McKinsey on Climate Change

September 2020

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Introduction

Amid a global pandemic, societal priorities have shifted dramatically. Governments, businesses, and communities are focused on navigating a public-health crisis and mitigating the effects of economic devastation. Against this backdrop, there is another threat to lives and livelihoods—climate change. Can we still focus on climate risks and the broader sustainability agenda? Our belief is that yes, we can, and we cannot afford to wait. McKinsey research shows that if we fail to adapt and dramatically reduce emissions, hundreds of millions of lives, trillions of dollars of economic activity, and the world's physical and natural capital will be at risk. Importantly, a low-carbon economic recovery could not only initiate the significant emissions reductions needed to halt climate change but also create more jobs and economic growth than a high-carbon recovery would.

This collection brings together recent McKinsey research and perspectives on the climate risks the world must confront and actions to reduce emissions. Physical risks from climate change are already present and growing. Facing threats are the world's socioeconomic systems, including food systems, physical assets, infrastructure, natural capital, and livability and workability. The extent of the impact ranges from disruption to destruction. In response, government and business leaders across countries and industries must adapt to the risks that are already locked in and prevent further risk by achieving net-zero greenhouse emissions.

In this selection of McKinsey work, readers will find detailed analyses of climate risks across geographies and industries—the physical hazards and socioeconomic impacts. These pages also provide guidance on the technological and strategic solutions that are necessary to protect people and assets, build resilience, reduce exposure, and decarbonize. Those solutions include, for example, adapting food systems and supply chains and rethinking infrastructure; adopting clean technologies to decarbonize the automotive industry; encouraging consumer behavior shifts that will have an impact in the fashion industry; and tapping the potential of carbon capture, use, and storage. We also explore the role of these efforts on business models and financial markets and seek ways to make sustainability a competitive advantage.

What countries do in the next decade will decide what world future generations will live in. Change requires courageous leadership and a willingness to confront and tackle climate risks alongside other complex and competing priorities. Previous crises have underscored an important lesson: it is essential to focus on both the short-term challenge and the longer-term horizon. Tackling climate risk won't be easy, but it will be worth it to build a more prosperous, equitable, resilient, and sustainable world.

Dickon Pinner
Senior partner, San Francisco

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Understanding climate risk

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Confronting climate risk

The changing climate is poised to create a wide array of economic, business, and social risks over the next three decades. Leaders should start integrating climate risk into their decision making now.

After more than 10,000 years of relative stability—the full span of human civilization—the Earth's climate is changing. Since the 1880s, the average global temperature has risen by about 1.1 degrees Celsius, driving substantial physical impact in regions around the world. As average temperatures rise, acute hazards such as heat waves and floods grow in frequency and severity, and chronic hazards such as drought and rising sea levels intensify. These physical risks from climate change will translate into increased socioeconomic risk, presenting policy makers and business leaders with a range of questions that may challenge existing assumptions about supply-chain resilience, risk models, and more.

To help inform decision makers around the world so that they can better assess, adapt to, and mitigate the physical risks of climate change, the McKinsey Global Institute (MGI) recently released a report, *Climate risk and response: Physical hazards and socioeconomic impact*. (For more on the methodology behind the report, see sidebar "About the research.") Its focus is on understanding the nature and extent of physical risk from a changing climate over the next three decades, absent possible adaptation measures.

This article provides an overview of the report. We explain why a certain level of global warming is locked in and illustrate the kinds of physical changes that we can expect as a result. We examine closely four of the report's nine case studies, showing how physical change might create significant socioeconomic risk at a local level. Finally, we look at some of the choices most business leaders will have to confront sooner than later.

Our hope is that this work helps leaders assess the risk and manage it appropriately for their company. The socioeconomic effects of a changing climate will be large and often unpredictable. Governments, businesses, and other organizations will have to address the crisis in different and often collaborative ways. This shared crisis demands a shared response. Leaders and their organizations will have to try to mitigate the effects of climate change even as they adapt to the new reality it imposes on our physical world. To do so, leaders must understand the new climate reality and its potential impact on their organizations in different locales around the world.

The new climate reality

Some climate change is locked in.

The primary driver of temperature increase over the past two centuries is the human-caused rise in atmospheric levels of carbon dioxide (CO_2) and other greenhouse gases, including methane and nitrous oxide. Since the beginning of the Industrial Revolution in the mid-18th century, humans have released nearly 2.5 trillion metric tons of CO_2 into the atmosphere, raising atmospheric CO_2 concentrations by 67 percent. Carbon dioxide lingers in the atmosphere for hundreds of years. As a result, nearly all of the warming that occurs is permanent, barring large-scale human action to remove CO_2 from the atmosphere. Furthermore, the planet will continue to warm until we reach net-zero emissions.

If we don't make significant changes, scientists predict that the global average temperature may increase by 2.3 degrees Celsius by 2050, relative to the preindustrial average. Multiple lines of evidence suggest that this could trigger physical feedback loops (such as the thawing of permafrost leading to the release of significant amounts of methane) that might cause the planet to warm for hundreds or thousands of years. Restricting warming to below 1.5 or 2.0 degrees would reduce the risk of the earth entering such a "hothouse" state.

The nature of climate-change risk

Stakeholders can address the risk posed by climate change only if they understand it clearly and see the nuances that make it so complicated to confront.

About the research

This article was adapted from the McKinsey Global Institute (MGI) report *Climate risk and response: Physical hazards and socioeconomic impacts*.[1] Its authors are **Jonathan Woetzel** (a director of MGI and a senior partner in McKinsey's Shanghai office), **Dickon Pinner** (senior partner in the San Francisco office and global leader of McKinsey's Sustainability Practice), **Hamid Samandari** (senior partner in the New York office and chair of McKinsey's knowledge council), **Hauke Engel** (partner in the Frankfurt office), **Mekala Krishnan** (senior fellow at MGI), **Brodie Boland** (associate partner in the Washington, DC, office), and **Carter Powis** (consultant in the Toronto office).

The 131-page MGI report, released in January 2020, measures the impact of climate change based on the extent to which it could affect human beings, human-made physical assets, and the natural world. Most of the climatological analysis performed for the report was completed by the Woods Hole Research Center. There are a range of estimates for the pace of global warming; we have chosen the Representative Concentration Pathway (RCP) 8.5 scenario because it enables us to assess physical risk in the absence of further decarbonization. Action to reduce emissions could delay projected outcomes. Download the full report on McKinsey.com.

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

We find that physical climate risk has seven characteristics:

— *Increasing.* Physical climate risks are generally increasing across the globe, even though some countries may find some benefits (such as increased agricultural yields in Canada, Russia, and parts of northern Europe). The increased physical risk would also increase socioeconomic risk.

— *Spatial.* Climate hazards manifest locally. There are significant variations between countries and even within countries. The direct effects of physical climate risk must be understood in the context of a geographically defined area.

— *Nonstationary.* For centuries, financial markets, companies, governments, and individuals have made decisions against the backdrop of a stable climate. But the coming physical climate risk is ever-changing and nonstationary. Replacing a stable environment with one of constant change means that decision making based on experience may prove unreliable. For example, long-accepted engineering parameters for infrastructure design may need to be rethought; homeowners and banks may need to adjust assumptions about long-term mortgages.

— *Nonlinear.* Physiological, human-made, and ecological systems have evolved or been optimized over time to withstand certain thresholds. Those thresholds are now being threatened. If or when they are breached, the impact won't be incremental—the systems may falter, break down, or stop working altogether. Buildings designed to withstand floods of a certain depth won't withstand floods of greater depths; crops grown for a mild climate will wither at higher temperatures. Some adaptation can be carried out fairly quickly (for example, better preparing a factory for a flood). But natural systems such as crops may not be able to keep pace with the current rate of temperature increase. The challenge becomes even greater when multiple risk factors are present in a single region.

— *Systemic.* Climate change can have knock-on effects across regions and sectors, through interconnected socioeconomic and financial systems. For example, flooding in Florida might not only damage housing but also raise insurance costs, lower property values, and reduce property-tax revenues. Supply chains are particularly vulnerable systems, since they prize efficiency over resilience. They might quickly grind to a halt if critical production hubs are affected by intensifying hazards.

— *Regressive.* The poorest communities and populations of the world are the most vulnerable. Emerging economies face the biggest increase in potential impact on workability and livability. The poorest countries often rely on outdoor work and natural capital, and they lack the financial means to adapt quickly.

— *Unprepared.* Our society hasn't confronted a threat like climate change, and we are unprepared. While companies and communities are already adapting, the pace and scale of adaptation must accelerate. This acceleration may well entail rising costs and tough choices, as well as coordinated action across multiple stakeholders.

How climate risk plays out on a local level

There is already plenty of evidence of the extensive damage that climate risk can inflict. Since 2000, there have been at least 13 climate events that have resulted in significant negative socioeconomic impact, as measured by the extent to which it disrupted or destroyed "stocks" of capital—people, physical, and natural. The events include lethal heat waves, drought, hurricanes, fires, flooding, and depletion of water supply.

More frequent and more intense climate hazards will have large consequences. They are likely to threaten systems that form the backbone of human productivity by breaching historical thresholds for resilience. Climate hazards can undermine livability and workability, food systems, physical assets, infrastructure services, and natural capital. Some events strike at multiple systems at once. For example, extreme heat can curtail outdoor work, shift food systems, disrupt infrastructure services, and endanger natural capital such as glaciers. Extreme precipitation and flooding can destroy physical assets and infrastructure while endangering coastal and river communities. Hurricanes can damage global supply chains, and biome shifts can affect ecosystem services.

The best way to see how this will play out is to look at specific cases. MGI looked at nine distinct cases of physical climate risk in a range of geographies and sectors. Each considers the direct impact and knock-on effects of a specific climate hazard in a specific location, as well as adaptation costs and strategies that might avert the worst outcomes. Let's look at four of those cases (see also sidebar "Global problem, local impact").

Will it get too hot to work in India?

The human body provides one example of the nonlinear effect of breaching physical thresholds. The body must maintain a relatively stable core temperature of approximately 37 degrees Celsius to function properly. An increase of just 0.9 of a degree compromises neuromuscular coordination; 3 degrees can induce heatstroke; and 5 degrees can cause death. In India, rising heat and humidity could lead to more frequent breaches of these thresholds, making outdoor work far more challenging and threatening the lives of millions of people.

As of 2017, some 380 million of India's heat-exposed outdoor workers (75 percent of the labor force) produced about 50 percent of the country's GDP. By 2030, 160 million to 200 million people could live in urban areas with a nonzero probability of such heat waves occurring. By 2050, the number could rise to between 310 million and 480 million. The average person living in these regions has a roughly 40 percent chance of experiencing a lethal heat wave in the decade centered on 2030. In the decade centered on 2050, that probability could rise to roughly 80 percent.

India's productivity could suffer. Outdoor workers will need to take breaks to avoid heatstroke. Their bodies will protectively fatigue, in a so-called self-limiting process, to avoid overheating. By 2030, diminished labor productivity could reduce GDP by between 2.5 and 4.5 percent.

India does have ways to adapt. Increased access to air-conditioning, early-warning systems, and cooling shelters can help combat deadly heat. Working

Global problem, local impact

Case studies based on the Representative Concentration Pathway (RCP) 8.5 scenario

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Will it get too hot to work in India?

Increasing risk: in India, the probability of anyone experiencing a lethal heat wave is effectively 0 today, but by 2030, 160 million to 200 million people could be at risk

Degree of exposure: as of 2017, heat-exposed work in India produced ~50% of GDP, drove ~30% of GDP growth, and employed ~75% of the labor force

Effect on labor productivity: by 2050, some parts of India may be under such intense heat and humidity duress that working outside would be unsafe for ~30% of annual daylight hours

Adaptation: adaptation measures for India could include providing early-warning systems, building cooling shelters, shifting work hours for outdoor laborers, and accelerating the shift to service-sector employment

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Will mortgages and markets stay afloat in Florida?

Increasing risk: rising sea levels, increased tidal flooding, and more severe storm surges from hurricanes are likely to threaten Florida's vulnerable coastline

Physical damage to real estate: in 2050, a once-in-100-years hurricane might cause $75 billion worth of damage to Florida real estate, up from $35 billion today

Knock-on effects: in Florida, prices of exposed homes could drop, mortgage rates could rise, more homeowners may strategically choose to default, and property-tax revenue could drop 15–30% in directly affected countries

Adaptation: adaptation measures in Florida could include improving the resilience of existing structures, installing new green infrastructure, and building seawalls

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Can supply chains weather climate change?

Increasing risk: a once-in-100-years hurricane in the western Pacific, which will be 4x more likely by 2040, could shut down the semiconductor supply chain

Potential damage: supply chains are optimized for efficiency, not resilience, so production could halt for months; unprepared downstream players could see revenue dip 35% in 1 year

Upstream mitigation: protecting semiconductor plants against hazards could add 2% to building costs

Downstream mitigation: increasing inventory to provide a meaningful buffer could be cost-effective

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Can coastal cities turn the tide on rising flood risk?

Increasing risk: increased flooding and severe storm surges threaten to cause physical damage to coastal cities, while knock-on effects would hamper economic activity even more

Infrastructure threats: ports, low-lying train stations, and underground metros could be at risk, as could factories close to the coast

Total damage: in Bristol, England, a once-in-200-years flood in 2065 could cause ≤$3 billion in damage; in Ho Chi Minh City, Vietnam, a once-in-100-years flood in 2050 could wreak ~$10 billion in damage

Adaptation: it would take up to $500 million for Bristol to protect itself now from that scenario; Ho Chi Minh City might need seawalls, which could be very costly hours for outdoor personnel could be shifted, and cities could implement heat-management efforts. At the extreme, coordinated movement of people and capital from high-risk areas could be organized. These would be costly shifts, of course. Adaptation to climate change will be truly challenging if it changes how people conduct their daily lives or requires them to move to areas that are less at risk.

Will mortgages and markets stay afloat in Florida?

Florida's expansive coastline, low elevation, and porous limestone foundation make it vulnerable to flooding. The changing climate is likely to bring more severe storm surge from hurricanes and more tidal flooding. Rising sea levels could push salt water into the freshwater supply, damaging water-management systems. A once-in-100-years hurricane (that is, a hurricane of 1 percent likelihood per year) would damage about $35 billion in real estate today. By 2050, the damage from such an event could be $50 billion—but that's just the beginning. The accompanying financial effects may be even greater.

Real estate is both a physical and a financial store of value for most economies. Damage, and the expectation of future damage, to homes and infrastructure could drive down the prices of exposed homes. The devaluation could be even more significant if climate hazards also affect public-infrastructure assets such as water, sewage, and transportation systems, or if homeowners increasingly factor climate risk into buying decisions.

Lower real-estate prices could have significant knock-on effects in a state whose assets, people, and economic activity are largely concentrated in coastal areas. Property-tax revenue in affected counties could drop 15 to 30 percent, which could lower municipal-bond ratings and the spending power of local governments. Among other things, that would make it harder for cities and towns to invest in the infrastructure they need to combat climate change.

The impact on insurance and mortgage financing in high-risk areas could also be significant. There's a duration mismatch between mortgages, which can be 30 years long, and insurance, which is repriced every year. This mismatch means that current risk signals from insurance premiums might not build in the expected risk over an asset's lifetime, which could lead to insufficiently informed decisions. However, if insurance premiums do rise to account for future climate-change risk, lending activity for new homes could slow, and the wealth of existing homeowners could diminish.

When home values fall steeply with little prospect of recovery, even homeowners who are not financially distressed may choose to strategically default. One comparison point is Texas: during the first months after Hurricane Harvey hit Houston, in 2017, the mortgage-delinquency rate almost doubled, from about 7 to 14 percent. Now, as mortgage lenders start to recognize these risks, they could raise lending rates for risky properties. In some cases, they might even stop providing 30-year mortgages.

To adapt, Florida will have to make hard choices. For example, the state could increase hurricane and flooding protection, or it could curtail—and perhaps even abandon—development in risk-prone areas. The Center for Climate Integrity estimates that 9,200 miles of seawalls would be necessary to protect Florida by 2040, at a cost of $76 billion. Other strategies, such as improving the resilience of existing infrastructure and installing new green infrastructure, come with their own hefty price tags.

Can supply chains weather climate change?

Supply chains are typically optimized for efficiency over resilience, which may make them vulnerable to extreme climate hazards. Any interruption of global supply chains can create serious ancillary effects. Let's focus on two such supply chains: semiconductors, a specialty supply chain, and heavy rare earths, a commodity.

The risk to each is slightly different. Key parts of semiconductor supply chains are located in the Western Pacific, where the probability of a once-in-100-years hurricane occurring in any given year might double or even quadruple by 2040. Such hurricanes could potentially lead to months of lost production for the directly affected companies. Unprepared downstream players—for example, chipmakers without buffer inventories, insurance, or the ability to find alternative suppliers—could see revenue in a disaster year drop by as much as 35 percent.

Mining heavy rare earths in southeastern China could be challenged by the increasing likelihood of extreme rainfall. The probability of downpours so severe that they could trigger mine and road closures is projected to rise from about 2.5 percent per year today to about 4.0 percent per year in 2030 and 6.0 percent in 2050. Given the commoditized nature of this supply chain, the resulting production slowdowns could result in increased prices for all downstream players.

Mitigation is relatively straightforward for both upstream and downstream players. Securing semiconductor plants in southeast Asia against hazards, for example, might add a mere 2 percent to building costs. Downstream players in both the rare-earth and semiconductor pipelines could mitigate impacts by holding higher inventory levels and by sourcing from different suppliers across multiple regions. This can be done efficiently. For buyers of semiconductors, for example, raising inventory to provide a meaningful buffer could be cost effective, with estimated costs for warehousing and working capital increasing input costs by less than 1 percent. Nonetheless, the price of climate prudence will almost always be some decrease in production efficiency—for example, by creating limitations on lean or just-in-time inventory.

Can coastal cities turn the tide on rising flood risk?

Many coastal cities are economic centers that have already confronted flood risk. But the potential direct and knock-on effects of flooding are likely to surge dangerously.

Bristol is a port city in the west of England that has not experienced major flooding for decades. But without major investment in adaptation, extreme flood risk there could grow from a problem potentially costing millions of dollars today to a crisis costing billions by 2065. During very high tides, the Avon River becomes "tide locked" and limits land drainage in the lower reaches of the river-catchment area. As a result, Bristol is vulnerable to combined tidal and pluvial floods, which are sensitive to both sea-level rise and precipitation increase. The likelihood of both are expected to climb with climate change.

While Bristol is generally hilly and most of the urban area is far from the river, the most economically valuable areas of the city center and port regions are on comparatively low-lying land. More than 200 hectares (494 acres) of automotive storage near the port (often harboring up to 600,000 vehicles) could be vulnerable to even low levels of floodwater, and the main train station could become inaccessible. Bristol has flood defenses that would prevent the vast majority of damage from an extreme flood event today. By 2065, however, more extreme floods could overwhelm the defenses, in which case water would reach infrastructure that was previously safe.

We estimate that a 200-year flood today (that is, a flood of 0.5 percent likelihood per year) in Bristol would cause infrastructure-asset damage totaling between $10 million and $25 million. This may rise to $180 million to $390 million by 2065. The costs of knock-on effects would rise even more, from $20 million to $150 million today to as much as $2.8 billion by 2065, when an extreme flood might shut down businesses, destroy industrial stores, and halt transportation.

