climate risk and response: Physical hazards and socioeconomic impacts," McKinsey Global Institute, January 2020, McKinsey.com.

About this article

This article was a collaboration between **Kimberly Henderson** (partner in McKinsey's Washington, DC, office and leader of the research effort underpinning this article), **Dickon Pinner** (senior partner in the San Francisco office and global leader of McKinsey's Sustainability Practice), **Matt Rogers** (senior partner in the San Francisco office and North American leader of McKinsey's Sustainability Practice), **Bram Smeets** (associate partner in the Amsterdam office), **Christer Tryggestad** (senior partner in the Oslo office), and **Daniela Vargas** (consultant in the Mexico City office).

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We also assessed, with the help of McKinsey experts in multiple industrial sectors, critical stress points—such as the pace of vehicle electrification and the speed with which the global power mix shifts to cleaner sources. We then built a set of scenarios intended to show the trade-offs: If one transition (such as the rise of renewables) lags, what compensating shifts (such as increased reforestation) would be necessary to get to a 1.5-degree pathway?

The good news is that a 1.5-degree pathway is technically achievable. The bad news is that the math is daunting. Such a pathway would require dramatic emissions reductions over the next ten years—starting now. This article seeks to translate the output of our analytic investigation into a set of discrete business and economic variables. Our intent is to clarify a series of prominent shifts—encompassing food and forestry, large-scale electrification, industrial adaptation, clean-power generation, and carbon management and markets—that would need to happen for the world to move rapidly onto a 1.5-degree pathway.

None of what follows is a forecast. Getting to 1.5 degrees would require significant economic incentives for companies to invest rapidly and at scale in decarbonization efforts. It also would require individuals to make changes in areas as fundamental as the food they eat and their modes of transport. A markedly different regulatory environment would likely be necessary to support the required capital formation. Our analysis, therefore, presents a picture of a world that could be, a clear-eyed reality check on how far we are from achieving it, and a road map to help business leaders and policy makers better understand, and navigate, the challenges and choices ahead.

Understanding the challenge

While it might seem intuitive, it's worth emphasizing at the outset: every part of the economy would need to decarbonize to achieve a 1.5-degree pathway. Should any source of emissions delay action, others would need to compensate through further GHG reductions to have any shot at meeting a 1.5-degree standard.

No easy answers

And the stark reality is that delay is quite possible. McKinsey's *Global Energy Perspective 2019: Reference Case*, for example, which depicts what the world energy system might look like through 2050 based on current trends, is among the most aggressive such outlooks on the potential for renewable energy and electric-vehicle (EV) adoption. Yet even as the report predicts a peak in global demand for oil in 2033 and substantial declines in CO_2 emissions, it notes that a "1.5-degree or even a 2-degree scenario remains far away" (Exhibit 1). Similarly, the McKinsey Center for Future Mobility (MCFM)—which foresees a dramatic inflection point for transportation[2]—does not envision EV penetration hitting the levels that our analysis finds would be needed by 2030 to achieve a 1.5-degree pathway. MCFM analysis also underscores a related challenge: the need to take a "well to wheel" perspective that accounts for not only the power source of the vehicles but also how sustainably that power is generated or produced.

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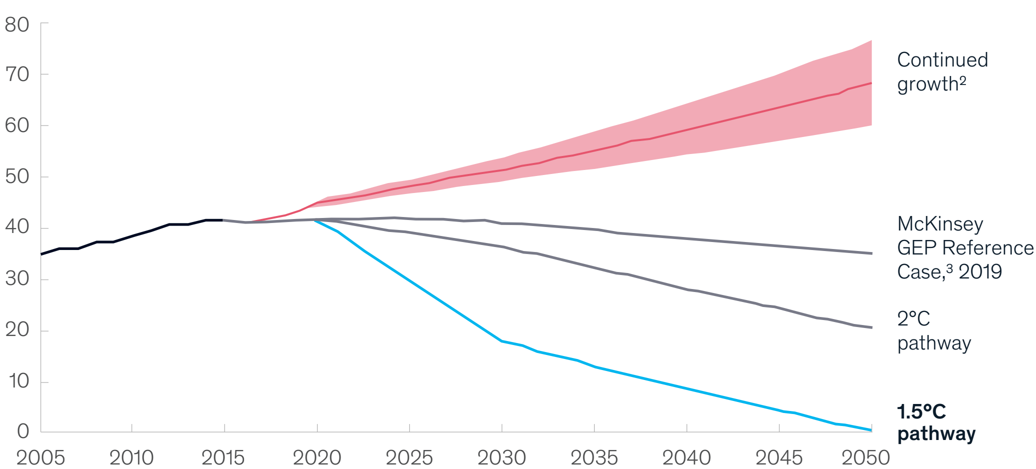
[2] See Rajat Dhawan, Russell Hensley, Asutosh Padhi, and Andreas Tschiesner, "Mobility's second great inflection point," *McKinsey Quarterly*, February 2019, McKinsey.com.

Exhibit 1

Rapid declines in CO_2 emissions would be required to reach a 1.5°C pathway.

Projected global CO_2 emissions per scenario[1]

Metric gigatons of CO_2 ($GtCO_2$) per year



[1] In addition to energy-related CO_2 emissions, all pathways include industry-process emissions (eg, from cement production), emissions from deforestation and waste, and negative emissions (eg, from reforestation and carbon-removal technologies such as bioenergy with carbon capture and storage, or BECCS, and direct air carbon capture and storage, or DACCS). Conversely, emissions from biotic feedbacks (eg, from permafrost thawing, wildfires) are not included.
[2] Lower bound for "continued growth" pathway is akin to IEA's *World Energy Outlook 2019* Current Policies Scenario; higher bound based on IPCC's Representative Concentration Pathway 8.5.
[3] GEP = Global Energy Perspective; reference case factors in potential adoption of renewable energy and electric vehicles.

Source: Global Carbon Budget 2019; *World Energy Outlook 2019*, IEA, expanded by Woods Hole Research Center; McKinsey *Global Energy Perspective 2019: Reference Case*; McKinsey 1.5°C scenario analysis

Given such uncertainties and interdependencies, we created three potential 1.5-degree-pathway scenarios. This allowed us to account for flexibility in the pace of decarbonization among some of the largest sources of GHGs (for example, power generation and transportation) without being predictive (see sidebar "About the research"). All the scenarios, we found, would imply the need for immediate, all-hands-on-deck efforts to dramatically reduce GHG emissions. The first scenario frames deep, sweeping emission reductions across all sectors; the second assumes oil and other fossil fuels remain predominant in transport for longer, with aggressive reforestation absorbing the surplus emissions; and the third scenario assumes that coal and gas continue to generate power for longer, with even more vigorous reforestation making up the deficit (see "Three paths to 1.5°C," on page 8).