We estimate that protecting the city from this 2065 scenario would cost $250 million to $500 million today. However, the actual costs will largely depend on the specific adaptation approach.

Vietnam's Ho Chi Minh City is prone to monsoonal and storm-surge flooding. Today, the direct infrastructure-asset damage from a 100-year flood could be on the order of $200 million to $300 million, rising to $500 million to $1 billion in 2050. Here, too, the knock-on costs in disrupted economic activity are expected to be more substantial, rising from between $100 million and $400 million today to $2 billion to $8.5 billion in 2050.

Many new infrastructure assets in the city, particularly the local metro system, were designed to tolerate an increase in flooding. Yet the hazards to which these assets may be subjected could be greater than even the higher thresholds. In a worst-case scenario, of 180 centimeters of sea-level rise, these thresholds could be breached in many locations, and some assets might be damaged beyond repair.

Compared with Bristol, Ho Chi Minh City has many more adaptation options, as less than half of the city's major infrastructure needed for 2050 exists today. But adaptation may carry a hefty price tag. One potential comparison is Jakarta's major coastal-defense plans, which have a potential cost of roughly $40 billion. That is comparable to Ho Chi Minh City's current GDP.

An effective response

Local climate threats are increasing in most of the world. The changing environment is steadily altering the very nature of regions around the world. At the same time, the likelihood of "long tail" climate events that create cascading systemic risk is growing. Physical climate risk will affect everyone, directly or indirectly.

We think there are three steps that stakeholders could consider as they seek an effective response to the socioeconomic impacts of physical climate risk: integrating climate risk into decision making, accelerating the pace and scale of adaptation, and decarbonizing at scale to prevent a further buildup of risk.

Integrate climate risk into decision making

Climate change needs to become a major feature in corporate and public-sector decision making. As we have noted, physical climate risk is simultaneously spatial and systemic, nonstationary, and nonlinear in its effect. Potential impacts are regressive and rising over time, and stakeholders today may be underprepared to manage them. Decision making will need to reflect these characteristics.

For companies, this will mean taking climate considerations into account when looking at capital allocation, development of products or services, and supply-chain management, for example. Large capital projects would be evaluated in a way that reflects the increased probability of climate hazards at their location: How will that probability change over time? What are the possible changes in cost of capital for exposed assets? How will climate risk affect the broader market context and other implicit assumptions in the investment case? Cities will have to ask similar questions for urban-planning decisions. Moreover, while the MGI report focuses on physical risk, a comprehensive risk-management strategy will also need to include an assessment of transition and liability risk, as well as the interplay between these forms of risk.

Changes in mindset, operating model, and tools and processes will be needed to integrate climate risk into decision making. For centuries, we have made decisions based on a world of relative climate stability. We are not accustomed to planning for a world with a changing climate. For example, statistical risk management is often not part of ordinary processes in industrial companies. With the changing climate, it will be important to understand and embrace the probabilistic nature of climate risk and be mindful of possible biases and outdated mental models; experiences and heuristics of the past may no longer be a reliable guide to the future. The systemic nature of climate risk requires a holistic approach to understand and identify the full range of possible direct and indirect impacts.

One of the biggest challenges from climate risk will be rethinking the current models we use to quantify risk. These range from financial models used to make capital-allocation decisions to engineering models used to design structures. There is some uncertainty associated with a methodology that leverages global and regional climate models, makes underlying assumptions on emission paths, and seeks to translate climate hazards to potential physical and financial damage. But exploring new ways to quantify climate risk is not the highest "model risk." Continued reliance on current models based on stable historical climate and economic data may be even riskier.

Indeed, current models have at least three potential flaws. First, they lack geographic granularity, at a time when companies need to know how their key locations—and those of their suppliers—are exposed to different forms of climate threat. Second, they don't consider that the climate is constantly changing, a critical factor in determining such things as how resilient to make new factories, what tolerance levels to employ in new infrastructure, and how to design urban areas. And third, they are subject to potential sample bias, since decision makers are accustomed to trusting their own experience as they make decisions about the future.

Accelerate the pace and scale of adaptation

The pace and scale of adaptation will likely need to increase significantly. But adaptation is challenging. With hazard intensity projected to increase, the economics of adaptation could worsen over time. Technical limits may crop up. Difficult trade-offs may need to be assessed, including who and what to protect and who and what to relocate. Many instances may require coordinated action by multiple stakeholders.

Despite all that, many stakeholders will have to figure out ways to adapt. Key measures include protecting people and assets, building resilience, reducing exposure, and ensuring that appropriate insurance and financing are in place.

Protecting people and assets. In response to the record-breaking 2010 heat wave in India that killed 300 people in a single day, the Ahmedabad Municipal Corporation developed the country's first heat-action plan. Its measures included establishing a seven-day probabilistic heat-wave early-warning system, developing a citywide cool-roof program, and setting up teams to distribute cool water and rehydration pills to vulnerable populations during heat waves. Steps such as these are crucial for protecting people. Stakeholders must also be prepared to prioritize emergency response and preparedness, erect cooling shelters, and adjust working hours for outdoor workers who are exposed to heat.

Measures to make existing infrastructure and assets more resilient can help limit risk. Some of this would address "gray" infrastructure—for example, raising the elevation level of buildings in flood-prone areas—while other moves would protect "green" infrastructure. The Dutch program Room for the River, for example, gives rivers more room to manage higher water levels.

On the other hand, it will sometimes be more cost effective to erect new buildings than to retrofit old ones. Some $30 trillion to $50 trillion will be spent on infrastructure in the next ten years, much of it in developing countries. These infrastructure systems and factories could be designed to withstand the withering storms of the future, rather than what passes for a once-in-200-years event now.

Building resilience. Decisions about strengthening assets will need to go hand in hand with measures to drive operational resilience in systems. An important aspect of this is understanding the impact thresholds for systems and how and when they could be breached. Examples of resilience planning for a world of rising climate hazards include building global inventories to mitigate the risk of food or raw-material shortages, building inventory levels in supply chains to protect against interrupted production, establishing the means to source from alternate locations or suppliers, and securing backup power sources.

Reducing exposure. Adaptation strategies for many physical assets will have to reflect their full life cycle. For example, it may make sense not only to invest in addressing asset vulnerabilities for the next decade but also to shorten asset life cycles. In subsequent decades, as climate hazards intensify, the cost–benefit equation of physical resilience measures may no longer be attractive. At that point, it may become necessary to redesign asset footprints altogether by relocating employees and assets. We have already seen some examples of this, such as the buyout programs in Canada for residents in flood-prone areas. Quebec prohibits both the building of new homes and the rebuilding of damaged homes in its floodplain.

Decisions will need to be made about when to focus on protecting people and assets versus when to find ways to reduce their exposure to hazards, which regions and assets to spend on, how much to spend on adaptation, and what to do now as opposed to in the future. Companies need to develop a long-term perspective on how risk and adaptation costs will probably evolve, and they will need to integrate voices of affected communities into their decision making.

Rethinking insurance and finance. People are reluctant to carry insurance for unlikely events, even if they can cause significant damage. Today, only about 50 percent of losses are insured. That percentage is likely to decrease as the changing climate brings more—and more extreme—climate events. Without insurance, recovery after disaster becomes harder, and secondary effects become more probable. Underinsurance reduces resilience.

To adjust to constantly changing physical risk, insurers will have to reconsider current data and models, current levels of insurance premiums, and their own levels of capitalization. Indeed, the entire risk-transfer process (from insured to insurer to reinsurer to governments as insurers of last resort) may need examination, looking at whether each constituent is still able to fulfill its role. Without changes in risk reduction, risk transfer, and premium financing or subsidies, some risk classes in certain areas may become harder to insure, widening the insurance gap that already exists in some parts of the world. New questions will have to be asked, and innovative approaches will be needed.

Finance will also have to adjust if it is to play a significant role in funding adaptation measures, especially in developing countries. Public–private partnerships or participation by multilateral institutions is needed to prevent capital flight from risky areas. Innovative products and ventures have already been developed to broaden the reach and effectiveness of such measures. They include "wrapping" a municipal bond into a catastrophe bond, to allow investors to hold municipal debt without worrying about hard-to-assess climate risk.

Decarbonizing at scale
There is one critical part of addressing climate change that the MGI report does not examine: decarbonization. While adaptation is urgent, climate science tells us that further warming and risk increase can only be stopped by achieving net-zero greenhouse-gas emissions. Decarbonization is a daunting challenge that leaders will need to address in parallel with adaptation during the years ahead. For a closer look, see "Climate math: What a 1.5-degree pathway would take," on McKinsey.com.

To prepare for the climate of tomorrow, stakeholders will have to learn, mitigate, and adapt. Individuals, businesses, communities, and countries will need to recognize physical climate risk and integrate it into decision making. The next decade will be critical, as decision makers rethink the infrastructure, assets, and systems of the future, and the world collectively sets a path to manage the risk from climate change.

To read the full report, "Climate risk and response: Physical hazards and socioeconomic impacts," visit McKinsey.com/climaterisk.

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Climate risk and response in Asia: Research preview

Get an early view on how climate risk could affect the region, with a look at both physical hazards and socioeconomic impacts.

by Jonathan Woetzel, Oliver Tonby, Mekala Krishnan, Yuito Yamada, Dickon Pinner, and Ruslan Fakhrutdinov

COVID-19 is highlighting the importance of risk and resilience, and as the world focuses on recovery, it is important to not lose sight of climate risk.[1] The Earth's climate is changing after more than 10,000 years of relative stability, and Asia is on the front line. Climate science tells us that, absent adaptation and mitigation, the climate hazards the region faces in the future, from heat waves to flooding, are likely to be more severe, more intense, or both. The impacts in Asia in some cases could be more severe than in many other parts of the world. As Asia seeks to grow its economy—and remain a key source of growth for the world—climate is thus a critical challenge that the region will need to manage.

Asia is also well positioned to address these challenges and capture the opportunities that come from managing climate risk effectively. Infrastructure and urban areas are still being built out in many parts of Asia, which gives the region the chance to ensure that what goes up is more resilient and better able to withstand heightened risk. Like all parts of the world, Asia can also contribute to reducing emissions; climate science tells us that further warming will continue until net zero emissions are reached. If policy makers and business leaders can harness the region's innovative spirit, talent, and flexibility, Asia could lead a global response to climate risk by adapting and by mitigating the most severe potential consequences.

This paper, part of an ongoing series about the Future of Asia, is a preview of research to be published in 2020 that examines how climate risk could play out in Asia, both in physical hazards and in the socioeconomic impacts resulting from those hazards, and what measures can be taken to manage the risk.[2] This regional view follows the publication in January 2020 of the McKinsey Global Institute's global report, *Climate risk and response: Physical hazards and socioeconomic impacts*.

We look at the impacts across five systems: workability and livability, food systems, physical assets, infrastructure services, and natural capital. While McKinsey employs many scientists, including climate scientists, we are not a climate research institution. The Woods Hole Research Center (WHRC) produced much of the scientific analyses of physical climate hazards that we use in our research. Methodological design and results were independently reviewed by Dr. Luke Harrington, an expert in the modeling of climate extremes and a Research Fellow at the University of Oxford's Environmental Change Institute. The review reflects his independent perspectives. Final design choices and interpretation of climate hazard results were made by WHRC. In addition, WHRC scientists produced maps and data visualization for the report.

Our research focuses on assessing "inherent" risk—that is, risk absent mitigation and adaptation—to understand the magnitude of the risk and the response needed. Separately, we assess a potential adaptation and mitigation response to manage the risk. We look at two time periods: between now and 2030, and from 2030 to 2050. Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO2 concentrations. We have chosen to focus on RCP 8.5 for our analysis, because the higher-emission scenario it portrays enables us to assess the full inherent physical risk of climate change in the absence of further decarbonization.[3]

Climate hazards in Asia to 2050

Asia faces a range of climate hazards, with potentially different impacts depending on geography. Already, climate scientists find evidence of the growing effect of climate change on the likelihood and intensity of extreme events. In China, the 2017 floods in Hunan province affected 7.8 million people and resulted in $3.55 billion of direct economic loss, including severe infrastructure damage.[4] Researchers have examined the likelihood of fires in Australia, and found that the risk of

[1] Dickon Pinner, Matt Rogers, and Hamid Samandari, Addressing climate change in a post-pandemic world, McKinsey & Company, April 7, 2020.
[2] Discussion papers and articles in the series are featured on the McKinsey & Company website at McKinsey.com/featured-insights/future-of-asia/overview.
[3] For a full discussion of our choice of RCP 8.5 and details of our methodology, see the technical appendix of our global report, *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020. See also Christopher R. Schwalm, Spencer Glendon, and Philip B. Duffy, "RCP 8.5 tracks cumulative CO_2 emissions," Proceedings of the National Academy of Sciences, August 2020.
[4] Yin Sun et al., "Anthropogenic influence on the heaviest June precipitation in southeastern China since 1961," *Bulletin of the American Meteorological Society*, January 2019, Volume 100, Number 1.

weather conditions that result in fires as severe as observed in 2019-2020 (measured with a so-called Fire Weather Index) has increased by at least 30 percent since 1900.[5]

In the high-emissions RCP 8.5 scenario considered here, climate science predicts significant temperature increases across Asia and conditions of rising heat and humidity in many parts of Asia. More than 75 percent of global capital stock that could be damaged from riverine flooding in a given year is in Asia.

Based on the RCP 8.5 scenario, we list some of Asia's key climate hazards below. We illustrate these hazards with maps that show local areas most likely to see more severe or frequent hazards over the coming decades. We examine hazards out to 2030 and to 2050.[6]

Average temperatures.[7] Under an RCP 8.5 scenario, Asia is expected to see an increase in average temperature of more than two degrees by 2050 compared with preindustrial levels, with the magnitude and pace of warming varying across locations (Exhibit 1).[8] Climate science predicts significant temperature increases, for example, in parts of China, Australia, and the Indian subcontinent. These effects will start to accumulate over the coming decade.

Lethal heat waves.[9] Lethal heat waves are defined as three-day events during which the average daily maximum wet-bulb temperature exceeds the

[5] Geert Jan van Oldenborgh et al.,"Attribution of the Australian bushfire risk to anthropogenic climate change," *Natural Hazards and Earth System Sciences*, March 11, 2020.

[6] Following standard practice, we define future states as the average climatic behavior over multidecade periods. The climate state today is defined as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 as the average between 2041 and 2060. Unless otherwise noted, projections are from WHRC analysis of 20 Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Models (GCMs).

[7] Some research has documented occurrences of 35 degrees Celsius wet-bulb in some parts of the world for a short duration and finds that extreme humid heat overall has more than doubled in frequency since 1979. See Colin Raymond, Tom Matthews, and Radley M. Horton, "The emergence of heat and humidity too severe for human tolerance," *Science Advances*, May 8, 2020.

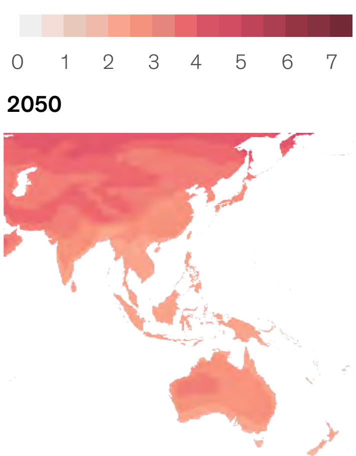
[8] We define preindustrial levels as the period between 1880 and 1910.

[9] Modeled by WHRC using the mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 GCMs. Models were independently bias corrected using the ERA-Interim data set. High levels of atmospheric aerosols provide a cooling effect that masks the risk.

Exhibit 1

Average temperatures are projected in increase in many parts of Asia.

Increase in average annual temperature,[1]
°C shift compared with preindustrial climate



The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.

Note: See Technical Appendix, *Climate risk and response: Physical hazards and socioeconomic impacts*, MGI, Jan 2020, for why we chose RCP 8.5. Projections based on RCP 8.5 CMIP 5 multimodel ensemble. Heat-data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today defined as avg 1998–2017, 2030 avg 2021–40, and 2050 avg 2041–60.
[1]Taken from KNMI Climate Explorer, 2019, using mean of full CMIP5 ensemble of models. Preindustrial levels defined as period between 1880–1910.
Source: KNMI Climate Explorer, 2019; Woods Hole Research Center; McKinsey Global Institute (MGI) analysis

survivability threshold for a healthy human resting in the shade.[10] Under the RCP 8.5 scenario, for example, large cities in parts of India, Bangladesh, and Pakistan could be among the first places in the world to experience heat waves that exceed the survivability threshold (Exhibit 2).[11]

Extreme precipitation.[12] The risk of extreme precipitation events—defined as once-in-50-year occurrences (that is, with a 2 percent annual likelihood) in the 1950–81 period—is expected to increase. The likelihood of such events could increase three- or fourfold by 2050 under the RCP 8.5 scenario in areas for example including eastern Japan, central and eastern China, parts of South Korea, and Indonesia.

Severe typhoons.[13] While climate change is unlikely to increase the frequency of typhoons in Asia, it could boost their average severity (and thus increase the frequency of severe events). The likelihood of severe typhoon precipitation—an event which had a 1 percent annual likelihood in the 1981–2000 period—is expected to triple by 2040 in some parts of Asia, including coastal areas of China, South Korea, and Japan (Exhibit 3).

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[10] Wet-bulb temperature is the lowest temperature to which air can be cooled by the evaporation of water at a constant pressure. We took the average wet-bulb temperature of the hottest six-hour period across each rolling three-day period as the relevant threshold. We define a lethal heat wave as a three-day period with maximum daily wet-bulb temperatures exceeding 34 degrees Celsius. This temperature was chosen because the commonly defined heat threshold for human survivability is 35 degrees Celsius wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. At this temperature, a healthy human being, resting in the shade, can survive outdoors for four to five hours. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. A global analysis of 419 major cities showed that the average daytime temperature difference between urban areas and their immediate surroundings is +1.5°C ± 1.2°C, with some outliers up to 7°C warmer. Shushi Peng et al., "Surface urban heat island across 419 global big cities," Environmental Science & Technology, January 2012, Volume 46, Issue 2. If a nonzero probability of lethal heat waves in certain regions occurred in the models for today, it was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. For details, see the technical appendix of *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.

[11] Some research has documented occurrences of 35 degrees Celsius wet-bulb in some parts of the world for a short duration and finds that extreme humid heat overall has more than doubled in frequency since 1979. See Colin Raymond, Tom Matthews, and Radley M. Horton, "The emergence of heat and humidity too severe for human tolerance," *Science Advances*, May 8, 2020.

[12] Modeled by WHRC using the median projection from 20 CMIP5 GCMs.

[13] Modeled by WHRC using the Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel, MIT, 2019. Time periods available for the hurricane modeling were 1981–2000 (baseline) and 2031–50 (future). These are the results for one of the main hurricane regions of the world. Others, for example those affecting the Indian subcontinent, have not been modeled here.

Exhibit 2

Parts of Asia could experience lethal heat waves with increasing likelihood.

Lethal heat wave, probability,[1] % per year

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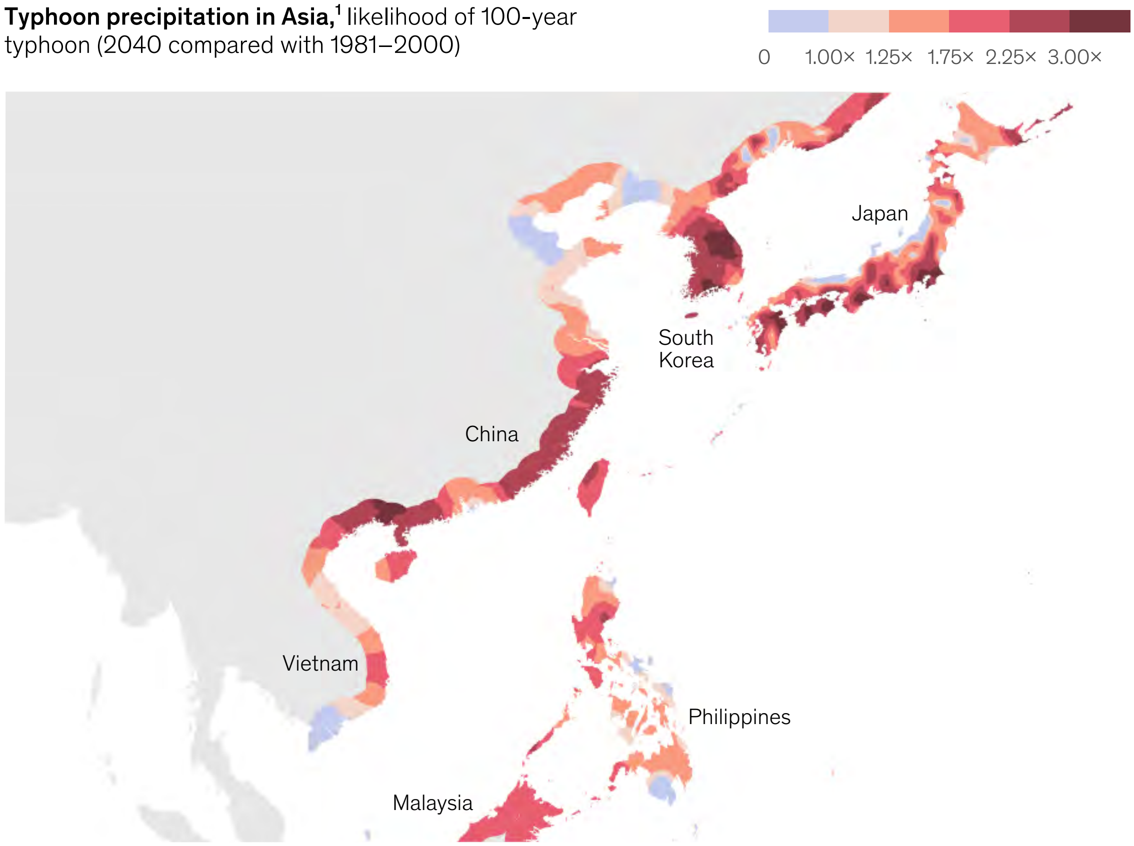
Note: See Technical Appendix, *Climate risk and response: Physical hazards and socioeconomic impacts*, MGI, Jan 2020, for why we chose RCP 8.5. Projections based on RCP 8.5 CMIP 5 multimodel ensemble. Heat-data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today defined as avg 1998–2017, 2030 avg 2021–40, and 2050 avg 2041–60.
[1]Lethal heat wave defined as 3-day period with maximum daily wet-bulb (WB) temperature exceeding 34°C WB; WB temp defined as lowest temp parcel of air can be cooled by evaporation at constant pressure. Threshold chosen since commonly defined heat threshold for human survivability = 35°C WB. Big cities with significant urban-heat-island effects could push 34°C WB heat waves over threshold; as such, healthy, well-hydrated human resting in shade would see core body temp rise to lethal level after ~4–5 hours. Projections subject to uncertainty related to future behavior of atmospheric aerosols and urban heat- or cool-ing-island effects. Modeled by Woods Hole Research Center using mean projection of daily max surface temp and daily mean relative humidity taken from 20 CMIP5 global climate models.
Source: KNMI Climate Explorer, 2019; Woods Hole Research Center; McKinsey Global Institute (MGI) analysis

Exhibit 3

The likelihood of severe typhoons in Asia could increase.

Typhoon precipitation in Asia,[1] likelihood of 100-year typhoon (2040 compared with 1981–2000)



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Note: See Technical Appendix, *Climate risk and response: Physical hazards and socioeconomic impacts*, MGI, Jan 2020, for why we chose RCP 8.5. Projections based on RCP 8.5 CMIP 5 multimodel ensemble. Heat-data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as average climatic behavior over multidecade periods.
[1]For typhoon modeling, available time periods = 1981–2000 baseline, and 2031–50 future. Results = 1 of main typhoon regions in world. Others, eg, those affecting Indian subcontinent, have not been modeled here.
Source: Woods Hole Research Center using the Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel, MIT, 2019; McKinsey Global Institute analysis (disputed boundaries)

Drought.[14] As the Earth warms, the spatial extent of and share of time spent in drought conditions is projected to increase (Exhibit 4). The share of a decade spent in drought conditions in southwestern Australia could grow to more than 80 percent by 2050, and some parts of China could spend 40 to 60 percent of the time in drought.

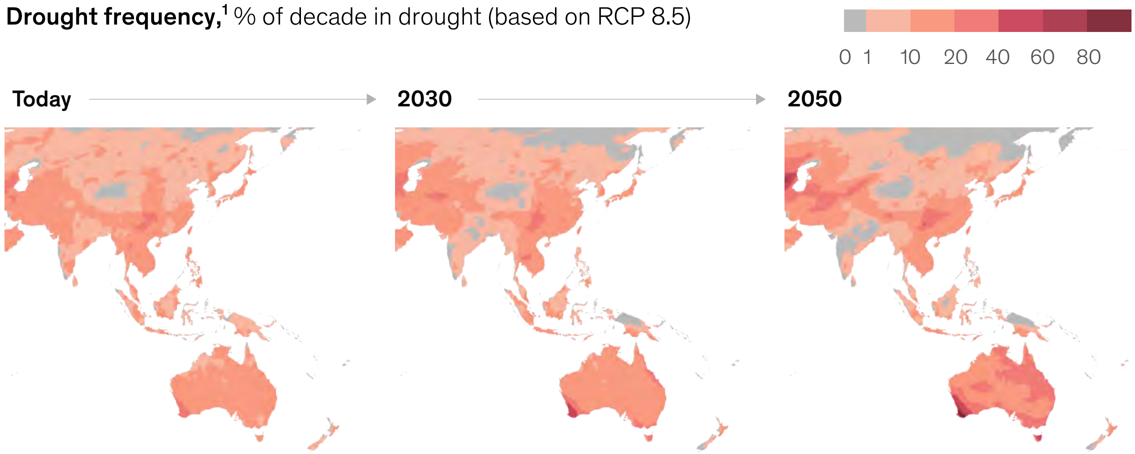
Changes in water supply.[15] The renewable freshwater supply will be affected by factors including rainfall patterns and evaporation. In several parts of Australia, mean annual surface water supply could significantly decrease by 2050. Conversely, in parts of China, water supply could increase by more than 20 percent. Parts of the Indian subcontinent could also see an increase in water supply.

[14] Modeled by WHRC using the median projection of 20 CMIP5 GCMs, using the self-correcting Palmer Drought Severity Index (PDSI). Projections were corrected to account for increasing atmospheric CO2 concentrations.
[15] Taken from the World Resources Institute Water Risk Atlas, 2018, which relies on six underlying CMIP5 models. Time periods of this raw data set are the 20-year spans centered on 2020, 2030, and 2040. The 1998–2017 and 2041–60 data were linearly extrapolated from the 60-year trend provided in the base data set. Note that this is a measure of surface water supply and does not account for changes in demand of water. Available here: https://www.wri.org/resources/maps/aqueduct-water-risk-atlas.

Exhibit 4

Drought could become more frequent in some parts of Asia, and less frequent in other parts.

Drought frequency,[1] % of decade in drought (based on RCP 8.5)



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[1]Measured using 3-month rolling average. Drought defined as a rolling 3-month period with Average Palmer Drought Severity Index (PDSI) <–2. PDSI = temperature- and precipitation-based drought index calculated based on deviation from historical mean. Values generally range from +4 (extremely wet) to –4 (extremely dry). Modeled by Woods Hole Research Center using median projection 20 CMIP5 GCMs, using self-correcting PDSI. Projections corrected to account for increasing atmospheric CO2 concentrations.
Source: Woods Hole Research Center; McKinsey Global Institute analysis (disputed boundaries)

Translating climate hazards into socioeconomic impacts

We then translate the hazards into socioeconomic impacts across a range of systems. We look at socioeconomic impacts on five systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital. To do this, we typically overlay data on a the evolution of a hazard (for example, floods of different depths, with their associated likelihoods) with exposure to that hazard (for example, capital stock exposed to flooding) and a damage function that assesses resilience (for example, what share of capital stock is damaged when exposed to floods of different depths). The socioeconomic impacts of these physical changes are nonlinear: once hazards exceed certain thresholds, the affected physiological, human-made, or ecological systems work less well or break down and stop working altogether. This is because the systems have evolved or been optimized over time for historical climates. Rising heat and humidity levels, for example, could affect the human body's ability to work outdoors and also the survivability of healthy human beings, as discussed above. The knock-on effects can be systemic, because direct impacts in a particular geography could spread and have cascading impacts. In Ho Chi Minh City, where direct infrastructure damage from a 100-year flood could be between $500 million and $1 billion by 2050, knock-on costs could be between $1.5 billion and $8.5 billion.[16]

Our analysis finds that the socioeconomic impacts from intensifying climate hazards could in many cases be more severe for Asia than for other parts of the world, in the absence of adaptation and mitigation.[17] Under RCP 8.5, by 2050, between 600 million and one billion people in Asia will be living in areas with a nonzero annual probability of lethal heat waves.

[16] Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Peter Cooper, *Can coastal cities turn the tide on rising flood risk?*, McKinsey & Company, April 20, 2020.
[17] For our analysis in this report, we look at 16 countries that account collectively for around 95 percent of Asia's population and GDP. They are: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar. New Zealand, Pakistan, Philippines, South Korea, Thailand, and Vietnam. Collectively, these 16 countries make up 54 percent of global population and one-third of global GDP.

That compares with a global total of 700 million to 1.2 billion; in other words, a substantial majority of these people are in Asia. By 2050, on average, between $2.8 trillion and $4.7 trillion of GDP in Asia annually will be at risk from a loss of outdoor working hours because of increased heat and humidity; that accounts for more than two-third of the total annual global GDP impact. Finally, about $1.2 trillion in capital stock in Asia could be damaged by riverine flooding in a given year by 2050, equivalent to about 75 percent of the global impact.

How climate change will affect the "Four Asias"

We examine the impacts of climate change on 16 countries in Asia. For each of the countries, we consider the direct effects of rising hazards on livability and workability, food systems, physical assets, infrastructure services, and natural capital. For each of these, we derive an indicator or indicators that serve to illustrate exposure to climate hazards and proximity to physical resilience thresholds. The indicators include the following:[18]

— Share of population living in areas experiencing a nonzero annual probability of lethal heat waves (a measure of impact on livability and workability)

— Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions (a measure of impact on livability and workability). Linked with this, we also measured the GDP at risk from working hours affected by heat and humidity

— Water stress, measured as the annual demand of water as a share of the annual supply of water (a measure of impact on livability and workability)[19]

— Annual share of capital stock at risk of riverine flood (a measure of impact on physical assets and infrastructure)[20]

— Annual probability of a change in agricultural yields for four major crops (a measure of impact on food systems)[21]

— Share of land surface changing climate classification, referred to as "biome shift" (a measure of impact on natural capital)[22]

Applying these indicators, we find that all 16 countries may see an increase in potential direct impacts from climate change for at least one indicator by 2050. Twelve countries may see an increase in three or more indicators by 2050. Most countries are expected to see rising impact on the annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, the annual share of capital stock at risk of flood damage, and the share of land surface changing climate classification. We categorize each of the 16 countries in the "Four Asias" framework that we have identified in our previous Future of Asia work.[23] While impacts vary across as well as within countries, we broadly find that these factors will play out differently across the Four Asias.

[18] See the technical appendix of the global report for further details on the indicators and sizing methodology. *Climate risk and response: Physical hazards, socioeconomic impacts*, McKinsey Global Institute, January 2020.
[19] Water stress is measured as annual demand of 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, and not the impacts of increased population and GDP growth. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
[20] For estimation of capital stock at risk of riverine flooding we used a country level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under a business-as-usual scenario (RCP 8.5, SSP 2) and existing levels of flood protection.
[21] Rice, corn, soy, and wheat; distribution of agricultural yields modeled by WHRC using the median of nitrogen limited crop models from the AgMIP ensemble.
[22] The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. We have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.
[23] Our Four Asias framework is based on a methodology developed in McKinsey's Future of Asia report and reflects measures of scale (including GDP and population), economic development, regional integration and trade, and global connectedness. In all, for our analysis in this report, we look at 16 countries that account collectively for about 95 percent of the region's population and GDP. They are: Australia, Bangladesh, Cambodia, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, New Zealand, Pakistan, the Philippines, South Korea, Thailand, and Vietnam. Note that our broader body of research includes a wider range of countries, but we have limited the analysis here to 16 countries based on data availability. For a detailed discussion of the Four Asias, see *The future of Asia: Asian flows and networks are defining the next phase of globalization*, McKinsey Global Institute, September 2019.

We use the Four Asias framework to contextualize climate hazards, their socioeconomic impacts, and potential responses. Each category is exposed to different combinations of hazards at varying levels of intensity, suggesting that they will require distinct response frameworks. All risks discussed below are on a timeline to 2050 unless specified otherwise.

Frontier Asia in our analysis consists of Bangladesh, India, and Pakistan. These rapidly urbanizing economies have historically seen low levels of regional integration and have a diverse global base of trading partners and investors. All three countries could see extreme increases in heat and humidity, which may significantly affect workability and livability. For example, by 2050, Frontier Asia could face increased likelihood of lethal heat waves than the rest of Asia. We estimate that by 2050, between 500 million and 700 million people in Frontier Asia could live in regions that have an annual probability of a lethal heat wave of about 20 percent. Rising heat and humidity could also affect human beings' ability to work outdoors, as they tire more easily or need more breaks. We estimate that by 2050, in an average year 7 to 13 percent of GDP could be at risk as a result. These countries could see extreme precipitation events more frequently by 2050 than in the second half of the 20th century. Indeed, despite rising heat in some areas, the countries in aggregate may be subject to reduced drought. Based on analysis by the World Resources Institute, we find that the amount of capital stock at risk from riverine flooding could rise from 0.5 percent of the total today to 3 percent in 2050, a total of $800 billion of stock at risk.[24] Climate change would also have the biggest negative impact on Asian crop yield in this group of countries. For example, the annual probability of a yield decline of 10 percent or more for four major crops (rice, corn, wheat, and soy) is expected to increase from 12 percent today to 39 percent by 2050 for India, and from 40 percent to 53 percent for Pakistan. Annual probability of a yield improvement of 10 percent or more for four major crops (rice, corn, wheat, and soy) is expected to decrease from 17 percent today to 5 percent by 2050 for India, and from 38 percent to 27 percent for Pakistan. Frontier Asia is also expected to see an increase in the share of land changing climate classification between today and 2050.

Emerging Asia in our analysis consists of Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam. These culturally diverse countries see a high share of regional trade, capital, and people flows, and are a major source of labor. Like Frontier Asia, they are expected to see increases in heat and humidity. By 2050, in an average year, between 8 and 13 percent of GDP could be at risk as a result of rising heat and humidity. The region could also experience growing exposure to extreme precipitation events and flooding. The socioeconomic impacts of these hazards could potentially be severe. Based on analysis by the World Resources Institute, we find that capital stock at risk from riverine flooding in Frontier Asia countries is expected to double from 0.7 percent today to 1.5 percent by 2050, or $220 billion. Drought could become less frequent in this region. Agriculture yields could see increased volatility here. In agriculture crop yield, annual probability of a 10 percent yield decline will increase 2 percent today to 8 percent by 2050. At the same time, annual probability of a 10 percent yield increase will decrease from 5 percent to day to 1 percent by 2050.

Advanced Asia in our analysis here consists of Australia, Japan, New Zealand, and South Korea. Overall, these countries are expected to see slightly lower impacts of climate change along many dimensions than Frontier Asia and Emerging Asia countries. Under RCP 8.5, for some countries in the region, the impact on water supply and drought are the main challenges, as described above. Indeed, by 2050, southwestern parts of Australia are expected to spend more than 80 percent of a decade in drought conditions.[25] One potential impact the region is likely to see is biome shift, or share of land

[24] By capital stock at risk, we mean expected damages—that is, damage incurred should an event occur times the likelihood of an event occurring. For estimation of capital stock at risk of riverine flooding, we used a country-level Urban Damage risk indicator from WRI Aqueduct Flood Analyzer 2019 under a business-as-usual scenario (RCP 8.5, SSP 2) and existing levels of flood protection. This analysis factors in increases in capital stock over time.

[25] This could also be linked with rising wildfire risk, which we will explore further in our forthcoming research.

changing climate classification. For example, under the RCP 8.5 scenario, biome shift is projected to climb in Japan and South Korea by an average of 27 percentage points between today and 2050, as measured against a 1901-25 baseline. Typhoon and extreme precipitation risk could also increase in some parts of Japan and South Korea, as noted earlier. In agriculture crop yield, no significant risk increase has been observed for this group. Rather, by 2050, annual probability of a 10 percent yield increase could increase; for example this could rise from 21 percent today to 45 percent for the Australia and New Zealand region.

China is large and distinct enough from other parts of Asia to sit in its own category. It acts as an anchor economy for the region and as a connectivity and innovation driver for neighboring countries. Due to its location on a wide range of latitudes, it is climatically heterogeneous. Still, the country on aggregate is projected to become hotter. In addition, eastern parts could see threats of extreme heat, including lethal heat waves. Central, northern, and western China could experience more frequent extreme precipitation events.[26] In the country overall, the average share of outdoor working hours lost each year to extreme heat and humidity would increase from 4 percent in 2020 to as much as 6 percent in 2030 and 8.5 percent in 2050. As a result, the share of China's GDP that could be lost to heat and humidity could double from 1.5 to 2 to 3 percent by 2050—equivalent to $1 trillion to $1.5 trillion in GDP at risk in an average year.[27] China is expected to see a growing biome shift by 2050, with an increase of about 27 percentage points in the share of land changing climate classification, measured against a 1901-25 baseline. The country is expected to be an agricultural net beneficiary from climate change over the near term, with increasing statistically expected yields and volatility skewed toward positive outcomes. China could see expected yields increase by about 2 percent by 2050 relative to today. The annual probability of a breadbasket failure of greater than 10 percent relative to a today baseline would decrease from 5 percent to 2 percent by 2050, while the annual probability of a bumper year with a greater than 10 percent increase in yield would increase from 1 percent to approximately 12 percent by 2050.