Urgency amid uncertainty

These scenarios represent rigorous, data-driven snapshots of the decarbonization challenge, not predictions; reality may play out quite differently. Still, the implied trade-offs underscore just how stark a departure a 1.5-degree pathway is from the global economy's current trajectory. Keeping to 1.5 degrees would require limiting all future net emissions of carbon dioxide from 2018 onward to 570 gigatons (Gt),[3] and reaching net-zero emissions by 2050 (Exhibit 2). How big a hill is this to climb? At the current pace, the world would exceed the 570-Gt target in 2031. Although an "overshoot" of the 570-Gt carbon budget is common in many analyses, we have avoided it in these scenarios: the impact of an overshoot in temperature, and thus in triggering climate feedbacks, as well as the effectiveness of negative emissions at decreasing temperatures, are unknown—multiplying the uncertainties in any such scenarios.

And CO_2 is just part of the picture. Although as much as 75 percent of the observed warming since 1850 is attributable to carbon dioxide,[4] the remaining warming is linked to other GHGs such as methane and nitrous oxide. Methane, in fact, is 86 times more potent than CO_2 in driving temperature increases over a 20-year time frame,[5] though it persists in the atmosphere for much less time. Our analysis, therefore, encompassed all three major greenhouse gases: carbon dioxide, methane, and nitrous oxide. Our scenarios imply achieving a reduction of more than 50 percent in net CO_2 by 2030 (relative to 2010 levels)[6] and a reduction of other greenhouse gases by roughly 40 percent over that time frame.

[3] Our analysis draws on the work of the Intergovernmental Panel on Climate Change (IPCC) by using a remaining carbon budget of 570 metric gigatons (Gt) CO_2 as of January 1, 2018. Remaining within this budget would equate to a 66 percent chance of limiting warming to 1.5 degrees Celsius. For more about the IPCC methodology and how it differs from other carbon-budget estimates (for example, a 420 $GtCO_2$ for a 66 percent chance, and 580 $GtCO_2$ for a 50 percent chance), see Myles R. Allen et al., *Special report: Global warming of 1.5°C*, IPCC, 2018, ipcc.ch.

[4] Karsten Haustein et al., "A real-time global warming index," *Nature*, November 13, 2017, Nature Scientific Reports 7, Article Number 15417, nature.org; Richard J. Millar and Pierre Friedlingstein, "The utility of the historical record for assessing the transient climate response to cumulative emissions," *Philosophical Transactions of the Royal Society*, May 2018, Volume 376, Number 2119, royalsocietypublishing.org.

[5] Any discussion of methane in this article, unless noted otherwise, assumes GWP 20 with inclusion of climate–carbon feedbacks; GWP20 = 20-year global warming potential (GWP). See Gunnar Myhre et al., "Anthropogenic and natural radiative forcing," *AR5 Climate change 2013: The physical science basis*, Intergovernmental Panel on Climate Change, 2018, Assessment Report 5, Chapter 8, ipcc.ch.

[6] Assumes a 50 percent reduction in gross anthropogenic CO_2 emissions—approximately 19 gigatons (Gt)—coupled with approximately 2 Gt of negative emissions, for a net reduction of 54 percent (reaching net emissions of approximately 17 Gt); 2010 emissions at 38.5 Gt, see Joeri Rogelj et al., "Mitigation pathways compatible with 1.5°C in the context of sustainable development," *Special report: Global warming of 1.5°C*, Intergovernmental Panel on Climate Change, 2018, Chapter 2, ipcc.ch.

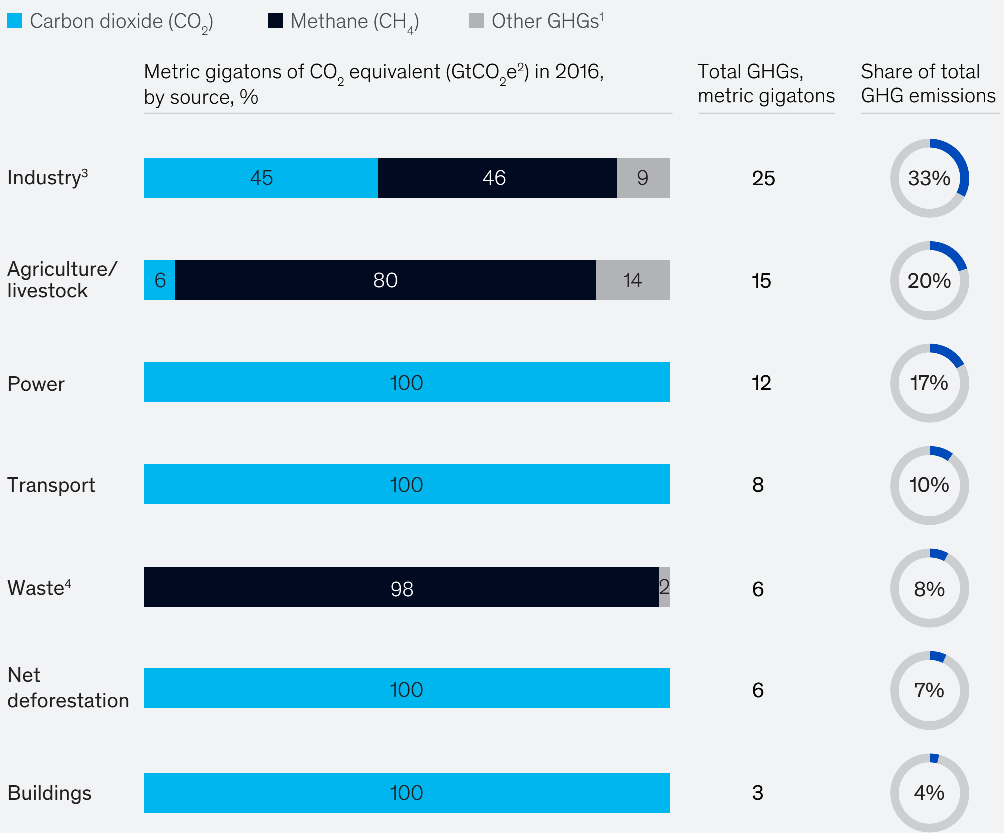
Sidebar

About the research

This article's foundation is a bottom-up, sector-by-sector assessment of greenhouse-gas emissions and abatement potential. Starting with the status quo for each source of emissions (exhibit), we reviewed with McKinsey colleagues and select external experts the technically feasible emission-reduction levers over different time horizons. It was immediately clear that a 1.5-degree pathway would be unreachable if all investments modeled must deliver positive economic returns (and many likely won't, given that the externalities of emissions and related climate effects are not fully priced in). We therefore relaxed this assumption, which implies the need for regulatory incentives to account for challenging abatement opportunities.

To create 1.5-degree-pathway scenarios, we established a binding constraint based on forecasts from the Intergovernmental Panel on Climate Change (IPCC): a remaining carbon budget of 570 gigatons (Gt) for CO_2 as of January 1, 2018, and a complementary reduction of non-CO_2 gases to tackle the warming effects of methane and nitrous oxide. An infinite set of permutations could, theoretically, enable the global economy to remain within these parameters. But constraints such as the time it takes for emerging technologies to achieve meaningful penetration, along with politics and regional barriers, reduce the degrees of freedom. As shown in the accompanying scenario descriptions, the three future states depicted here incorporate different variations on such barriers to implementation.