Each of the Four Asias will need to take steps to manage their exposure to physical climate risk, and pay particular attention to the areas of risk highlighted above. Frontier Asia, Emerging Asia, and China are still building out large parts of their infrastructure and rapidly urbanizing. They will need to ensure that climate risk is embedded into forward-looking capital and urban planning decisions. For example, Emerging Asia is expected to see an influx of labor-intensive industries as manufacturing migrates away from China, and the countries will need to focus on the impact of rising heat and humidity, as well as potential impacts of flooding, on those industries. Given China's role in regional and global trade, and the potential exposure of many of its industries and geographies, companies in China will need to pay particular attention to increasing resiliency in supply chains.

Another characteristic of climate risk is its regressive nature; the poor will be hit hardest. We find this to be the case in Asia, too. While different parts of Asia are affected differently, countries with lower levels of per capita GDP are probably most at risk from the impacts of climate change. They are often exposed to climates that are closer to physical thresholds than those of wealthier countries. They rely more on outdoor work and natural capital and have fewer financial means to adapt.

Our Frontier Asia and Emerging Asia groupings illustrate how this regressive impact may play out in both human and socioeconomic terms. Both of these sets of countries face potentially

[26] Woods Hole Research Center analysis. It is important to note that near-term regional projections of precipitation extremes have been assessed as highly sensitive to the influence of natural variability, particularly in lower latitudes. For more details on the relevant uncertainties, see Ben Kirtman et al., "Near-term climate change: Projections and predictability," in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[27] The lower end of the range assumes that today's sectoral composition persists, while the higher end is based on projections from IHS Markit Economics and Country Risk on sectoral transitions and GDP increases. The dollar impact is calculated by multiplying the share of hours lost in outdoor sectors with GDP in these sectors (this assumes that consensus projections do not factor in losses to GDP from climate change). We used backward multipliers from input-output tables to include knock-on effects.

disproportionate impacts on workability from extreme heat and humidity, our research finds. By 2050, under RCP 8.5 scenario, some 7 to 13 percent of GDP in Frontier Asia and Emerging Asia could be at risk. This compares to 0.6 to 0.7 percent for Advanced Asia. The regressive impacts of climate change, if allowed to proceed without adaptation or mitigation, thus could put the Asian growth story at risk and potentially affect the lives and livelihoods of millions.

Adaptation and mitigation: Challenges and opportunities in Asia

As the Earth continues to warm, physical climate risk is ever-changing or nonstationary. Climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions. Furthermore, given the thermal inertia of the Earth system, some amount of warming will also likely occur after net-zero emissions are reached.[28]

Given the potentially significant effects of climate change in Asia, the onus is on policy makers, companies, and individuals to develop and implement adaptation strategies that will soften impacts and enable economic activities to continue to their maximum potential, even as they consider how to mitigate the rise in carbon emissions and avoid an even more damaging scenario in future decades. These goals will require ambition and a concerted effort to build on and extend recent successful efforts.

The good news is that, in many ways, Asia is well placed to adapt and lead global adaptation and mitigation efforts. A significant opportunity lies in infrastructure development. To maintain its current growth trajectory, Asia must invest $1.7 trillion annually through 2030,[29] according to the Asian Development Bank. Incorporating climate adaptation into projects will make a difference to regional development and resilience. As they build out their economies, policy makers in Frontier Asia and Emerging Asia can also exploit synergies between infrastructure needs and opportunities for emissions reductions. Stakeholders can also embrace public-private-sector collaboration and explore new approaches to incorporate climate factors into planning. More broadly, Asia is home to some of the world's largest and most innovative companies, and almost half of R&D investments globally take place in Asia. Over the past decade, the region accounted for the highest share of global growth in key technology metrics—namely, technology company revenue, venture capital funding, spending on research and development, and number of patents filed.[30] With concerted effort, Asian countries can help manage their own exposure to climate risk and can lead the way on global adaptation and mitigation efforts.

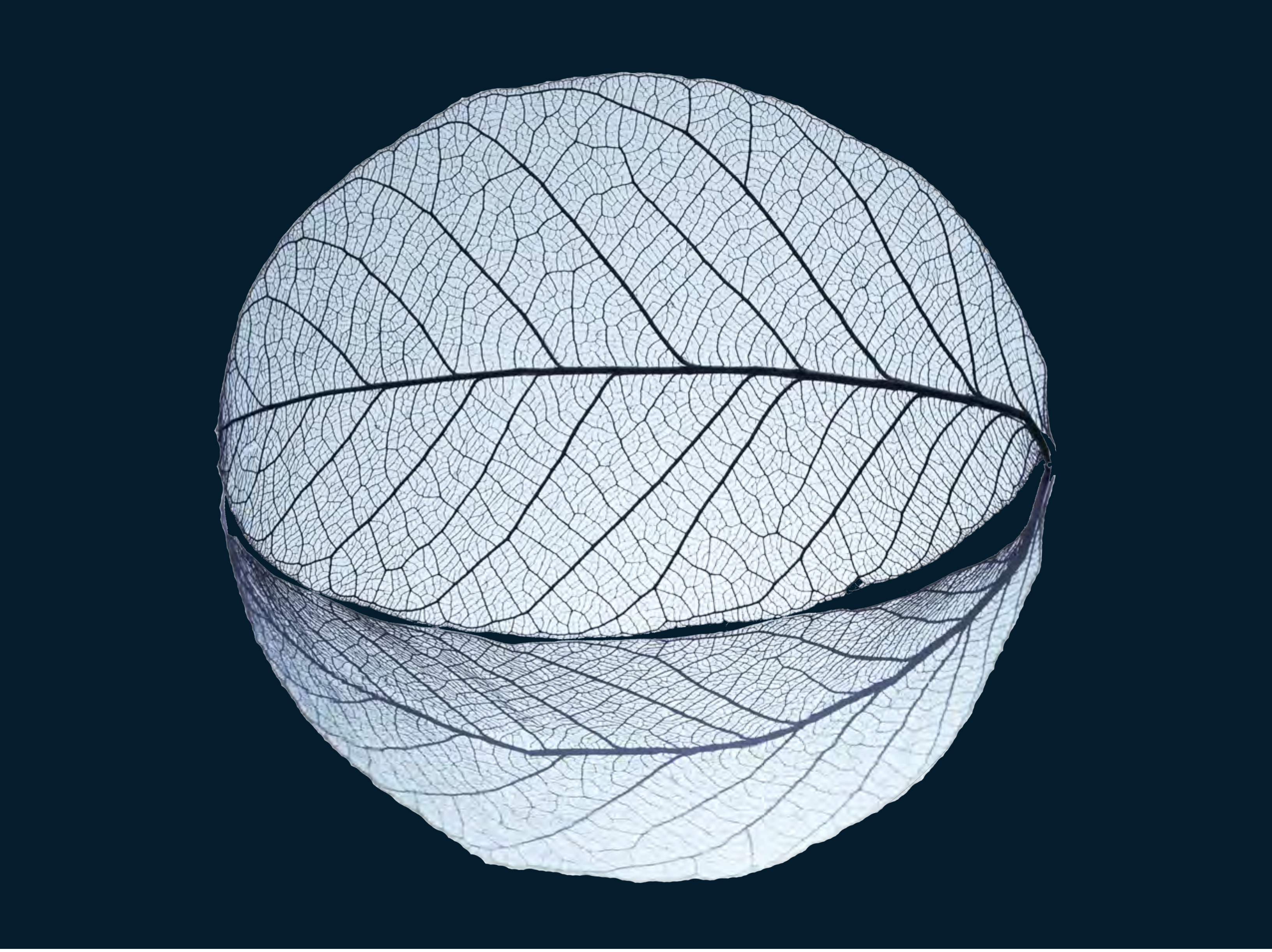
Rising to the climate risk challenge will require efforts by policy makers and business leaders. In our forthcoming report on climate risk and response in Asia, we will highlight measures that Asian leaders could consider for the region to be a global leader in protecting lives and livelihoods from physical climate risk across three dimensions: integrating climate risk into business and policy decisions, adopting measures that are effective in adapting to the changing climate, and seeking to mitigate climate risk through decarbonization.

[28] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," Environmental Research Letters, January 2018, Volume 13, Number 1; H. Damon Matthews and Ken Caldeira, "Stabilizing climate requires near zero emissions," Geophysical Research Letters, February 2008, Volume 35; Myles Allen et al, "Warming caused by cumulative carbon emissions towards the trillionth tonne," *Nature*, April 2009, Volume 485.

[29] Infrastructure investment is defined as fixed-asset investments in four sectors: transportation (road, rail, air, and ports), energy, telecommunications, and water and sanitation (including dams, irrigation, and flood control waterworks. Asian Development Bank, *Meeting Asia's infrastructure needs*, 2017.

[30] See Oliver Tonby, Jonathan Woetzel, Noshir Kaka, Wonsik Choi, Jeongmin Seong, Brant Carson, and Lily Ma, *How technology is safeguarding health and livelihoods in Asia*, McKinsey & Company, May 2020.

Jonathan Woetzel is a McKinsey senior partner and director of the McKinsey Global Institute (MGI), based in Shanghai; **Oliver Tonby** is a senior partner in Singapore and chairman, McKinsey Asia; **Mekala Krishnan** is an MGI senior fellow in Boston; **Yuito Yamad**a is a partner in Tokyo; **Dickon Pinner** is a senior partner in San Francisco and leader of McKinsey's global Sustainability Practice; and **Ruslan Fakhrutdinov** is an associate in Moscow.



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Banking imperatives for managing climate risk

More than regulatory pressure is driving banks to manage climate risk. Financing a green agenda is also a commercial imperative—but specialized skills are needed to protect balance sheets.

by Joseba Eceiza, Holger Harreis, Daniel Härtl, and Simona Viscardi

The surface temperature of the Earth has risen at a record pace in recent decades, creating risks to life, ecosystems, and economies. Climate science tells us that further warming is unavoidable over the next decade, and probably after that as well. In this uncertain environment, banks must act on two fronts: they need both to manage their own financial exposures and to help finance a green agenda, which will be critical to mitigate the impact of global warming. An imperative in both cases is excellent climate-risk management.

The physical risks of climate change are powerful and pervasive. Warming caused by greenhouse gases could damage livability and workability—for example, through a higher probability of lethal heat waves. Global warming will undermine food systems, physical assets, infrastructure, and natural habitats. The risk of a significant drop in grain yields—of 15 percent or more—and damage to capital stock from flooding will double by 2030. In aggregate, we expect that around a third of the planet's land area will be affected in some way.[1]

Disruptive physical impacts will give rise to transition risks and opportunities in the economy, including shifts in demand, the development of new energy resources, and innovations arising from the need to tackle emissions and manage carbon, as well as necessary reforms in food systems. Sectors that will bear the brunt include oil and gas, real estate, automotive and transport, power generation, and agriculture. In oil and gas, for example, demand could fall by 35 percent over the next decade. The good news is that these changes should also precipitate a sharp decline in emissions.

January 2020 was the warmest January on record. As temperatures rise in this way, it is incumbent on banks to manage the relevant risks and opportunities effectively (Exhibit 1).

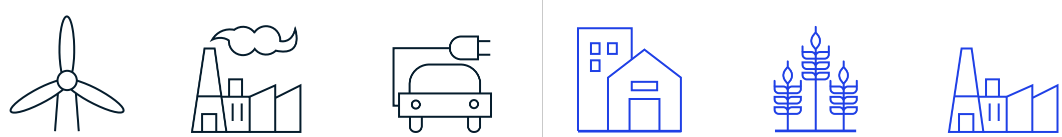
Furthermore, regulation increasingly *requires* banks to manage climate risk. Some have made a start, but many must still formulate strategies, build their capabilities, and create risk-management frameworks. The imperative now is to act decisively

[1] This estimate is based on a higher-emission scenario of RCP (Representative Concentration Pathway) 8.5 CO_2 concentrations (Intergovernmental Panel on Climate Change, a UN body). Lethal heat waves are defined as a wet-bulb temperature of 35° Celsius, at which level the body-core temperatures of healthy, well-hydrated human beings resting in the shade would rise to lethal levels after roughly five hours of exposure. Estimates are subject to uncertainty about aerosol levels and the urban heat-island effect. For further details, see the McKinsey Global Institute report "Climate risk and response: Physical hazards and socioeconomic impacts" (January 2020).

Exhibit 1

Climate change creates opportunities and challenges for the banking industry.

Opportunity: Financing a green agenda			Challenge: Protecting balance sheets from uncertainty		
Transformation of energy production toward renewables	Plant refurbishments to avoid or capture and store carbon emissions	Electrification of transport and automation of mobility	Real-estate market collapse in low-lying areas	Increased risk of major crop failures with implications for meat and dairy producers	Closures of coal-powered power plants before end of useful life
Up to $500 billion in annual adaptation costs[1]			For banks in the European Union, up to 15% of the balance sheet is at risk[2]		



[1]Costs until 2050, according to the UN *Adaptation Gap Report* (2018).
[2]Based on analysis of 46 sample EU banks and their portfolio composition in industries and geographies likely affected by physical and transition risks.

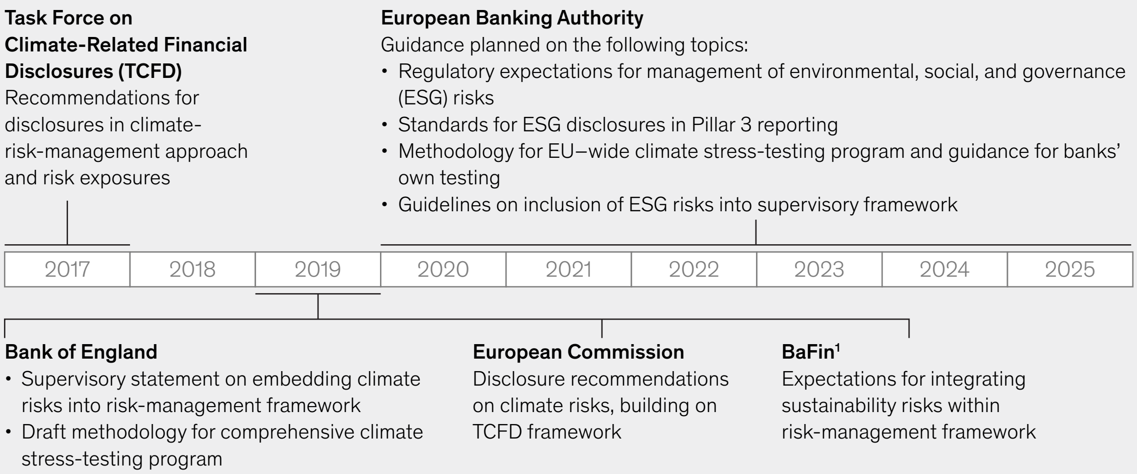
The regulatory agenda

Regulatory initiatives that require banks to manage climate risks have gathered pace over the recent period (exhibit). The United Kingdom's Prudential Regulation Authority was among the first to set out detailed expectations for governance, processes, and risk management. These require banks to identify, measure, quantify, and monitor exposure to climate risk and to ensure that the necessary technology and talent are in place. Germany's BaFin[1] has followed with similar requirements.

Exhibit

Regulation is evolving at high speed.

Regulation timeline



[1]Bundesanstalt für Finanzdienstleistungsaufsicht.

Among upcoming initiatives, the Bank of England plans to devote its 2021 Biennial Exploratory Scenario (BES) to the financial risks of climate change. The BES imposes requirements that will probably force many institutions to ramp up their capabilities, including the collection of data about physical and transition risks, modeling methodologies, risk sizing, understanding challenges to business models, and improvements to risk management. The European Banking Authority (EBA) is establishing regulatory and supervisory standards for environmental, social, and governance (ESG) risks and has published a multiyear sustainable-finance action plan. The EBA may provide a blueprint for authorities in geographies including the United States, Canada, and Hong Kong, which are also considering incorporating climate risk into their supervisory regimes.

[1] Bundesanstalt für Finanzdienstleistungsaufsicht.

and with conviction, so effective climate-risk management will be an essential skill set in the years ahead.

Regulatory and commercial pressures are increasing

Banks are under rising regulatory and commercial pressure to protect themselves from the impact of climate change and to align with the global sustainability agenda. Banking regulators around the world, now formalizing new rules for climate-risk management, intend to roll out demanding stress tests in the months ahead (see sidebar "The regulatory agenda"). Many investors, responding to their clients' shifting attitudes, already consider environmental, sustainability, and governance (ESG) factors in their investment decisions and are channeling funds to "green" companies.

The commercial imperatives for better climate-risk management are also increasing. In a competitive environment in which banks are often judged on their green credentials, it makes sense to develop sustainable-finance offerings and to incorporate climate factors into capital allocations, loan approvals, portfolio monitoring, and reporting. Some banks have already made significant strategic decisions, ramping up sustainable finance, offering discounts for green lending, and mobilizing new capital for environmental initiatives.

This increased engagement reflects the fact that climate-risk timelines closely align with bank risk profiles. There are material risks on a ten-year horizon (not far beyond the average maturity of loan books), and transition risks are already becoming real, forcing banks, for example, to write off stranded assets. Ratings agencies, meanwhile, are incorporating climate factors into their assessments. Standard & Poor's saw the ratings impact of environmental and climate factors increase by 140 percent over two years amid a high volume of activity in the energy sector.

As climate risk seeps into almost every commercial context, two challenges stand out as drivers of engagement in the short and medium terms.

Protecting the balance sheet from uncertainty

As physical and transition risks materialize, corporates will become increasingly vulnerable to value erosion that could undermine their credit status. Risks may be manifested in such effects as coastal real-estate losses, land redundancy, and forced adaptation of sites or closure. These, in turn, may have direct and indirect negative impact on banks, including an increase in stranded assets, uncertain residual values, and the potential loss of reputation if banks, for example, are not seen to support their customers effectively. Our analysis of portfolios at 46 European banks showed that, at any one time, around 15 percent of them carry increased risk from climate change. The relevant exposure is mostly toward industries (including electricity, gas, mining, water and sewerage, transportation, and construction) with high transition risks.

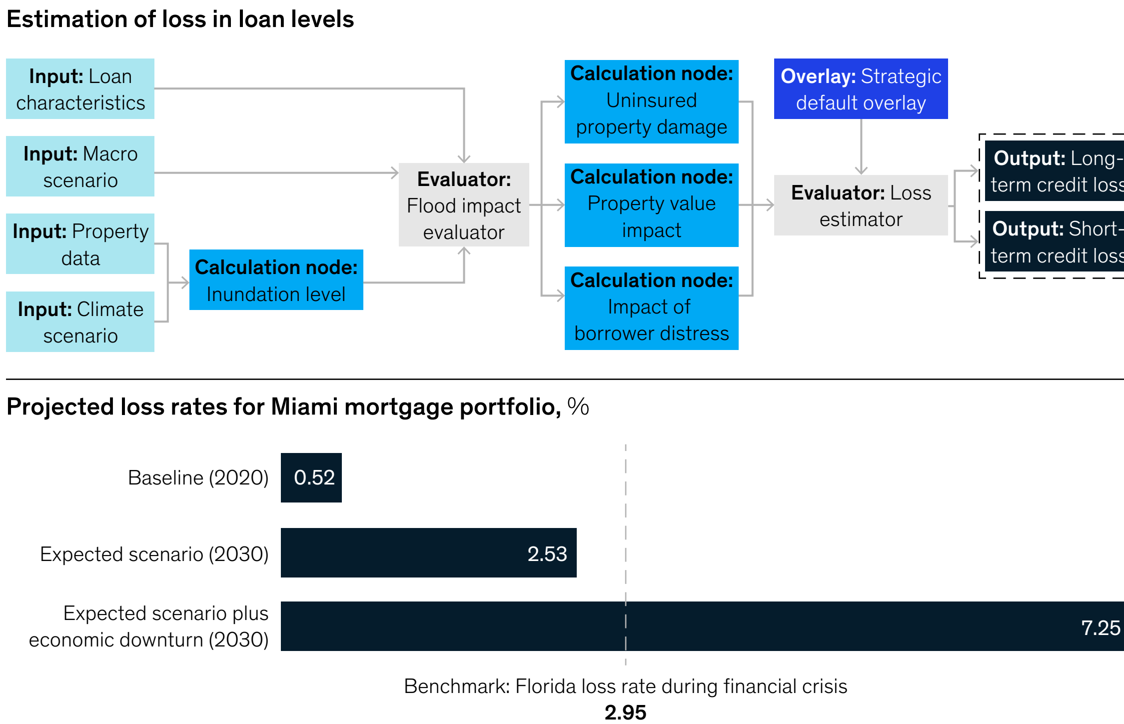
When we looked at the potential impact of floods on mortgage delinquencies in Florida, for example, we gathered flood-depth forecasts for specific locations and translated them into dollar-value damage levels. The analysis in Exhibit 2 is based on geographic levels associated with specific climate scenarios and probabilities. We then used these factors to generate numbers for depreciation and the probability of default and loss-given default. Based on the analysis, we calculated that more frequent and severe flooding in the Miami–Dade region may lead to an increase in mortgage defaults and loss rates close to those seen at the peak of the financial crisis and higher than those in extreme stress-test projections. Our severe-flooding scenario for 2030 predicts a 2.53 percent loss rate, just a bit lower than the 2.95 percent rate at the peak of the financial crisis. However, in the event of an economic slowdown, the rate could go as high as 7.25 percent.

Financing a green agenda

Renewable energy, refurbishing plants, and adaptive technologies all require significant levels of financing. These improvements will cut carbon emissions, capture and store atmospheric carbon, and accelerate the transition away from fossil fuels. Some banks have already acted by redefining their

Exhibit 2

This model was developed to measure the impact of flooding on Florida home-loan markets.



goals to align their loan portfolios with the aims of the Paris Agreement.[2]

Oil and gas, power generation, real estate, automotive, and agriculture present significant green-investment opportunities. In the United Kingdom, for example, 30 million homes will require sizable expenditure if they are to become low-carbon, low-energy dwellings.[3] In energy, opportunities are present in alternatives, refining, carbon capture, aviation, petrochemicals, and transport. As some clients exit oil and coal, banks have a role in helping them reduce their level of risk in supply contracts or in creating structured finance solutions for power-purchase agreements. In renewables, significant capital investment is needed in energy storage, mobility, and recycling.

A sharper lens: Five principles for climate-risk management

As they seek to become effective managers of climate risk, banks need to quantify climate factors across the business and put in place the tools and processes needed to take advantage of them effectively. At the same time, they must ensure that their operations are aligned with the demands of external stakeholders. Five principles will support this transformation. They should be applied flexibly as the regulatory landscape changes.

[2] The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping any global temperature rise this century well below 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5° Celsius.
[3] Angela Adams, Mary Livingstone, and Jason Palmer, "What does it cost to retrofit homes? Updating the cost assumptions for BEIS's energy efficiency modelling," UK Department for Business, Energy & Industrial Strategy, April 2017; assets.publishing.service.gov.uk.

Formulate climate-risk governance. It will be of crucial importance for top management to set the tone on climate-risk governance. Banks should nominate a leader responsible for climate risk; chief risk officers (CROs) are often preferred candidates. To ensure that the board can keep an eye on exposures and respond swiftly, banks should institute comprehensive internal-reporting workflows. There is also a cultural imperative: responsibility for climate-risk management must be cascaded throughout the organization.

Tailor business and credit strategy. Climate considerations should be deeply embedded in risk frameworks and capital-allocation processes. Many institutions have decided not to serve certain companies or sectors or have imposed emissions thresholds for financing in some sectors. Boards should regularly identify potential threats to strategic plans and business models.

Align risk processes. To align climate-risk exposure with risk appetite and the business and credit strategy, risk managers should inject climate-risk considerations into all risk-management processes, including capital allocations, loan approvals, portfolio monitoring, and reporting. Some institutions have started to develop methodologies for assessing climate risk at the level of individual counterparties (see sidebar "A leading bank incorporates climate risk into its counterparty ratings").

Counterparty credit scoring requires detailed sectoral and geographic metrics to interpret physical and transition risks as a view of financial vulnerability, taking into account mitigation measures. The resulting risk score can be used to inform credit decisions and to create a portfolio overview. The score can also be embedded in internal and external climate-risk reporting, such as responses to the disclosure recommendations of the Financial Stability Board (Task Force on Climate-Related Financial Disclosures) or the European Banking Authority (Non-Financial Risk Disclosure Framework).

Get up to speed on stress testing. Scenario analyses and stress tests, which are high on business and regulatory agendas, will be critical levers in helping banks assess their resilience. In preparing for tests, they should first identify important climate hazards and primary risk drivers by industry, an analysis they can use to generate physical and transition-risk scenarios. These in turn can help banks estimate the extent of the damage caused by events such as droughts and heat waves. Finally, banks have to quantify the impact by counterparty and in aggregate on a portfolio basis. Risk-management teams should also prepare a range of potential mitigants and put in place systems to translate test results into an overview of the bank's position. Since regulators are prioritizing stress testing for the coming period, acquiring the necessary climate-modeling expertise and climate-hazard and asset-level data is an urgent task.

Focus on enablers. Banks often lack the technical skills required to manage climate risk. They will need to focus on acquiring them and on developing a strategic understanding of how physical and transition risks may affect their activities in certain locations or industry sectors. Banks usually need "quants," for example—the experts required to build climate-focused counterparty- or portfolio-level models. They should therefore budget for increased investment in technology, data, and talent.

Reaching for risk maturity: Three steps

As banks ponder how to incorporate climate-change considerations into their risk-management activities, they will find that it is important to remain pragmatic. The climate issue is emotive. Stakeholders want robust action, and banks feel pressure to respond. Those that make haste, however, increase the risk of missteps. The best strategy is adequate, comprehensive preparation: a bank can create a value-focused road map setting out an agenda fitted to its circumstances and taking into account both the physical and regulatory status quo. Once the road map is in place, banks should adopt a

A leading bank incorporates climate risk into its counterparty ratings

A leading international bank aimed to increase its share of climate markets. To get there, it needed to incorporate climate factors into the risk-management function and to develop tools for assessing climate risks, on the counterparty level, for its entire portfolio.

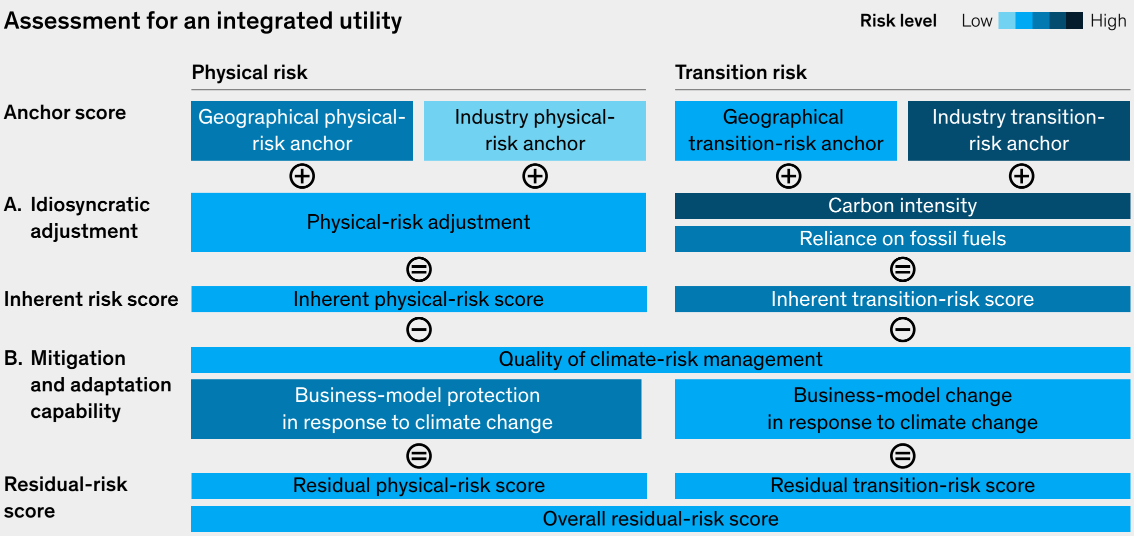
The bank aimed to assess climate risk for each of its 2,500 counterparties on an annual basis, and its solution had to be sufficiently simple and scalable for individual loan officers to use on counterparties of all sizes. The eventual solution was based on the production of scorecards for physical and transition risks (exhibit).

The bank's calculations were predicated on anchor scores that reflected the counterparty's industry and geographical footprint. These were adjusted for idiosyncratic effects to reflect transition risk arising from a company's greenhouse-gas emissions or the reliance of its business model on fossil fuels and related products. Additional parameters helped assess the potential for mitigation and adaptation—including a qualitative assessment of the company's climate-risk management, actions to protect physical assets from future physical hazards, and initiatives to adopt a more sustainable business and operating model. The final output of the calculations was a counterparty rating that incorporated inputs from physical and transition-risk scorecards.

Exhibit

An international banking group embedded climate risk into counterparty ratings.

Assessment for an integrated utility



The counterparty model was useful to differentiate the climate risk among companies within sectors. Testing for the bank's utilities subportfolio, for example, showed that electricity providers and multi-utilities fared worse than regulated networks. Companies with a higher proportion of renewables generally fared better.

One concern during model development was the shortage of available climate data and climate-related corporate information. The bank had to strike a balance between model accuracy and feasibility. Finally, it decided to work largely with publicly available data selectively augmented with climate-hazard data. As the bank developed, tested, and rolled out the methodology, cross-functional teams emerged as a success factor. These teams consisted of model developers, analysts, economists, and climate experts.

modular approach to implementation, ensuring that investments are tied to areas of business value by facilitating finance, offering downside protection, and meeting external expectations.

For developing a comprehensive approach to risk management, we see three key steps, which should be attainable in four to six months.

1. Define and articulate your strategic ambition
Effective climate-risk management should be based on a dedicated strategy. Individual banks must be sure about the role they want to play and identify the client segments and industry sectors where they can add the most value. They should also establish and implement governance frameworks for climate risk—frameworks that include the use of specialized senior personnel, as well as a minimum standard for reporting up and down the business.

Some are already taking action. One financial institution made its CRO the executive accountable for climate change and head of the climate-change working group. Another institution divided these responsibilities among the board of directors, executive management, business areas, group functions, and the sustainable-finance unit. Banks should also factor in adjacencies because lending to some clients in riskier geographies and industries—even to finance climate-related initiatives—is still riskier. This will ensure that banks formulate a structured approach to these dilemmas.

2. Build the foundations
Banks should urgently identify the processes, methodologies, and tools they will need to manage climate risk effectively. This entails embedding climate factors into risk and credit frameworks—for example, through the counterparty-scoring method described above. Scenario analyses and stress tests will be pillars of supervisory frameworks and should be considered essential capabilities. Outcomes should be hardwired into reporting and disclosure frameworks. Finally, banking, like most sectors, does not yet have the climate-risk resources it needs. The industry must therefore accumulate skills and build or buy relevant IT, data, and analytics.

3. Construct a climate-risk-management framework
Banks must aim to embed climate-risk factors into decision making across their front- and back-office activities and for both financial and nonfinancial risks (including operational, legal, compliance, and reputational risks). Data will be a significant hurdle. Data are needed to understand the fundamentals of climate change as well as the impact it will have on activities such as pricing, credit risk, and client-relationship management. However, a paucity of data should not become an impediment to action. As far as possible, banks should measure climate exposures at a number of levels, including by portfolio, subportfolio, and even transaction. This will enable the creation of heat maps and detailed reports of specific situations where necessary. In corporate banking, this kind of measurement and reporting might support a climate-adjusted credit scorecard (covering cash flows, capital, liquidity diversification, and management experience) for individual companies. Banks may then choose to assign specific risk limits. Indeed, some banks have already moved to integrate these types of approaches into their loan books.

As intermediaries and providers of capital, banks play a crucial role in economic development that now includes managing the physical and transition risks of climate change. The task is complex, and the models and assumptions needed to align the business with climate priorities will inevitably be revised and refined over time. However, as temperatures rise, speed is of the essence in managing the transition to a more sustainable global economy.

Joseba Eceiza is a partner in McKinsey's Madrid office, **Holger Harreis** is a senior partner in the Düsseldorf office, **Daniel Härtl** is an associate partner in the Munich office, and **Simona Viscardi** is a partner in the Milan office.

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Climate risk case studies

Introduction

In *Climate risk and response: Physical hazards and socioeconomic impact*, we measured the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. We explored risks today and over the next three decades and examined specific cases to understand the mechanisms through which climate change leads to increased socioeconomic risk.

In order to link physical climate risk to socioeconomic impact, we investigated cases that illustrated exposure to climate change extremes and proximity to physical thresholds. These cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of McKinsey Global Institute research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We found these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We selected these case studies to reflect these systems and to represent leading-edge examples of climate change risk. Each case is specific to a geography and an exposed system, and thus is not representative of an "average" environment or level of risk across the world. Our cases show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). We typically define the climate state today as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. (We also choose a sea-level-rise scenario for one of our cases that is consistent with the RCP 8.5 trajectory). Such an "inherent risk" assessment allows us to understand the magnitude of the challenge and highlight the case for action. For a detailed description of the reason for this choice see the technical appendix of the full report.

Our case studies cover each of the five systems we assess to be directly affected by physical climate risk, across geographies and sectors. While climate change will have an economic impact across many sectors, our cases highlight the impact on construction, agriculture, finance, fishing, tourism, manufacturing, real estate, and a range of infrastructure-based sectors. The cases include the following:

— For livability and workability, we look at the changing Mediterranean climate and how that could affect sectors such as wine and tourism.

— For food systems, we focus on the likelihood of a multiple-breadbasket failure affecting wheat, corn, rice, and soy, and, specifically in Africa, the impact on wheat and coffee production in Ethiopia and on cotton and corn production in Mozambique.

— For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

— For infrastructure services, we examine 17 types of infrastructure assets, including the potential impact on coastal cities such as Bristol in England and Ho Chi Minh City in Vietnam.

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Will infrastructure bend or break under climate stress?

Infrastructure is the backbone of the global economy, connecting people, enhancing quality of life, and promoting health and safety. But climate change is revealing infrastructure vulnerabilities.

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, Peter Cooper, and Byron Ruby

When Hurricane Sandy struck the eastern seaboard of the United States in October 2012, subways, airports, and roads were flooded, causing transportation to grind to a halt. Millions lost power, some for days or weeks, shutting down businesses and creating public safety issues. In addition to winds knocking out one-fourth of cell phone towers in the Northeast, the loss of electricity forced many towers offline after depleting their emergency batteries. Eleven billion gallons of sewage flowed into rivers, bays, and coastal waters, because severe inundation overwhelmed municipal wastewater systems. In total, the storm caused about $70 billion in damages. But despite being one of the costliest and most destructive storms on record, this event was not an aberration. Nine of the costliest, mainland US hurricanes on record have occurred in the past 15 years. Going forward, climate change is expected to further intensify these risks.[1]

Infrastructure usually involves large investments in assets that are designed to operate over the long term. Coal-fired plants are designed for 40 to 50 years, for example, and hydropower dams and large geotechnical structures for up to 100 years. To date, the design of these facilities typically has assumed a future climate that is much the same as today's. However, a changing climate and the resulting more extreme weather events mean those climate bands are becoming outdated, leaving infrastructure operating outside of its tolerance levels. This can present direct threats to the assets as well as significant knock-on effects for those relying on the services those assets deliver.

In this case study, we examine four critical infrastructure systems—the electric power grid; water storage, treatment, and purification; transportation; and telecommunications—to determine how vulnerable global infrastructure is to a changing climate. In the four major infrastructure classes, we identify a total of 17 types of assets to evaluate against seven climate hazards: tidal flooding amplified by sea-level rise; riverine and pluvial flooding; hurricanes/typhoons and storms; tornadoes and other wind events; drought; heat (temperature increases in both air and water); and wildfires. Each type of infrastructure system has specific elements vulnerable to specific climate hazards; we map those hazard infrastructure intersections where risks will most be exacerbated by climate change.

The climate risk for infrastructure is both pervasive and diverse

Overall, we find that climate change could increasingly disrupt critical systems, increase operating costs, exacerbate the infrastructure funding gap, and create substantial spillover effects on societies and economies. We find that there is a range of unique vulnerabilities of different types of infrastructure assets to different categories of climate hazards. Few assets will be left completely untouched. In certain countries, heat-related power outages could increase in severity and may push the grid to cascading failure; aircraft could also be grounded more frequently as both planes and airports cross heat-related thresholds. Understanding these differences is crucial for successful planning. To that end, we have produced a heat map that explores the risk of potential future interruptions from typical exposure to climate hazards by 2030 (Exhibit 1).

Our analysis reveals two different sets of risks involving infrastructure: direct (for example, a power plant goes offline because it floods) and indirect (for example, a power plant cannot transmit power because the power transmission lines have gone down). A typical asset's direct risk is estimated in our heat map analysis. But direct vulnerabilities are only half the story. Risk is further exacerbated by the vulnerabilities of a specific infrastructure asset to failures in the infrastructure systems within which

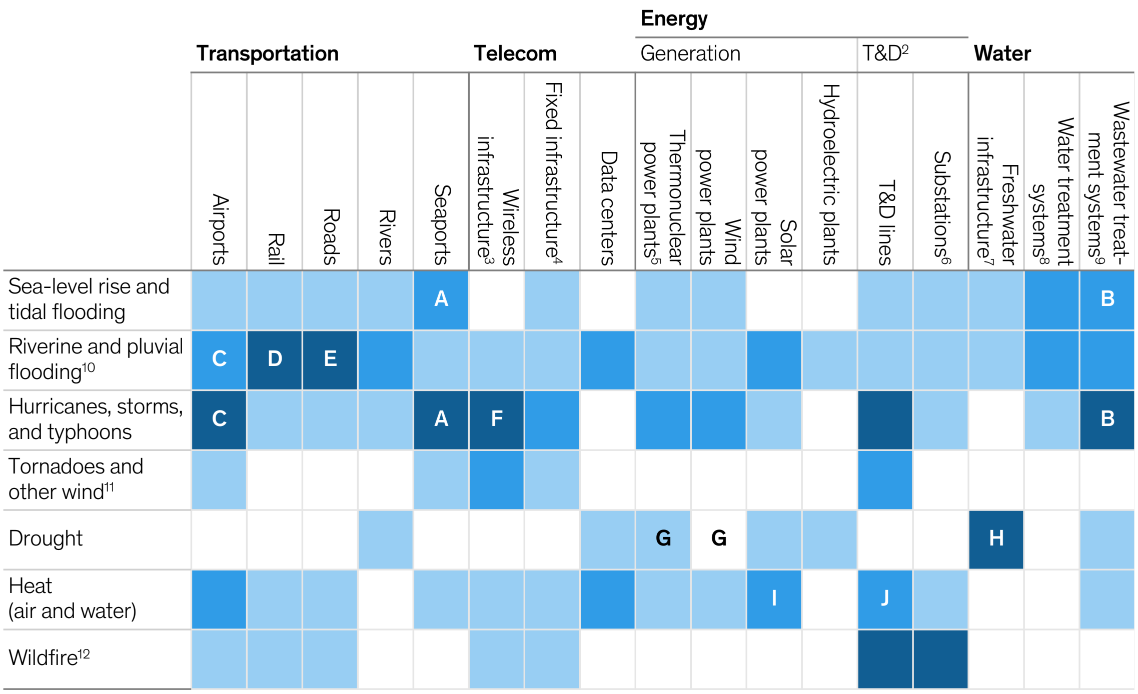
[1] Of the nine costliest hurricanes that have struck the United States over the past 15 years, scientists have investigated the influence of climate change on three: Hurricane Katrina (2005), Hurricane Sandy (2012), and Hurricane Harvey (2017). For all three, climate change was found to have amplified impact severity, whether through high storm surges or increased precipitation.