Anthropogenic greenhouse-gas (GHG) emissions per sector and type of gas



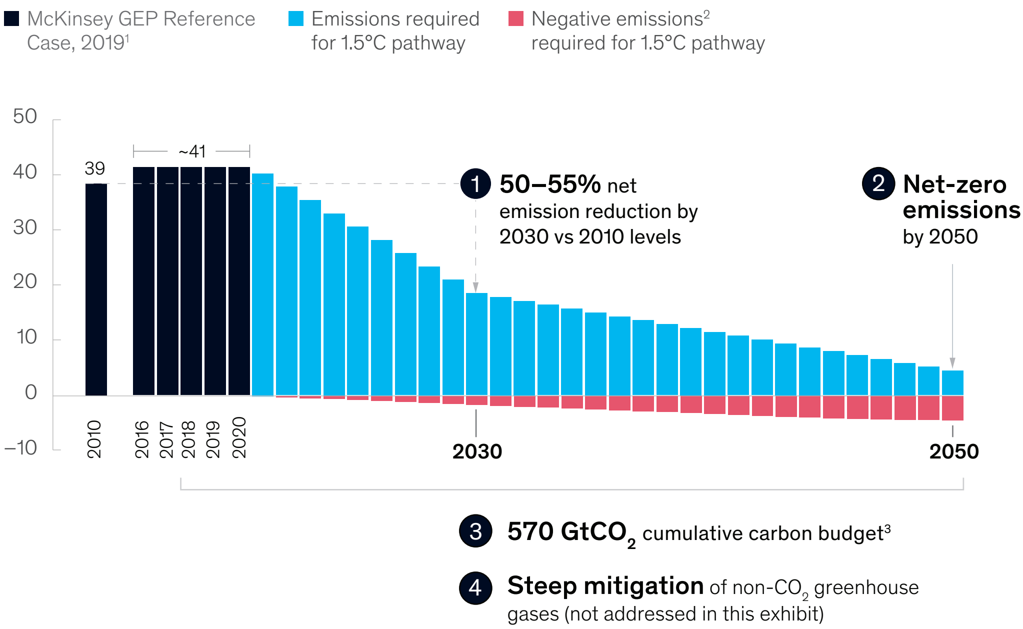
[1] Includes emissions from hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.
[2] Non-CO_2 emissions converted into CO_2e using 20-year global-warming-potential values from IPCC Assessment Report 5.
[3] Includes cement, chemical production, iron and steel, mining, oil and gas, and low- to medium-temperature and high-temperature industries, among others.
[4] Includes food waste, biological treatment of solid waste, incineration and open burning of waste, solid-waste disposal, and wastewater treatment and discharge.

Source: Emissions Database for Global Atmospheric Research (EDGAR), 2015; FAOSTAT, 2015; IEA, 2015; McKinsey *Global Energy Perspective 2019: Reference Case*; McKinsey 1.5°C scenario analysis

Exhibit 2

A paced transition to a 1.5°C pathway has four requirements.

Cumulative global CO_2 emissions, current and historical, metric gigatons of CO_2 ($GtCO_2$) per year



[1] GEP = Global Energy Perspective reference case.
[2] Achieved, for example, from reforestation and carbon-removal technologies such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).
[3] Budget of 570 $GtCO_2$ emissions from 2018 onward offers a 66% chance of limiting global warming to 1.5°C, when assessing historical temperature increases from a blend of air and sea-surface temperatures.

Source: Corinne Le Quéré et al., Global Carbon Budget 2018, *Earth Systems Science Data*, 2018, Volume 10, Number 4, doi.org; IPCC; McKinsey *Global Energy Perspective 2019: Reference Case*; McKinsey 1.5°C scenario analysis

The implication of all this is that reaching a 1.5-degree pathway would require rapid action. Our scenarios reflect a world in which the steepest emission declines would need to happen over the next decade. Without global, comprehensive, and near-term action, a 1.5-degree pathway is likely out of reach.

Regardless of the scenario, five major business, economic, and societal shifts would underlie a transition to a 1.5-degree pathway. Each shift would be enormous in its own right, and their interdependencies would be intricate. That makes an understanding of these trade-offs critical for business leaders, who probably will be participating in some more than others but are likely to experience all five.

Shift 1: Reforming food and forestry

Although the start of human-made climate change is commonly dated to the Industrial Revolution, confronting it successfully would require taking a hard look at everything, including fundamentals such as the trees that cover the earth, as well as the food we eat and the systems that grow and supply it.

Changing what we eat, how it's farmed, and how much we waste

The world's food and agricultural systems are enormously productive, thanks in no small part to the Green Revolution that, starting in the 1960s, boosted yields through mechanization, fertilization, and high-yielding crop varieties. However, modern agricultural practices have depleted CO_2 in the soil, and, even though some CO_2 is absorbed by crops and plants, agriculture remains a net emitter of CO_2. Moreover, agricultural and food systems generate the potent greenhouse gases methane and nitrous oxide—meaning that this critical system contributes 20 percent of global GHG emissions[7] each year. Moreover, population growth, rising per capita food consumption in emerging markets, and the sustained share of meat in diets everywhere mean that agricultural emissions are poised to increase by about 15 to 20 percent by 2050, absent changes in global diets and food-production practices.

The livestock dilemma. The biggest source of agricultural emissions—almost 70 percent—is from the production of ruminant meat. Animal protein from beef and lamb is the most GHG-intensive food, with production-related emissions more than ten times those of poultry or fish and 30 times those of legumes. The culprit? Enteric fermentation inherent in the digestion of animals such as cows and sheep. In fact, if the world's cows were classified as a country in the emissions data, the impact of their GHG emissions (in the form of methane) would put cows ahead of every country except China.

Delivering the emissions reduction needed to reach a 1.5-degree pathway would imply a large dietary shift: reducing the share of ruminant animal protein in the global protein-consumption mix by half, from about 9 percent in current projections for 2050 to about 4 percent by 2050.

Changing the system. The agricultural system itself would need to change, too. Even if consumption of animal protein dropped dramatically, in a 1.5-degree world, the emissions from remaining agricultural production would need to fall as well.

New cultivation methods would help. Consider rice, which currently accounts for 14 percent of total agricultural emissions. The intermittent flooding of rice paddies is a common, traditional growing method—the flooding prevents weeds—that results in outsize methane emissions as organic matter rots. To reach a 1.5-degree pathway, new cultivation approaches would need to prevail, leading to a 53 percent reduction in the intensity of methane emissions from rice cultivation by 2050.

Finally, about one-third of global food output is currently lost in production or wasted in consumption. To achieve a 1.5-degree pathway, that proportion could not exceed 20 percent by 2050. Curbing waste would reduce both the emissions associated with growing, transporting, and refrigerating food that is ultimately wasted, and the methane released as the organic material in wasted food decomposes.

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[7] Does not include land use, land-use change, or forestry. Non-CO_2 emissions converted using 20-year global-warming-potential values. See T. F. Stocker et al., *AR5 Climate change 2013: The physical science basis*, Intergovernmental Panel on Climate Change, 2018, Assessment Report 5, ipcc.ch.