Exhibit 1

Global infrastructure assets have highly specific vulnerability to hazards: at least one element in each type of infrastructure system sees high risk.

Risk Defined as potential future losses as a result of exposure to climate hazards[1]

Little to no risk — Increased risk



A. Seaports, by definition, are exposed to risk of all types of coastal flooding. Typically, seaports are resistant and can more easily adjust to small sea-level rise. However, powerful hurricanes are still a substantial risk. In 2005, Hurricane Katrina destroyed ~30% of the Port of New Orleans.

B. Wastewater treatment plants often adjoin bodies of water and are highly exposed to sea-level rise and hurricane storm surge. Hurricane Sandy in 2012 led to the release of 11 billion gallons of sewage, contaminating freshwater systems.

C. Many airports are near water, increasing their risk of precipitation flooding and hurricane storm surge. Of the world's 100 busiest airports, 25% are less than 10m above sea level, and 12—including hubs serving Shanghai, Rome, San Francisco, and New York—are less than 5m. Only a few mm of flooding is necessary to cause disruption.

D. Rail is at risk of service interruption from flooding. Disruption to signal assets in particular can significantly affect rail reliability. Inundation of 7% of the UK's signaling assets would disrupt 40% of passenger journeys. Damage can occur from erosion, shifting sensitive track alignments.

E. Roads require significant flood depths and/or flows to suffer major physical damage, but incur ~30% speed limitations from 0.05m inundation and can become impassable at 0.3m. Compounding effects of road closures can increase average travel time in flooded cities 10–55%.

F. Cell phone towers are at risk from high wind speeds. During Hurricane Maria in 2018, winds of up to 175mph felled 90+% of towers in Puerto Rico. Risks are more moderate at lower wind speeds, with ~25% of towers downed by ~80mph winds during Hurricane Sandy.

G. Wind power plants are highly resistant to drought; thermoelectric power plants, which regularly use water for cooling (seen in >99% of US plants), are at risk during significant shortages.

H. Freshwater infrastructure and associated supplies are highly vulnerable to impact of drought, as seen when Cape Town narrowly averted running out of drinking water in 2018.

I. Solar panels can lose efficiency through heat, estimated at 0.1–0.5% lost per 1°C increase.

J. Transmission and distribution suffers 2 compounding risks from heat. Rising temperatures drive air conditioning use, increasing load. Concurrently, heat reduces grid efficiency.

1. Losses are defined as asset interruption, damage, or destruction. 2. Transmission and distribution. 3. Base substations and radio towers. 4. Including above- and below-ground cable. 5. Including nuclear, gas, and oil. 6. Including large power transformers. 7. Reservoirs, wells, and aquifers. 8. Plants, desalination, and distribution. 9. Plants and distribution. 10. Pluvial flooding is flooding caused by extreme precipitation, independent of the actions of rivers and seas. 11. Including both rain and wind impacts. 12. Wildfire is a derivative risk primarily driven by drought.
Source: Dawson et al., 2016; Federal Communications Commission, 2016; Mobile Association, 2018; *New York Times,* 2006; Pablo, 2005; Prelenato, 2019; Pyatkova, 2019; Xi, 2016; McKinsey Global Institute analysis

that asset is embedded. These dependencies can spread risk. We find that each system (for example, energy, water) has at least one severely vulnerable element. Because of the interdependency of these infrastructure systems, the high-risk assets may represent critical points of failure for the entire system, causing operational losses for all other assets in the chain and knock-on effects for a broader set of institutions and individuals.

The power grid: The power grid is highly vulnerable to climate risk from both acute and chronic impacts, amplified by fragile components and relatively low redundancy. The effects of climate-related hazards on the power grid is already apparent. Higher temperatures lower generation efficiency, increase losses in transmission and distribution, decrease the lifetime of key equipment including power transformers, boost peak demand, and force certain thermoelectric plants offline. Day to day, these pressures cause rising operating costs and reduced asset life. In rare cases, these stressors can overwhelm the grid and lead to load shedding and blackouts. Instances and associated costs of disruptions to the power grid are likely to rise as temperatures increase. As average heat levels increase, so does the frequency of extreme heat events and the duration of less severe periods of higher than average heat that cause efficiency losses. Hot periods will be hotter than systems are used to, increasing the degree of failure and thus the associated recovery times, lost revenues, and repair costs. For example, California's Fourth Climate Change Assessment states that by 2060, 5 percent a year probability heat waves in Los Angeles County may reduce overall grid capacity by 2 to 20 percent.

Transportation: Transportation infrastructure is widely distributed, interconnected, and can be affected by relatively minimal climate hazards, resulting in significant societal impacts. For example, extreme heat is already disrupting global air travel. In July 2017, approximately 50 flights were grounded for physical and regulatory reasons when temperatures in Phoenix, Arizona, skyrocketed to 48 degrees Celsius. We analyzed the effect of extreme heat on global air travel. Assuming regional aircraft are largely similar to today's and keeping the number of regional flights constant to isolate climate impact, if no adaptation measures are taken (for example, lengthening runways, improving aircraft technology), this translates into about 200 to 900 flights grounded per year by 2030 and about 500 to 2,200 flights by 2050 (Exhibit 2). This could directly affect about 16,000 to 75,000 passengers per year in 2030 and about 40,000 to 185,000 passengers per year in 2050, up from an estimated 4,000 to 8,000 today (these events not systematically recorded today) from extreme heat. More or fewer passengers may be affected depending on whether heat waves strike on heavier travel days (when flights are fuller) and how long the heat conditions persist. Air transportation delays cost the US economy $4 billion in 2007, with most direct costs falling on passengers.

Water supply and wastewater systems: Water supply systems can also experience long-lasting outages from acute shocks like hurricanes and flooding. Two weeks after Hurricane Katrina in 2005, 70 percent of affected drinking water facilities were still offline. Flooding can also result in long recovery periods. Effects are more dramatic in the developing world, where contamination of drinking water is common, and cholera and E. coli frequently cause widespread diarrhea outbreaks in the aftermath of floods. Water treatment systems, however, such as desalination plants, could be increasingly used to limit the impacts of drought. Wastewater systems also suffer as a result of climate shocks. During drought, sewers can have inadequate flow, resulting in blockages and the inability to process human waste. Blockages lead to the possibility of sewage systems bursting in the middle of urban areas. But the biggest threat to wastewater systems is flooding, particularly during

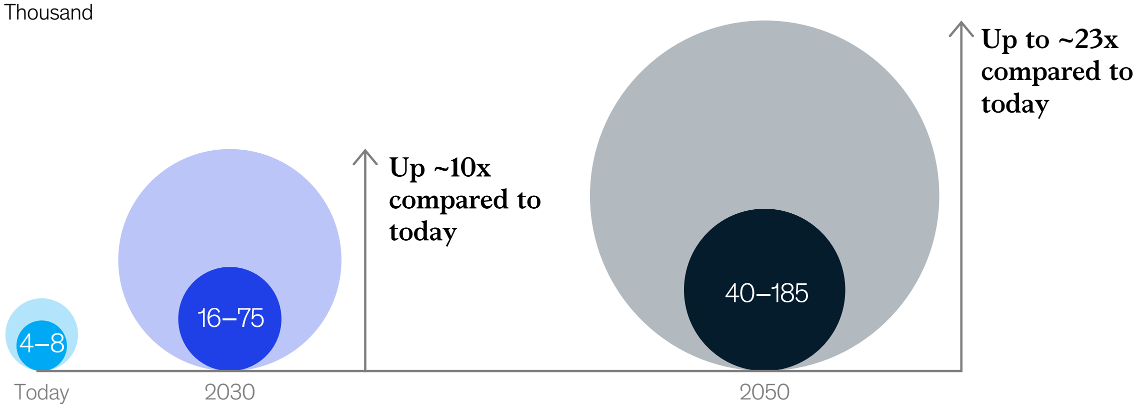
Exhibit 2

By 2050, up to 185,000 airline passengers per year may be grounded due to extreme heat (48°C), approximately 23 times more than today.

Based on RCP 8.5

Passengers affected by heat groundings each year[1]

Thousand



1. Assumes absence of targeted adaptation.

Assumptions: Covers aircraft typically used for regional flights; excludes larger international aircraft that have higher heat tolerances. Hazard is number of days when temperature reaches 48°C for at least 6 hours. Equal numbers of flights per day (no seasonal distribution applied). No growth in flights in future forecast. Heat-induced groundings are not widely documented today, but estimated at 50–100 per year based on a press search covering last 5 years, with allowance for underreporting. Based on RCP 8.5 scenario.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; Diio Mi flight database; Global Airport Database; Carpenter, 2018; McKinsey Global Institute analysis

hurricanes. Similar but more gradual wastewater overflows are also happening because of chronic stresses. In 2018, rainfall in the city of Richmond, Virginia, was more than 50 percent above average, and as a result 15,500 cubic meters of untreated sewage spilled into the James River.

Telecommunications: A fast-growing sector, telecommunications infrastructure has more agility and redundancy, yet as the world's dependence on the communications network increases, climate risks will also grow. High winds or trees can fell cell phone towers and telephone poles, blow down telephone lines and base stations, and knock microwave receivers out of alignment. Above-ground cabling is at more risk than buried lines of support and pole failures, damage from debris and falling objects (such as trees), and breakage from tension caused by extreme wind speeds. Flooding and hurricanes are the biggest threats. In 2015–16, floods in the United Kingdom inundated a number of key telecom assets, cutting off thousands of homes, businesses and critical public services such as the police. Hurricanes Irma and Maria caused devastation to telecom infrastructure in the Caribbean, with over 90 percent of mobile sites destroyed in Puerto Rico, St. Martin, Dominica, and Antigua and Barbuda. These threats interfere with the system just when it is needed most for disaster recovery.

What can be done to lessen the impact of climate change on global infrastructure?

Infrastructure is expected to bear the brunt of anticipated climate change adaptation costs, typically estimated to be between 60 and 80 percent of total climate change adaptation spending globally, which could average $150 billion to $450 billion per year on infrastructure in 2050. However, most estimates of the cost of adaptation relative to current assets are small compared with the scale of infrastructure investments. Estimates vary significantly, but consensus puts adaptation spending for new assets at about 1 to 2 percent of total infrastructure spending a year.

Adaptation should be tailored to the specific hazard and infrastructure risks. However, opportunities exist for adaptation that are relevant for all infrastructure sectors. Examples of ways to adapt current and future infrastructure to climate risks can be considered including by:

— Reducing exposure through transparency

— Accelerating investment in resilience

— Mobilizing capital to fund adaptation

For additional details, download the case study, *Will infrastructure bend or break under climate stress?*

How global infrastructure evolves over the next 50 years may be a major determinant of the impact of climate change on civilization. More money will need to be spent both on and in support of infrastructure, and in new ways. Building slightly higher walls, metaphorically or literally, may not be the best solution. And the risks extend beyond infrastructure. A failure to adapt by not taking climate change into account in the design, construction, and maintenance of infrastructure assets will not only cause costs to owners and operators but will leave entire communities exposed and vulnerable. Adaptation can deliver a strong return both by reducing costs from climate-related damage to infrastructure itself and by avoiding significant knock-on effects in wider society.

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Brodie Boland** is an associate partner in the Washington office. **Peter Cooper** is a consultant in the London office. **Byron Ruby** is a consultant in the San Francisco office.

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Could climate become the weak link in your supply chain?

Greater frequency and severity of climate hazards can create more disruptions in global supply chains—interrupting production, raising costs and prices, and hurting corporate revenues.

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Claudia Kampel, and Jakob Graabak

Much of global economic production is organized around a complex system of interdependent supply chains. Supply chains facilitate the production of everything from computers and cars to lifesaving medicines and food, and support world trade in goods that is worth almost $20 trillion annually. End products have up to many thousands of parts, sourced from diverse geographies around the world. Over time, these supply chains have been honed to deliver maximum efficiency and speed.

But questions about supply-chain risks and resilience are now being raised in the context of the global COVID-19 pandemic as well as acute weather events. As climate change makes extreme weather more frequent and/or severe, it increases the annual probability of events that are more intense than manufacturing assets are constructed to withstand, increasing the likelihood of supply chain disruptions.

Recent MGI research examines how industry value chains are exposed to a broader set of risks, including climate events. This work also examines vulnerabilities within specific companies and broader value chains, financial losses, and ways to bolster resilience.

In this case study, we examine how risks from climate hazards, already present in global supply chains, are likely to evolve over the next few decades. We identify three broad types of supply chains: specialty, intermediate, and commodity. Typically, the more specialized the supply chain, the more severe the impact could be for a downstream player as supply of a critical input may only be available from the source that has been disrupted. However, the more commoditized the supply chain is, the larger the number of downstream players that may be affected by spiking prices from a sudden reduction in supply (Exhibit 1).

For a deeper appreciation of the extent of risks, we focus on two supply chains that illustrate how disruption may play out. As an example of specialty supply chains, we examine the semiconductor industry; for commodity supply chains, heavy rare earth metals. Both create critical inputs for advanced industries. Semiconductor chips are ubiquitous in electronics from computers to smartphones to electronic watches. Rare earths are critical in aerospace and defense, electric vehicles, wind turbines, drones, medical appliances, and other electronics. Both supply chains are highly geographically concentrated in regions with an increasing probability of relevant climate hazards. However, these are only examples illustrating broader trends.

The probability of a hurricane of sufficient intensity to disrupt semiconductor supply chains may grow two to four times by 2040

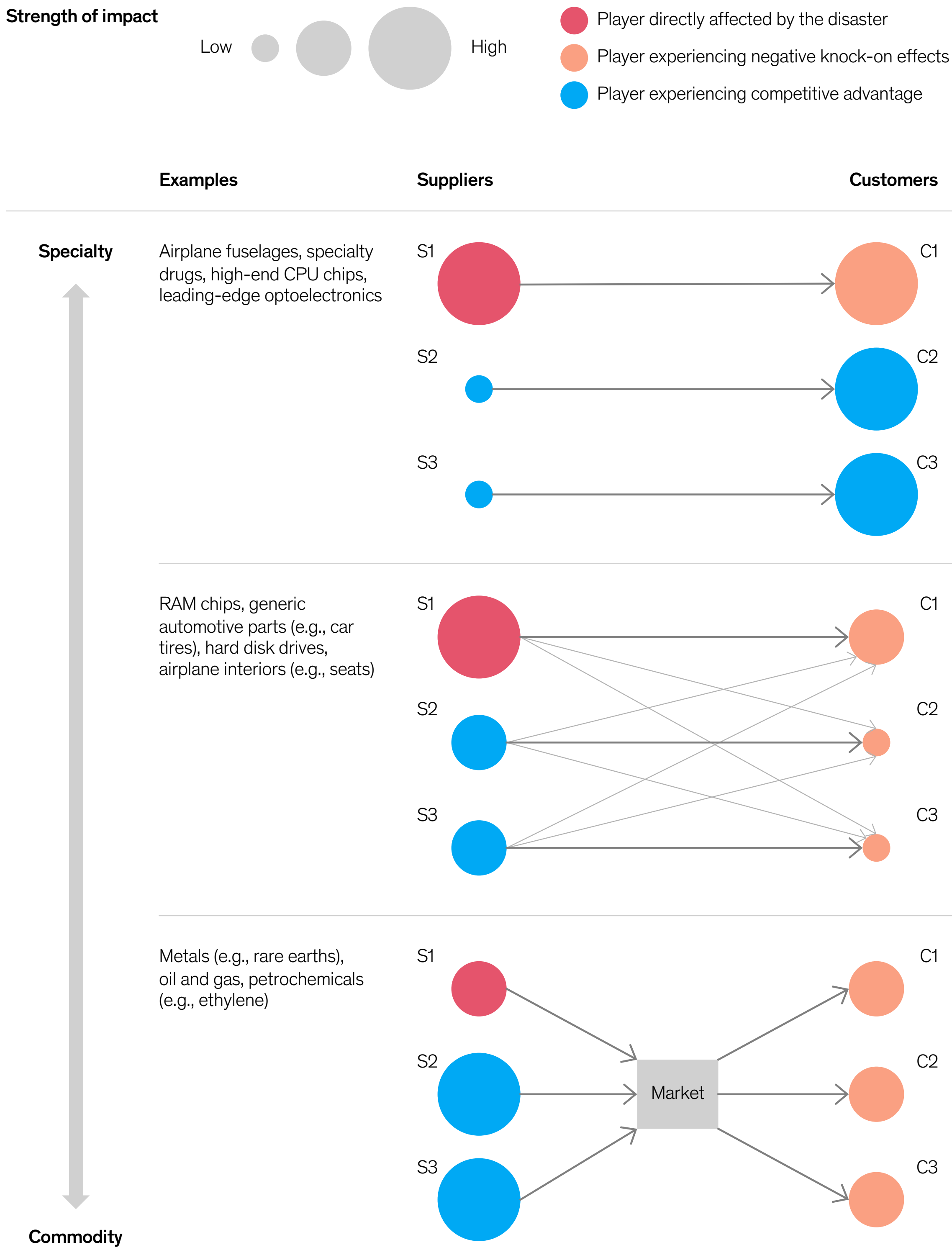
By 2040, a company using leading-edge chips (for example, with applications in memory, logic, communication, or optoelectronics) such as an automotive OEM, sourcing from geographies in Korea, Japan, Taiwan, or other hubs in the western Pacific, can expect that hurricanes sufficient to disrupt their suppliers will become two to four times more likely. Some of these disruptions may last for several months. This has implications for many industries as chips are increasingly critical to the modern economy. For example, electrical content in cars increased from 2 percent in 1960 to 35 percent in 2010.

There are three drivers of near-term losses for suppliers that are hit by such events, potentially leading to losses of up to 200 percent of annual profit and 35 percent of revenues: physical damages to assets, including facilities, production

Exhibit 1

Supply chains face different knock-on effects from production disruption depending on the degree of commoditization.