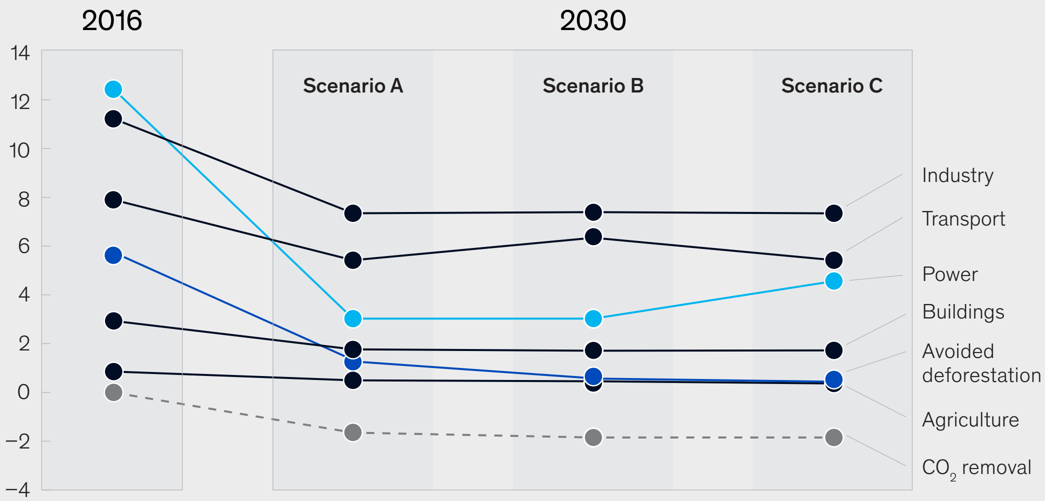
(continued on page 12)

Three paths to 1.5°C

To help understand the challenges of mitigating climate change, we modeled three scenarios. This allowed us to account for flexibility in how fast various large emitters of greenhouse gases (GHGs) might decarbonize—without being predictive. While the scenarios are not forecasts, we hope they nonetheless serve as a useful addition to existing analytic perspectives on GHG abatement. The scenarios address only CO_2 emissions (the most prevalent anthropogenic greenhouse gas and key to any GHG-abatement scenario). While achieving a 1.5°C pathway is technically achievable, it would require all sectors to decarbonize. Should one lag behind, others would need to move faster. The scenarios help define some of these trade-offs.

Three challenging—yet possible—scenarios could limit warming.

Emissions per source, metric gigatons of CO_2 ($GtCO_2$) in 2016 and 2030



Scenario A
The decarbonization pace is set by technology readiness, cost-effectiveness, and ease of implementation

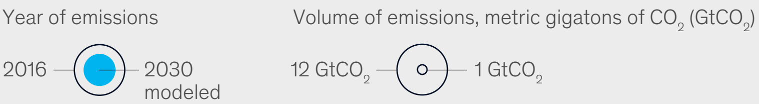
Scenario B
Oil fuels transport for longer; reforestation and curbing deforestation abate the additional emissions

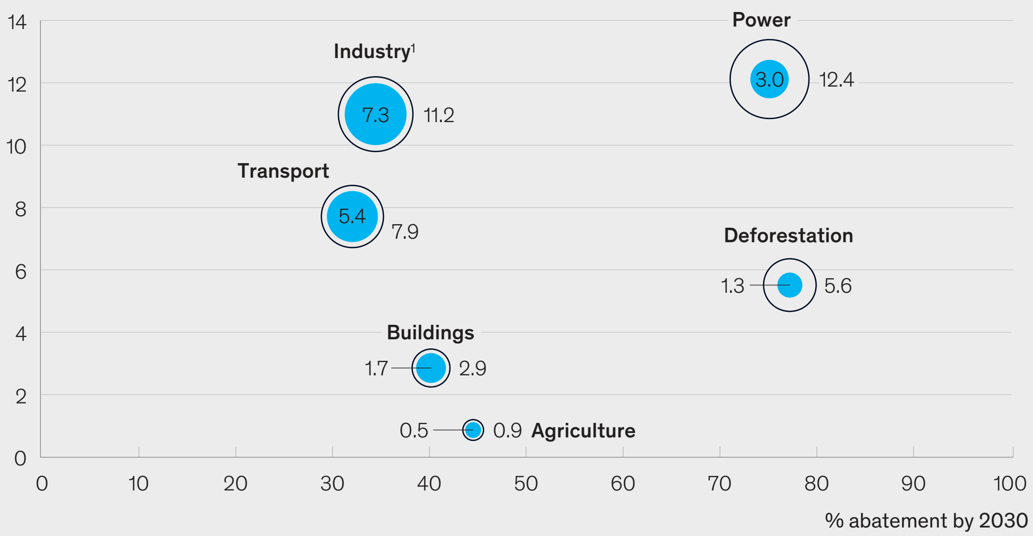
Scenario C
Coal and gas generate power for longer; reforestation and curbing deforestation abate the surplus CO_2

Source: McKinsey *Global Energy Perspective 2019: Reference Case*; McKinsey 1.5°C scenario analysis

Scenario A: Significant and steady decarbonization

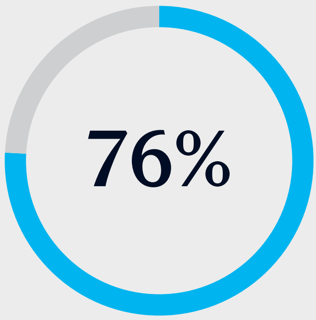
A paced transition, enabled by regulation and targeted investment, would require immediate action but would support a significant and steady decrease in emissions. By 2030, all sectors/sources would have abated at least 30% of their 2016 CO_2 emissions.



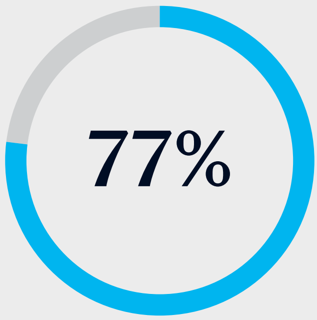


The heavy hitters

Share of category's total 2016 emissions



of the power sector's CO_2 emissions abated by 2030



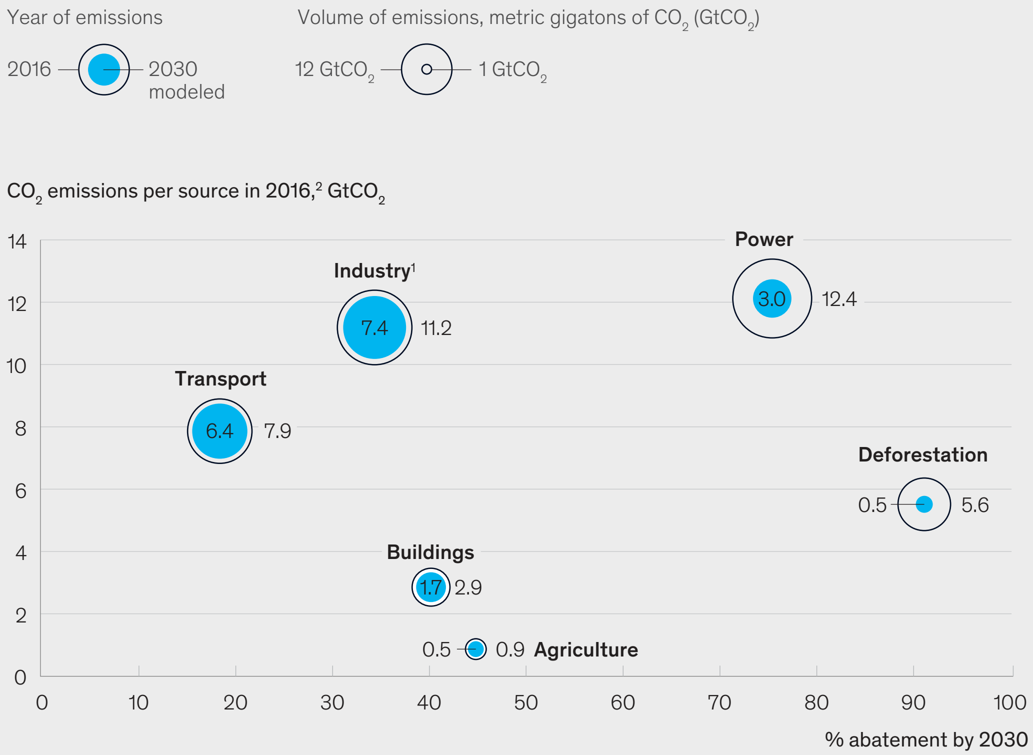
of deforestation's CO_2 emissions abated by 2030

[1] Includes cement, chemical production, iron and steel, mining, oil and gas, and low- to medium-temperature and high-temperature industries, among others.
[2] Carbon-dioxide removal (not pictured here) would abate 4% of 2016 CO_2 emissions in Scenario A.

Source: McKinsey 1.5°C scenario analysis

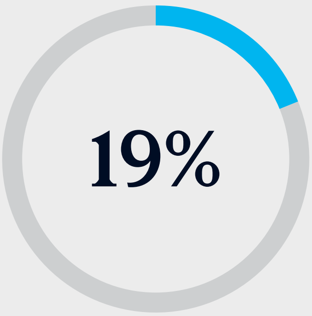
Scenario B: Oil decarbonizes more slowly

Oil continues to be the major fuel for transport, and that sector decarbonizes more slowly. To compensate, reforestation would need to speed up, and 90% of CO_2 emissions from deforestation would have to be abated by 2030. In this scenario, all sectors/sources except transport would manage to abate by at least one-third of their 2016 emissions by 2030.

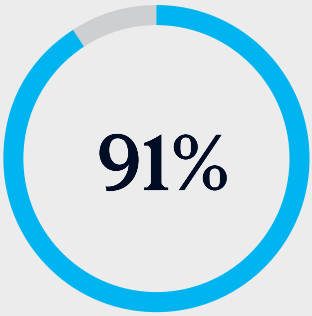


Trade-offs

Share of category's total 2016 emissions



of the transport sector's CO_2 emissions abated by 2030



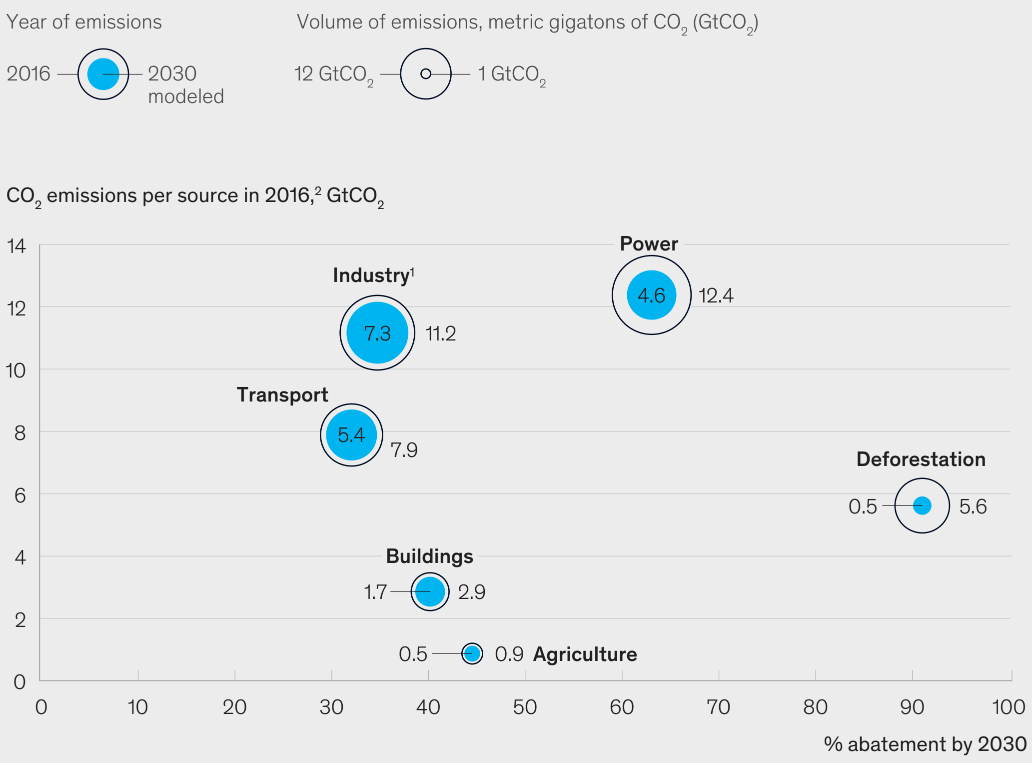
of deforestation's CO_2 emissions abated by 2030

[1] Includes cement, chemical production, iron and steel, mining, oil and gas, and low- to medium-temperature and high-temperature industries, among others.
[2] Carbon-dioxide removal (not pictured here) would abate 5% of 2016 CO_2 emissions in Scenario B.

Source: McKinsey 1.5°C scenario analysis

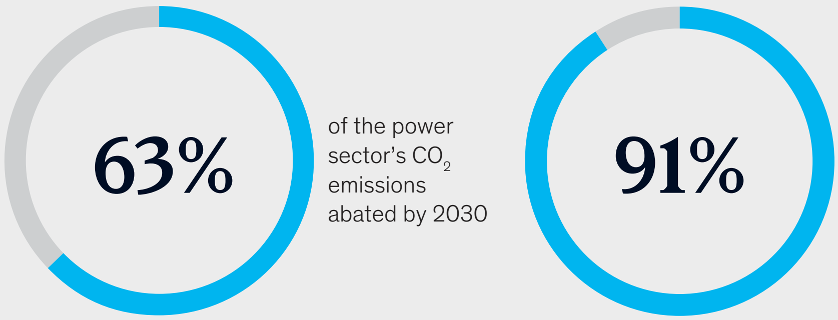
Scenario C: Power decarbonizes more slowly

Coal and gas generate power for longer, compensated by faster reforestation, and abate 90% of all CO_2 emissions from deforestation. In this scenario, all sectors/sources would abate more than 30% of their emissions.