Illustrative



Source: McKinsey Global Institute analysis equipment, and inventories; reduced sales, either because production is disrupted or because goods cannot be shipped to the market; and higher costs in the reconstruction phase and after the plant is back in production, as market prices of labor, energy, and logistics may spike following a disaster. The combination of these impacts may also limit suppliers' ability to quickly and efficiently restore production, by reducing their ability to raise capital for repairs or by choking short-term cash flow and presenting unusual operational obstacles.

Semiconductor supply could be reduced by an extreme hurricane in several ways: loss of infrastructure services such as roads or power, direct damages to manufacturing assets, and damages to critical internal systems such as specialized equipment. We find that a severe supply disruption can cause cascading production disruptions downstream, particularly for unprepared players (Exhibit 2). Using a hypothetical example, we estimate that downstream players could lose up to a third of annual revenue if supply is disrupted for an illustrative period of five months. This could be the case if no alternative source or substitute was able to keep supply going (beyond a minimal inventory of finished goods) and if no measures had been taken to limit losses from disrupted downstream production (for example, insurance or negotiations with customers to delay supply).

A well-prepared player, on the other hand, may only lose about 5 percent of revenue in a similar event. Preparations may include dual sourcing (so only 50 percent of supply is lost), increasing supplier resiliency through due diligence and collaboration with suppliers on asset hardening; this can limit the recovery time to less than one month. Several other actions can help further reduce the losses, including insurance, even faster recovery through best practice emergency procedures, and discounted cross-selling of substitute products (for example, premium models or older product versions) to end consumers. These adaptations come with a cost that needs to be considered, but many of these investments may be smaller than the loss avoided.

There are two key areas of adaptation for semiconductor supply chains: building disaster-proof plants (for producers) and raising inventory levels in order to continue production even if a supply chain is interrupted (for downstream players). We find that building disaster-proof plants means additional costs of roughly 2 percent of the building costs which equals an additional $20 million for an average plant. Raising the inventory to provide a meaningful buffer in case of supply disruption, with estimated costs for warehousing and working capital, could increase input costs by less than a percent.

The probability heavy rare earths production is severely disrupted from extreme rainfall may increase 2 to 3 times by 2030

Heavy rare earths production is concentrated in southeastern China, which is increasingly exposed to extreme rainfall. We find that heavy rare earth production in southeastern China will experience extreme precipitation events (defined as events that occurred historically with an annual probability of about 2 percent, corresponding to precipitation of about 170 millimeters per day in the relevant region) twice as often by 2030. Expert estimates and historical events indicate that such rainfall events significantly increase the risk of landslides in the region.

We estimate that the manifestation of an extreme precipitation event, or series of events, could cause at least a 20 percent drop in heavy rare

Exhibit 2

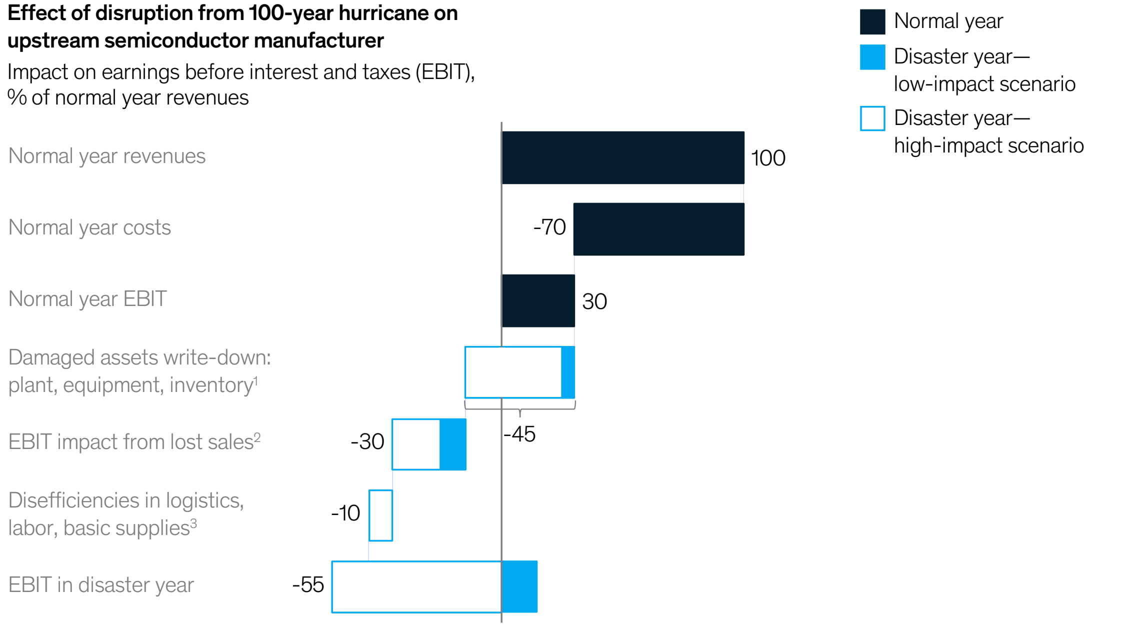
Being prepared for extreme weather impacts can minimize supply chain disruptions.

In the case of disruption to the semiconductor supply chain, an unprepared downstream company could lose about 35% of annual revenue while preparation limits the loss to about 5%.

Illustrative

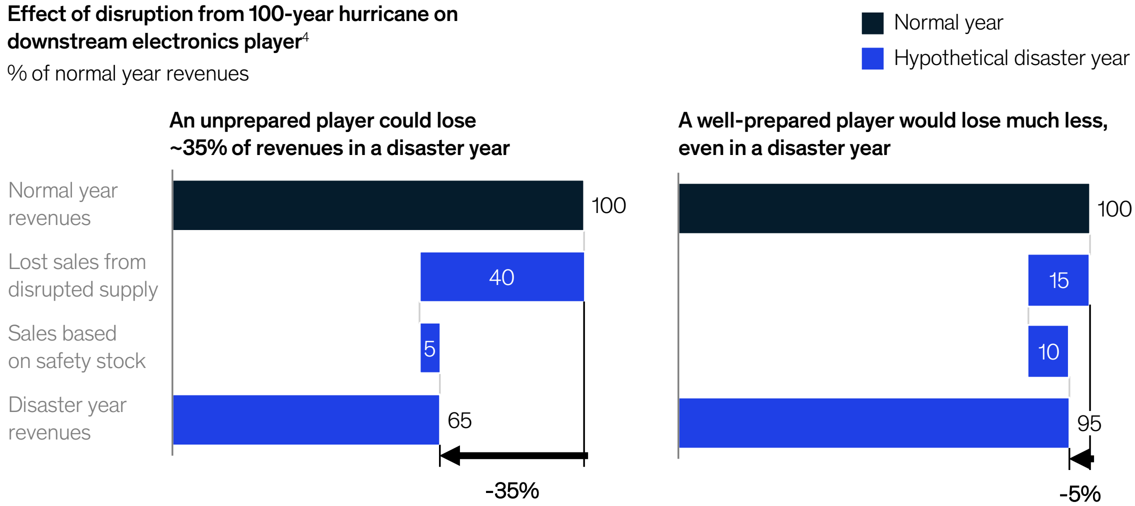
Effect of disruption from 100-year hurricane on upstream semiconductor manufacturer

Impact on earnings before interest and taxes (EBIT), % of normal year revenues



Effect of disruption from 100-year hurricane on downstream electronics player[4]

% of normal year revenues



5-month disruption of 100% of single-sourced supply

With 2 weeks of safety stock, resulting production disruption of 4.5 months

Dual sources and stronger asset resilience: only 3 months of 50% of supply disrupted

2x safety stock, spending at half pace due to dual sourcing, lasting for 2 months

Only 1 month disruption of 50% supply

1. Includes structural plant failure, replacement, repairs, and/or requalification of equipment, as well as raw material, work-in-progress inventory, and finished goods.
2. Lost revenues from disrupted sales, partly mitigated by reduced cost of goods sold proportional to reduction in sales volumes.
3. Includes costly additional labor, expensive backup power during grid failure, makeshift logistics solutions during rail or road disruptions, etc.
4. Excludes impact of insurance; exact outcomes vary considerably with local conditions and other factors.

Source: CP Analytics; Thailand government reports on 2011 floods; McKinsey Global Institute analysis earth output, and potentially much more in a worst-case scenario. Damage mechanisms include excessive mud and landslides in mines, flooding treatment ponds, and disrupted logistics to and from mines. Landslides are of particular concern, as they could both disrupt the ongoing leaching process in the mine if leach holes collapse and prevent production after the landslide if on-site repair works are required before new leach holes are dug (for example, to make sure that the soil has stabilized). This means a large landslide could disrupt production for up to 12 months in severely hit mines, though for most mines the disruption would be shorter if the landslide is shallow and only affects parts of the mine.

Even a limited supply shortfall could cause prices to rise substantially (Exhibit 3). During the supply crisis in 2010–11, prices of several rare earths increased more than ten times. Since the supply shortages, some rare earth consumers have attempted to build stockpiles in case of price spikes, but public data on the scale of the stockpiling are scarce. For downstream players without substantial inventories, a price spike would mean they either have to reduce their consumption of heavy rare earths or increase their spending.

A supply shortfall would be more critical for some heavy rare earths than others. Since the supply shortage in 2010–11, significant effort has been put into researching alternatives to rare earths, but with limited success in the key application areas. Going forward, there is concern about whether supply for some of these rare earth elements can keep up with demand for the materials that are used in high-growth segments like cleantech and consumer electronics, as well as high-end segments like aerospace and defense and medical appliances. Disruptions from climatic disruptions will add extra pressure to a supply chain that has little to no slack.

Downstream players dependent on rare earths can protect themselves from climate-change induced physical risk by raising inventory levels at the cost of additional working capital and storage space needed, similar to the semiconductor example above. Rare earth miners can also adapt in other ways, for example, by using different leaching products and processes that decrease the risk of landslides or moving leach holes away from the steepest slopes. We estimate these measures could increase COGS by less than 5 percent.

Other adaptation measures could slightly decrease the output of the mines: one option would be to select sites in areas with a lower concentration of mines in order to diversify risk, even if these mines have marginally lower potential. For example, Yunnan and Hunan have less than 2 mines today, while there are more than 54 mines in Jiangxi. Finally, if extreme rainfall is expected, miners could extract the leach in the most mature leach holes ahead of schedule. This would limit destruction of work in progress inventory when the rainfall turns mines to mud. All adaptation measures mentioned could be implemented in the short term and would eliminate about 50 to 80 percent of risk for rare earth miners, according to our estimates.

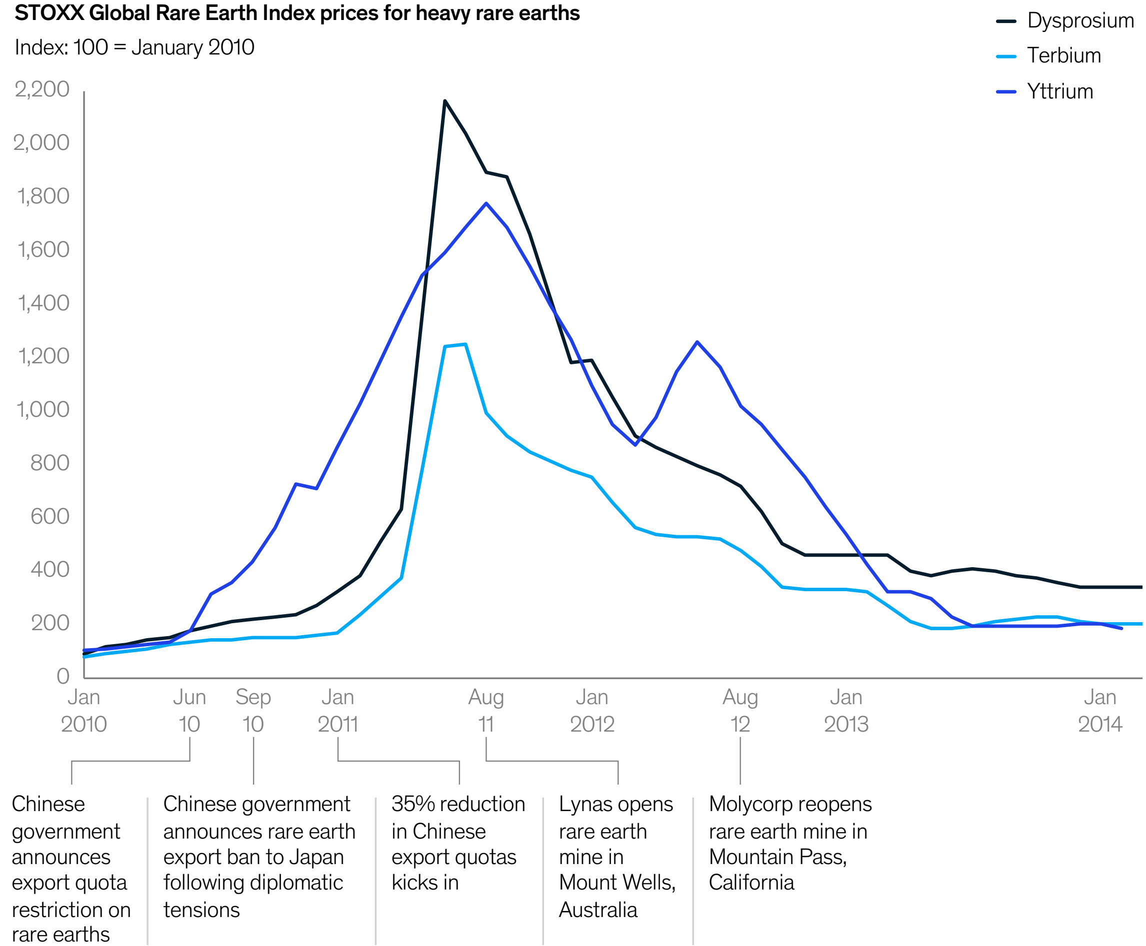
Supply chains and the infrastructure that supports them are designed for a stable climate. As hazards evolve, it will be necessary to increase investment in adaptation, possibly at the expense of efficiency.

Exhibit 3

Supply shortfalls in rare earths could cause price spikes as happened in 2010–11.

STOXX Global Rare Earth Index prices for heavy rare earths

Index: 100 = January 2010



Source: Croat, 2018; Lynas Corp.; Molycorp, 2014; *New York Times*; Wiley Rein

We find significant potential for many industries to adapt in the next decade, including conducting risk diagnostics, protecting manufacturing assets, redesigning operations (for example, by increasing safety stock of key inputs), broadening supplier base, shoring up infrastructure, etc. Indeed, measures of this kind are already underway in some areas, including from public authorities, suppliers in high-hazard locations, and customers in downstream sectors.

For additional details on the risks to supply chains and possible adaptation measures, download the case study, *Could climate become the weak link in your supply chain?*

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Claudia Kampel** is a consultant in the Stuttgart office. **Jakob Graabak** is a consultant in the Oslo office.

A Mediterranean basin without a Mediterranean climate?

The Mediterranean's signature climate drives tourism and agriculture in the region. What impact is climate change likely to have.

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Marlies Vasmel, and Johanna von der Leyen

Year-round, millions of visitors from all over the world flock to enjoy the mild climate, wine and food, and stunning scenery. However, climate change may harshen the Mediterranean climate and disrupt vital industries such as tourism and agriculture. The mean temperature in the Mediterranean basin has increased 1.4 degrees Celsius since the late 19th century, compared with the global average of 1.1 degrees—and absent targeted decarbonization, temperatures are projected to increase by an additional 1.5 degrees by 2050. Rising temperatures are expected to raise hydrological variability, increasing the risk of drought, water stress, wildfires, and floods, and noticeably change the Mediterranean climate.

In this case study, we examine the consequences of a changing climate for Mediterranean communities and economies. We focus on heat- and precipitation-related aspects of climate change, although coastal flooding will also have an impact.

How the Mediterranean climate may become harsher

The Mediterranean climate could change in multiple ways as temperatures rise, water stress increases, and precipitation becomes more volatile, in turn creating multiple knock-on effects from wildfires to the spread of disease (Exhibit 1).

Heat: Climate projections indicate that the number of days with a maximum temperature above 37 degrees will increase everywhere in the Mediterranean region, with a doubling in northern Africa, southern Spain, and Turkey from 30 to 60 by 2050.

Drought: In Italy, Portugal, Spain, and parts of Greece and Turkey, rainfall during the warm, dry season of April through September is projected to decrease by as much as 10 percent by 2030 and as much as 20 percent by 2050. By 2050, drought conditions could prevail for at least six months out of every year in these areas.[1]

Water stress: Many basins could see a decline of approximately 10 percent in water supplies by 2030 and of up to 25 percent by 2050. Water stress is already high in most countries in the Mediterranean and extremely high in Morocco and Libya. The decline in supply is projected to heighten water stress in all Mediterranean countries between now and 2050, with the greatest increases in Greece, Morocco, and Spain.[2]

Wildfires: Increased levels of heat and dryness are projected to cause larger areas—up to double the current areas on the Iberian Peninsula—to burn from wildfires.

Disease: High summer temperatures have also been linked with the increasing incidence of West Nile fever in Europe. The summer of 2019 saw the first reported case of West Nile virus infection as far north as Germany. Researchers have already projected that the West Nile virus is likely to spread by 2025 and to spread further by 2050.

How would a harsher climate affect agriculture?

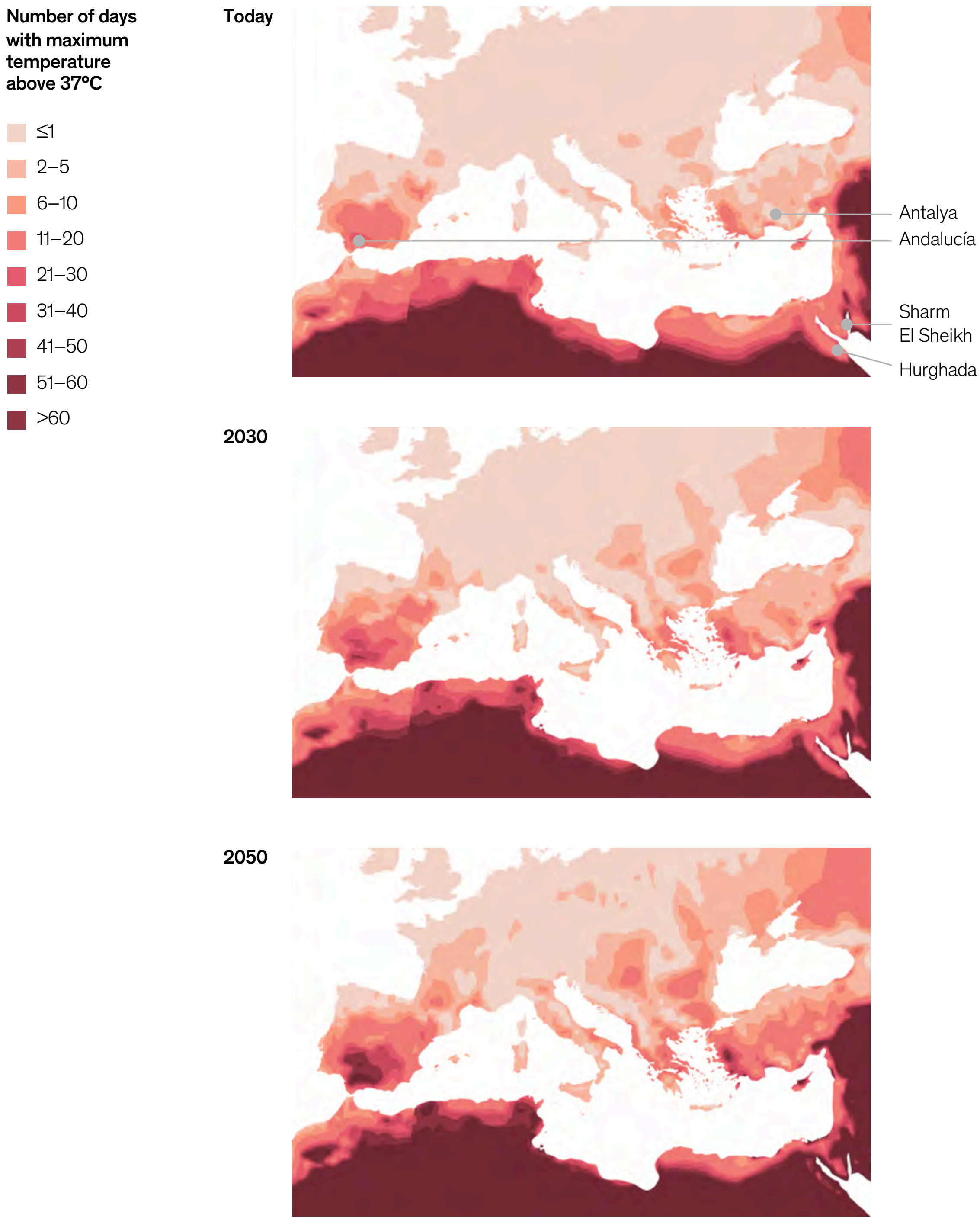
Nearly half of the Mediterranean region's agricultural production value comes from four crops: grapes (14 percent), wheat, tomatoes, and

[1] Based on Palmer Drought Severity Index of –2 (moderate drought) or lower. NOAA characterizes moderate drought by: some damage to crops and pastures; high fire risk; low streams, reservoirs, or wells; some water shortages developing or imminent; and voluntary water use restrictions requested. In general, drought means dry relative to what is normal for a given location and time of year.
[2] World Resources Institute.