Trade-offs

Share of category's total 2016 emissions



63% of the power sector's CO_2 emissions abated by 2030

91% of deforestation's CO_2 emissions abated by 2030

[1] Includes cement, chemical production, iron and steel, mining, oil and gas, and low- to medium-temperature and high-temperature industries, among others.
[2] Carbon-dioxide removal (not pictured here) would abate 4% of 2016 CO_2 emissions in Scenario C.

Source: McKinsey 1.5°C scenario analysis

Sidebar

Carbon avoided is carbon abated

The role of greater efficiency in achieving a 1.5-degree pathway goes beyond improving the operations of any single industry. After all, carbon avoided is as beneficial as carbon abated. As part of our analysis, we therefore studied the impact of greater efficiency, as well as how smart substitution of lower-carbon alternatives and demand-reducing regulations could help lower CO_2 across all scenarios. Taken together, these actions could potentially, by 2050, help bypass about 15 percent of today's emissions (exhibit).

By 2050, reducing demand could help bypass approximately 15 percent of today's CO_2 emissions.

Efficiencies
Insulation and home-energy management could reduce demand for space heating and cooling, lowering CO_2 emissions 30% by 2050

Substitutes
Alternative building materials—eg, cross-laminated timber—could reduce the demand for cement[1]

Recycling
Replacing an additional 20% of inputs to the steel-production process with scrap steel could lower emissions from iron ore use

Recycling could cover ~60% of plastics demand by 2050

Consumption patterns shift
Remote communication and modal shifts in transportation could reduce emissions in the aviation sector 10% by 2030

Measures such as a tax on internal-combustion-engine vehicles—eg, London's congestion charge—would decrease the kilometers traveled per vehicle

[1] In our scenarios, electrification also plays a modest role in decarbonizing marine transport, especially for coastal vessels such as ferries. In aviation, electrification could account for up to 2 percent of the sector's final energy consumption by 2030 and about 6 percent by 2050.

Source: *McKinsey Global Energy Perspective 2019: Reference Case*; McKinsey 1.5°C scenario analysis

Halting deforestation

Deforestation—quite often linked to agricultural practices, but not exclusively so—is one of the largest carbon-dioxide emitters, accounting for nearly 15 percent of global CO_2 emissions. Deforestation's outsize impact stems from the fact that removing a tree both *adds* emissions to the atmosphere (most deforestation today involves clearing and burning) and *removes* that tree's potential as a carbon sink.

Even after accounting for ongoing reforestation efforts, deforestation today claims an area close to the size of Greece every year. Achieving a 1.5-degree pathway would mean dramatically slowing this. By 2030, if all fossil-fuel emissions were rapidly reduced (as in our first scenario), and all sectors of the economy pursued rapid decarbonization, deforestation would still need to fall about 75 percent. In the other two scenarios, where reduced deforestation serves to help counteract slower decarbonization elsewhere, deforestation would need to be nearly halted as early as 2030. Either outcome would require a combination of actions (including regulation, enforcement, and incentives such as opportunity-cost payments to farmers) outside the scope of our analysis.

Shift 2: Electrifying our lives

Electrification is a massive decarbonization driver for transportation and buildings—powerful both in its own right and in combination with complementary changes such as increased public-transportation use and the construction or retrofitting of more efficient buildings.

Electrified road transport

The road-transportation sector—passenger cars and trucks, buses, and two- and three-wheeled vehicles—

accounts for 15 percent of the carbon dioxide emitted each year. Nearly all of the fuels used in the sector today are oil based. To decarbonize, this sector would need to shift rapidly to a cleaner source of energy, which in the scenarios we modeled was predominantly electricity, and leverage either batteries with sustainably produced electricity or fuel cells with sustainably produced hydrogen to power an electric engine.[8] (Biofuels would also contribute to road transportation. The role of those fuels is discussed later.)

In our first scenario (rapid fossil-fuel reduction), road transportation could reach a 1.5-degree pathway through a rapid migration to EVs powered by a mix of batteries and hydrogen fuel cells, and supported by deep, renewable power penetration. Sales of internal-combustion vehicles would account for less than half of global sales by 2030 and be fully phased out by 2050.

These shifts would, in turn, prompt a rapid increase in demand for batteries, challenging that industry to scale more quickly and improve its sustainability (for more, see "Building a more sustainable battery industry," on McKinsey.com).

One lever for smoothing the transition would be reducing overall mileage driven by personal vehicles through policies that discouraged private-vehicle usage, such as banning cars in city centers, taxing vehicles on a per-mile-traveled basis, and encouraging the use of public transport. By 2030, such measures could reduce by about 10 percent the number of miles traveled by passenger cars.

To be sure, the rate of change implied in this scenario is dramatic (sales of EV passenger vehicles,[9] for example, would need to grow nearly 25 percent a year between 2016 and 2030). Nonetheless, the scope of the task will be familiar to global OEMs, which have themselves been prioritizing the shift to electrification.

What if the electrification of road transportation was still aggressive but more gradual—specifically, if sales of internal-combustion vehicles still accounted for more than half of total sales by 2030, as we assumed in our second scenario? In that case, reaching a 1.5-degree pathway would necessitate dramatic levels of CO_2 sequestration, implying the need for unprecedented levels of reforestation to cover the difference, as we describe later.

Electrified buildings

Electrification would also help decarbonize buildings, where CO_2 emissions represent about 7 percent of the global total. Space and water heating, which typically rely on fossil fuels such as natural gas, fuel oil, and coal, are the primary emission contributors. By 2050, electrifying these two processes in those residences and commercial buildings where it is feasible would abate their 2016 heating emissions by 20 percent (if the electricity were to come from clean sources). By expanding the use of district heating and blending hydrogen or biogas into gas grids for cooking and heating, the buildings sector could potentially reduce nearly an additional 40 percent of emissions. Both would be required to reach a 1.5-degree pathway in our rapid fossil-fuel-reduction scenario.

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[8] In our scenarios, electrification also plays a modest role in decarbonizing marine transport, especially for coastal vessels such as ferries. In aviation, electrification could account for up to 2 percent of the sector's final energy consumption by 2030 and about 6 percent by 2050.

[9] Includes battery electric, fuel-cell electric, plug-in, and hybrid vehicles.

Across all three scenarios, the share of households with electric space heating would have to increase from less than 10 percent today to 26 percent by 2050. To make the most of electric heating, buildings would need to replace traditional heating equipment with newer, more efficient technologies. Improved insulation and home energy management would also be necessary to maximize the benefits of electric heating and enable further emissions reductions by 2050.

The good news is that electric technologies are already available at scale, and their economics are often positive. However, the combination of higher up-front costs, long payback times, and market inefficiencies often prevents consumers and companies from acting.[10] Moreover, the average life span of currently installed (but less efficient) equipment can span decades, making inertia tempting for many asset owners, and a broad-based shift to electric heating more challenging.

Shift 3: Adapting industrial operations

The role of electrification could not stop with buildings and cars. It would need to extend across a broad swath of industries as part of a collection of operational adaptations that would be part of achieving a 1.5-degree pathway.

Electrified industries

Industrial subsectors with low- and medium-temperature heat requirements, such as construction, food, textiles, and manufacturing, would need to accelerate electrification of their operations relatively quickly. By 2030, more than 90 percent of the abatement for mid- to low-temperature industries depends on electrifying production with power sourced from clean-energy sources. All told, these industries would need to electrify at more than twice their current level by 2050 (from 28 percent in 2016 to 76 percent in 2050) to achieve a 1.5-degree pathway (for more about the economics of industry electrification, see “Hybrid equipment: A first step to industry electrification,” on McKinsey.com).

Electrification would prove more difficult for process industries with high-temperature requirements, such as iron and steel, or cement (among the biggest CO_2 emitters). These subsectors, along with others such as chemicals, mining, and oil and gas that are also challenging and expensive to decarbonize, would put a premium on efficiency efforts (including recycling and the use of alternative materials) and would depend heavily on innovation in hydrogen and clean fuels.

Greater industrial efficiency

Across the board, embracing the circular economy and boosting efficiency would enable a wide cross-section of industries to decrease GHG emissions, reduce costs, and improve performance (see sidebar “Carbon avoided is carbon abated”). By 2050, for example, nearly 60 percent of plastics consumption could be covered by recycled materials.[11] Similarly, steelmakers might be able to reduce GHG emissions by further

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[10] For more on improving energy efficiency in buildings, see “Resource revolution: Meeting the world’s energy, materials, food, and water needs,” McKinsey Global Institute, November 2011, on McKinsey.com, and view the interactive.

[11] Thomas Hundertmark, Mirjam Mayer, Chris McNally, Theo Jan Simons, and Christof Witte, “How plastics waste recycling could transform the chemical industry,” December 2018, McKinsey.com.

leveraging scrap steel, which today accounts for nearly one-third of production. Cement manufacturers, meanwhile, would need to abate their current CO_2 emissions, which accounted for 6 percent of global CO_2 emissions in 2016, by more than 7 percent by 2030 through a range of short-term efficiency improvements, including the greater use of advanced analytics.

Tackling fugitive methane

Another big operational adaptation would be "fugitive methane," or the natural gas that is released through the activities of oil and gas companies, as well as from coal-mining companies (Exhibit 3). Each would need to tackle the issue to reach a 1.5-degree pathway.

For oil and gas companies, methane is the largest single contributor of GHGs. The good news, as our colleagues write, is that, while eliminating fugitive methane is challenging, many abatement options are available—often with favorable economics (for more, see "Meeting big oil's decarbonization challenge," on McKinsey.com).

Coal mines, meanwhile, release the gas as part of their underground operations. Solutions for capturing methane (and using it to generate power) exist but are not commonly implemented.[12] Moreover, there are no ready solutions for all types of mines, and the investment is not economical in many cases.

Shift 4: Decarbonizing power and fuel

Widespread electrification would hold enormous implications for the power sector. We estimate that electrification would at least triple demand for power by 2050, versus a doubling of demand, as reported in *Global Energy Perspective 2019: Reference Case*.[13] The power system would have to decarbonize in order for the downstream users of that electricity—everything from factories to fleets of electric vehicles—to live up to their own decarbonization potential. Renewable electricity generation is therefore a pivotal piece of the 1.5-degree puzzle. But it's not the only piece: expanding the hydrogen market would be vital, given the molecule's versatility as an energy source. Expanding the use of bioenergy would be important, too.

Renewables

Replacing thermal assets with renewable energy would require a dramatic ramp-up in manufacturing capacity of wind turbines and solar panels. By 2030, yearly build-outs of solar and wind capacity would need to be eight and five times larger, respectively, than today's levels.[14]

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[12] In the United States, for example, the Coalbed Methane Outreach Program—part of the Environmental Protection Agency—works with the coal-mining industry to support project development and to help overcome technical and other barriers to implementation.

[13] The impact of increased demand for electricity on its price is beyond the scope of our analysis. For further discussion of the issue, see *Global Energy Perspective 2019: Reference Case*, January 2019, McKinsey.com; and Arnout de Pee, Dickon Pinner, Occo Roelofsen, Ken Somers, Eveline Speelman, and Maaike Witteveen, "How industry can move toward a low-carbon future," July 2018, McKinsey.com, which examines the trade-offs involved in the decarbonization of four industrial commodities: ammonia, cement, ethylene, and steel.

[14] Nuclear power could also contribute to the supply of low-carbon power, but it is largely outside the scope of our analysis. In our modeling, we assumed that nuclear capacity will grow 6 percent between 2020 and 2050, in line with McKinsey's *Global Energy Perspective 2020: Reference Case* (forthcoming on McKinsey.com).

It would also entail a massive reduction in coal- and gas-fired power generation. Indeed, to remain on a 1.5-degree pathway, coal-powered electricity generation would need to decrease by nearly 80 percent by 2030 in our rapid fossil-fuel-reduction scenario. Even in the scenario where coal and gas generate power for longer, the reduction would need to be about two-thirds by 2030. The sheer scope of this shift cannot be overstated. Coal today accounts for about 40 percent of global power generation. What's more, by 2030 the amount of electricity generated by natural gas would have to decrease by somewhere between 20 and 35 percent. As it stands, nearly one-quarter of the world's power is generated using natural gas.

A fast migration to renewable energy would bring unique regional challenges, most notably the need to match supply and demand at times when the sun doesn't shine and the wind doesn't blow. In the nearer term, a mix of existing approaches could help with day-to-day and seasonal load balancing, although emerging technologies such as hydrogen, carbon capture and storage, and more efficient long-distance transmission would ultimately be needed to reach a 1.5-degree pathway.

Bioenergy
Increasing the use of sustainably sourced bioenergy—for instance, biokerosene, biogas, and biodiesel—would also be required in any 1.5-degree-pathway scenario. Our scenarios approached bioenergy conservatively (abating about 2 percent of the CO_2 needed by 2030 to reach a 1.5-degree pathway). Its most pressing mandate over that time frame would be substituting for oil-based fuels in aviation and marine transport, until which time sustainably sourced synthetic fuels would account for a larger share. Nonetheless, any scale-up of bioenergy would need to acknowledge the realities of land use, and it would also need to strike a balance between the desire for sustainable energy, on the one hand, and the basic human need to feed a growing world population, on the other.

Hydrogen
Hydrogen produced from renewable energy—so-called green hydrogen—would play a huge part in any 1.5-degree pathway. "Blue hydrogen," which is created using natural gas and the resulting CO_2 emissions stored via carbon capture and storage, would also play a role. This is because about 30 percent of the energy-related CO_2 emitted across sectors is hard to abate with electricity only—for example, because of the high heat requirements of industries such as steelmaking. Hydrogen's potential is strongest in the steelmaking and chemical industries; the aviation, maritime, and short-haul trucking segments of the transport sector; oil- and gas-heated buildings; and peak power generation. In addition, green hydrogen has at least some potential in a range of other sectors, including cement, manufacturing, passenger cars, buses and short-haul trucks, and residential buildings. Scaling the hydrogen market would require efforts across the board, from building the supporting infrastructure to store and distribute it to establishing new technical codes and safety standards. For more, see the Hydrogen Council's 2017 report, *Hydrogen scaling up: A sustainable pathway for the global energy transition*.

Shift 5: Ramping up carbon-capture and carbon-sequestration activity
Deep decarbonization would also require major initiatives to either capture carbon from the point at which it is generated (such as ammonia-production facilities or thermal-

power plants) or remove carbon dioxide from the atmosphere itself. Currently, it is impossible to chart a 1.5-degree pathway that does not remove CO_2 to offset ongoing emissions. The math simply does not work.

Carbon capture, use, and storage

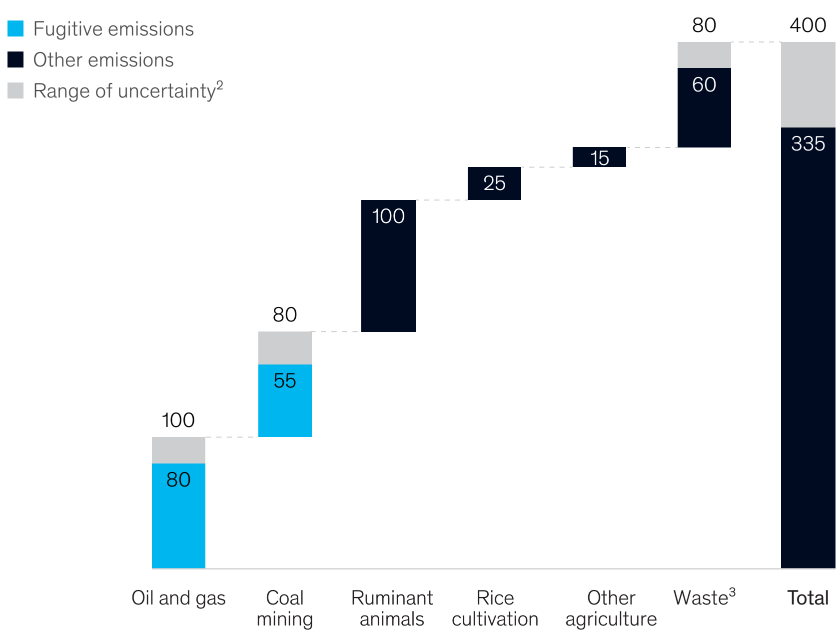
Developing the nascent carbon capture, use, and storage (CCUS) industry would be critical to remaining on a 1.5-degree pathway. In simplest terms, this suite of technologies collects CO_2 at the source (say, from industrial sites). CCUS would prevent emissions from entering the atmosphere by compressing, transporting, and either storing the carbon dioxide underground or using it as an input for products.

In the first, more rapid decarbonization scenario, the amount of CO_2 captured via CCUS each year would have to multiply by more than 125 times by 2050 from 2016 levels, to ensure that emissions stay within the 1.5-degree-pathway budget. This is a tall order that exceeds the relatively bullish forecasts of McKinsey researchers who have been investigating both the challenges and the potential of CCUS, suggesting that more innovation and regulatory support would be needed for it to play a central role.

Exhibit 3

Methane emissions would need to be reduced to reach a 1.5°C pathway.

Anthropogenic methane emissions,[1] 2016, metric megatons of methane ($MtCH_4$)



Note: Major uncertainties affect estimates of fugitive emissions. There is no global consensus on their monitoring.

[1] The methane emissions depicted here—when expressed as metric gigatons of CO_2 equivalents and based on 20-year global-warming-potential values (GWP20) from IPCC Assessment Report 5—are as follows: oil and gas (7 Gt); coal mining (5 Gt); ruminant animals (8 Gt); rice cultivation (2 Gt); other agriculture (1 Gt); waste (6 Gt). GWP20 values include climate-carbon feedbacks.

[2] Ranges of uncertainty: for oil and gas, assumes upper bound of +25% (shown); for coal mining, assumes a lower bound of –45%, an average of 55 Mt (shown), and an upper bound of +40% (shown); for waste, assumes a range based on lowest and highest values in available literature (shown).

[3] Includes treatment and disposal of solid waste, incineration and open burning of waste, and wastewater treatment and discharge.

Source: Emissions Database for Global Atmospheric Research (EDGAR), 2015; FAOSTAT; Global Carbon Project; IEA; McKinsey *Global Energy Perspective 2019: Reference Case*; McKinsey 1.5°C scenario analysis

Technology-based carbon-dioxide removal

While reducing CO_2 emissions is a vital part of reaching a 1.5-degree pathway, it would not be enough by itself. Additional carbon dioxide would need to be removed from the atmosphere. Carbon-dioxide removal involves capturing and permanently sequestering CO_2 that has already been emitted, through either nature-based solutions or approaches that rely on technology, which are promising but nascent. Examples of the latter include direct air capture (which is operating at a pilot plant in Iceland).

Reforestation at scale

Even in an extremely optimistic scenario for these technologies, though, we would still need large-scale, nature-based carbon-dioxide removal, which is proved at scale: it is what trees and plants have been doing for millions of years. Over the next decade, a massive, global mobilization to reforest the earth would be required to achieve a 1.5-degree pathway. In our scenarios, reforestation represents the key lever to compensate for the hardest-to-abate sectors, particularly for pre-2030 emissions.

All the scenarios we modeled would require rapid reforestation between now and 2030. At the height of the effort in that year, an area the size of Iceland would need to be reforested annually. By 2050, on top of nearly avoiding deforestation and replacing any forested areas lost to fire, the world would need to have reforested more than 300 million hectares (741 million acres)—an area nearly one-third the size of the contiguous United States. As we noted earlier, the pace of reforestation would need to be faster still should either the transport or power-generation sectors decarbonize more slowly than depicted in our scenarios. Under those circumstances, the requisite annual reforestation would need to be nearly half the size of Italy by 2030.

How feasible would this be? The necessary land appears to be available. Mass reforestation has taken place, admittedly at a much smaller scale, in China. And carbon-offset markets could help catalyze reforestation (and innovation). That said, it is difficult to imagine reforestation taking place on the scale or at the pace described in this article absent coordinated government action—on top of the shifts described in the scenarios themselves.

Will these five shifts become the building blocks of an orderly transition to a decarbonized global economy? Or will slow progress against them be a warning sign that the climate is headed for rapid change in the years ahead? While unknowable today, the answers to these questions are likely to emerge in a remarkably short period of time. And if the global economy is to move to a 1.5-degree pathway, business leaders of all stripes need knowledge of the shifts, clarity about each one's relevance to their companies, insights into the difficult trade-offs that will be involved, and creativity to forge solutions that are as urgent and far-reaching as the climate challenge itself. Q