Exhibit 1

The number of days above 37°C in southern Spain, Turkey, and Egypt is expected to double by 2050, from about 30 to 60.

Based on RCP 8.5



Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company. See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

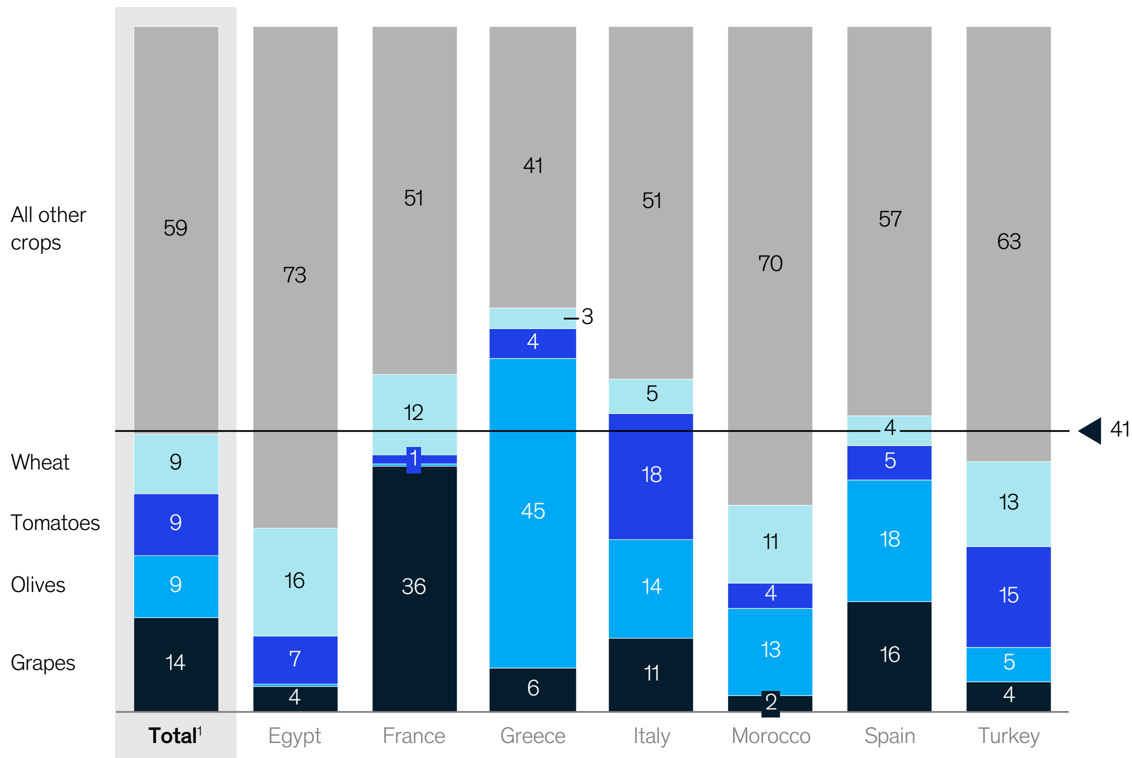
Source: EURO-CORDEX RCM ensemble; Woods Hole Research Center

Exhibit 2

About 40 percent of the Mediterranean region's agricultural production value comes from just four crops: wheat, tomatoes, olives, and grapes.

Crop production value in the Mediterranean region, 2016

% of total gross production value



1. Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, France, Greece, Israel, Italy, Lebanon, Malta, Morocco, Portugal, Slovenia, Spain, Tunisia, Turkey.

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

Source: FAO; McKinsey Global Institute analysis

olives (9 percent each) (Exhibit 2). Of the last three, Mediterranean countries produce about 90 percent of the total global supply. We focus on how climate change is likely to alter the production of grapes and wine in the period to 2050.

Production from traditional winemaking regions could diminish as the Mediterranean climate changes, since grapevines are highly sensitive to fluctuations in temperature and precipitation and can also be impacted by water stress and hail damage. Researchers have forecast a wide range of possible effects of climate change on grape yields. Some studies project that the Mediterranean area suitable for viticulture could fall by up to 70 percent at the high end of their range, though considerable debate surrounds these predictions, as others do not see negative impacts at all. As the Mediterranean region becomes warmer, it is also likely that specific grape varieties will no longer grow where they do now (for example, Merlot in Bordeaux), while at the same time the opportunity to plant new varieties may rise. Certain growing areas in Italy, Portugal, and Spain could experience large declines in production or even collapse.

Some researchers anticipate that the warming projected to occur throughout Europe could make it possible to grow wine grapes in regions farther to the north. In effect, Europe's grape growing belt would shift. But the characteristics of Mediterranean vineyards and wineries cannot be replicated instantaneously. Indeed, they might never be matched, because gaining similar levels of experience in new winemaking regions may take generations.

What impact could a harsher climate have on travel and tourism?

Travel and tourism, including indirect and induced impacts, generate about 15 percent of the GDP of Mediterranean countries on average. In certain areas, the local economy depends much more on tourism and we analyze several of these cities. For example:

Antalya, a beach and resort city of two million people on Turkey's southern coast, attracts more than ten million visitors each year, some 30 percent of all tourists who visit the country. The city is projected to experience a significant increase in the number of summer (June to August) days above 37 degrees: about 15 days each summer by 2030, and approximately 30 days (10 days per month) in 2050. These months are crucial to the tourism industry. They generate 40 percent of each year's visits and account for tourist spending of some $4.5 billion, as well as about 20 percent of Antalya's GDP and about 2 percent of Turkey's.

How can tourism and agricultural industries adapt?

Mediterranean destinations could adapt to climate change in a number of ways. Tourist destinations could extend their shoulder seasons as the Mediterranean climate changes. However, this may not be as simple as offering discounts. Large discounts already give tourists an incentive to travel outside the summer months, yet the summer tourist visit peaks have remained stable over the past ten years. One reason for this is that many tourists are restricted to traveling during school or work holiday periods. Tourist destinations may also offer year-round activities to increase the flow of tourists during the months now considered shoulder or off-season or target different markets such as those convening for meetings and conferences.

Wine growers already take measures to manage variations in production quantity and quality; these actions include cultivating grape varieties that ripen more slowly or require less water. Various hardening measures can help them cope with increased heat and drought. These include: harvesting earlier, reducing sunlight on grapes, irrigating vineyards. Wine growers can increase their resilience by planting different crops or moving to new locations, including higher altitudes and slopes other than the conventional south-facing ones.

Most regions in the Mediterranean will need to invest in adaptation. For example, forests can be made more resilient to wildfire risk by planting fire-resistant trees, reducing the amount of easily burning fuel available (such as leaf litter and brush), and even prescribed and controlled burning. These adaptation costs will likely need to be borne across the continent but will be particularly intense in the Mediterranean basin.

For additional details, download the case study, *A Mediterranean basin without a Mediterranean climate?*

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Marlies Vasmel** is a consultant in the Amsterdam office. **Johanna von der Leyen** is a consultant in the Berlin office.

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How will African farmers adjust to changing patterns of precipitation?

Agriculture is critical to Africa's growth and development, but climate change could destabilize local markets, curb economic growth, and heighten risk for agricultural investors.

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Ryan McCullough, Tilman Melzer, and Sara Boettiger

Climate change is expected to make agricultural development in Africa more challenging. Weather patterns are becoming less favorable in many instances, increasing the volatility of crop and livestock yields. The frequency and/or severity of extreme events is increasing as temperatures are projected to continue rising, and rainfall patterns are expected to shift more than they have already (Exhibit 1).

Overall, Africa is vulnerable because for many of its crops, it is at the edge of physical thresholds beyond which yields decline. Moreover, a substantial portion of some countries' economies (for example, one third of GDP for Ethiopia and one fifth of sub-Sahara Africa's economic output) depends on agriculture. Finally, some aspects of adaptation may be challenging; for example, African farmers are generally more vulnerable to higher temperatures, fluctuations in rainfall, and variable yields than farmers in developed countries, who can usually more easily secure crop insurance, adjust what they plant, irrigate their fields, or apply crop protection chemicals and fertilizers.

In this case study, we focus on major crops in Ethiopia and Mozambique. Using crop yield models, we assess the expected impact of climate change in 2030 on wheat and coffee in Ethiopia and on corn (maize) and cotton in Mozambique. It is important to note that Africa is a climatologically diverse continent and that the results presented here are not representative of the challenges or changes faced by other African nations. Climate change will affect some regions of Africa more or less than it affects Ethiopia and Mozambique.

By 2030, Ethiopia may face significant volatility in coffee yields while Mozambique may face greater volatility in corn production

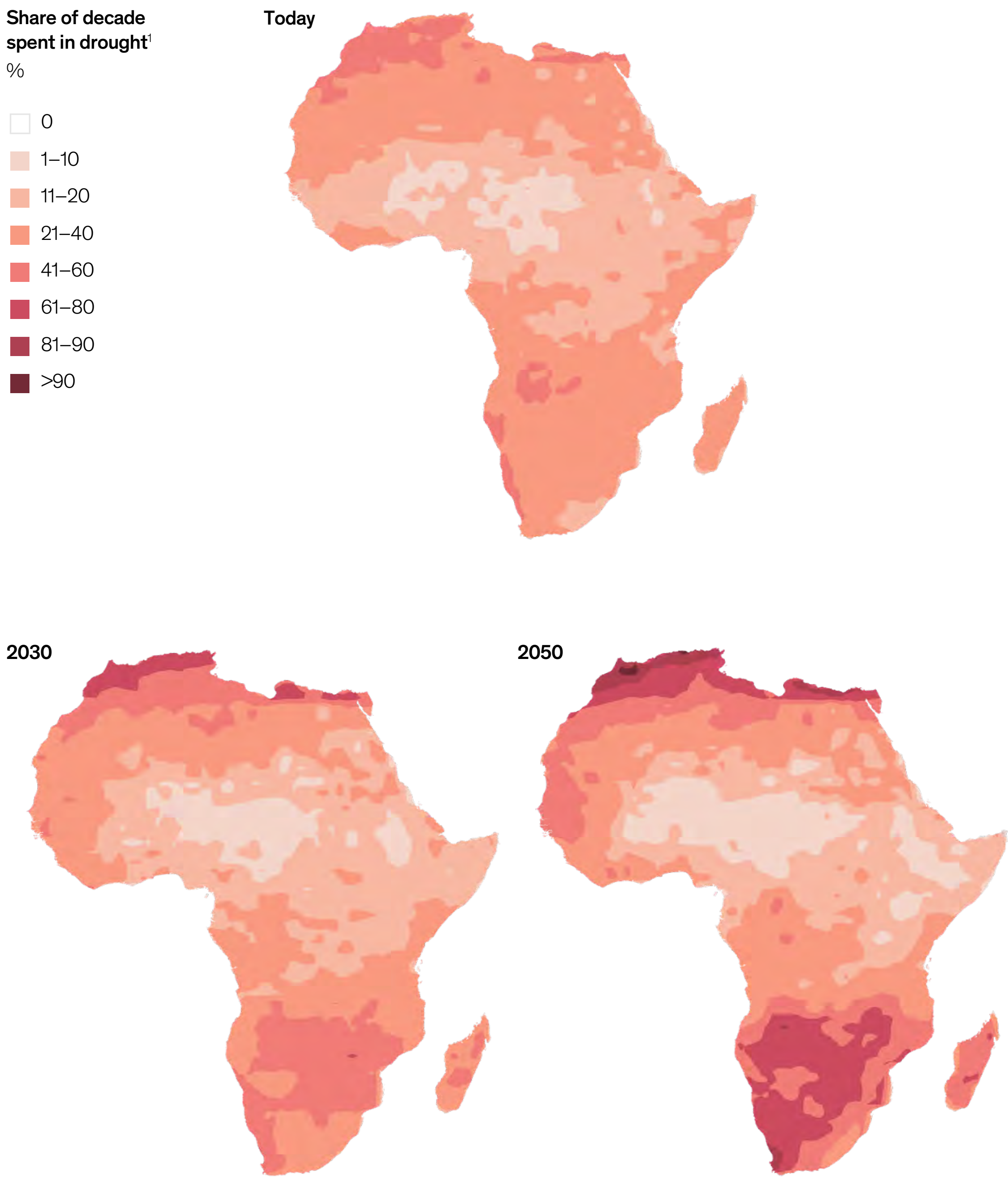
While volatility is often symmetric, meaning positive and negative shocks are roughly equally likely, we find that the overall effect of increasing volatility is negative. Farmers and other players in the value chain usually do not fully capture the benefits from good years due to a limited ability to sell bumper harvest into shallow local markets, absence of

Africa is vulnerable because for many of its crops, it is at the edge of physical thresholds beyond which yields decline.

Exhibit 1

Expected evolution of drought differs by region in Africa, with the most affected areas in the north and south.

Based on RCP 8.5



1. Drought is defined as a rolling 3-month period with Average Palmer Drought Severity Index (PDSI) <-2. PDSI is a temperature- and precipitation-based drought index calculated based on deviation from historical mean. Values range from +4 (extremely wet) to -4 (extremely dry).

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; McKinsey Global Institute analysis storage infrastructure to smooth supply over many years, and poor transportation infrastructure that makes sale into other markets difficult. At the same time, a bad year can have longer-lasting effects for farmers. For subsistence farmers, they may for example have to go into debt or not be able to service existing debts.

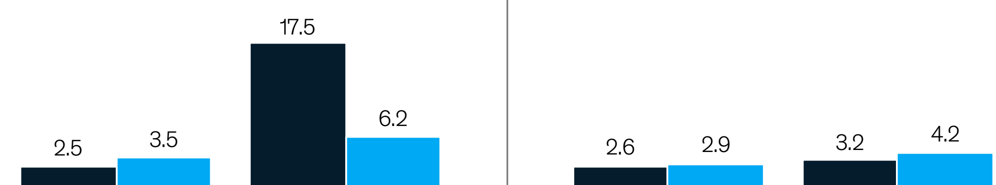
We find that by 2030, Ethiopia's wheat farmers are projected to face an 11 percent greater likelihood than today of a 10 percent or greater drop in annual yield. For coffee farmers in Ethiopia, the chance of experiencing a 25 percent or greater drop in annual yield could climb from 3.2 percent to 4.2 percent in 2030, which is a 31 percent increase, and a 28 percent cumulative likelihood over the next decade. Should yield shocks of this magnitude take place for both crops in the same year, we estimate that Ethiopia's GDP growth rate would be cut by approximately three percentage points (Exhibit 2).

Exhibit 2

The effects of climate change on African crop yields in 2030 are projected to be uneven.

Based on RCP 8.5

	Mozambique		**Ethiopia**	
	Corn (maize)	**Cotton**	**Wheat**	**Coffee**
Likelihood of extreme yield changes[1] %				
Today / 2030	25% yield decline or more	10% yield decline or more	10% yield decline or more	25% yield decline or more



Main climatological drivers				
Positive	Increasing rainfall during rainy season, which coincides with crop development	Rising temperatures from October–December	Minimum temperatures during wheat reproductive and primary growth phases are increasing	
Negative	Temperatures are rising and rainfall is decreasing around time of planting, potentially delaying planting	Less rainfall at end of dry season (October) may delay planting	Majority of wheat-growing regions will experience less rainfall	Temperatures are increasing and rainfall is decreasing during flowering and early fruit development, resulting in decreased water availability

1. Change in yield in a given year, relative to long-term average. Yield decline scenarios for each country crop combination were selected based on two considerations: the scenario is plausible, ie, the likelihood of occurrence is meaningful for most stakeholders (eg, once in a generation); and the decline is meaningful in terms of economic impact.

Note: See the Technical Appendix of the full report for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: CORDEX regional climate models; McKinsey Global Institute analysis

African countries are already working to counteract growing volatility, but better and more localized planning and financial mobilization will be key.

In Mozambique, we find a large seasonal loss (more than 30 percent) of the corn crop is expected to go from a highly improbable event to a 100-year event. We estimate that a 25 percent or greater drop in corn yields would reduce Mozambique's GDP by 2.5 percent. Conversely, we find that cotton yields would become more stable; however, given the small size of cotton farming, this does not provide a strong counterbalance to the negative impacts on corn.

What can African farmers do to mitigate the impact of climate change?

Higher volatility in the yields of major African food crops is likely to result in higher price volatility for both farmers and consumers. African countries are already working to counteract growing volatility, but better and more localized planning and financial mobilization will be key.

Modernizing Africa's agriculture in the face of a changing climate will require significant investment. Investments in irrigation can increase the likelihood that farmers maintain yields even when the weather is unfavorable. Better roads can help connect markets, which would help farmers sell their crops at fair prices. Improvements in the functioning of seed production systems would provide farmers with new varieties of seed that are suited to new conditions. Upgraded crop-storage facilities would prevent spoilage and food waste.

Climate change's varying effects on regions and crops underscore the importance of targeted planning on the part of governments, investors, and international donors. Today's planning models have difficulty accounting for these effects. First, published projections of climate change's impacts typically focus on 2050 or 2100—too far out to aid nearer-term decisions. Second, climate and economic models that focus on local contexts are less common than broader models. We believe that governments, companies, development banks, donors, and other organizations stand to benefit from bringing highly localized, commodity-specific forecasts into agricultural planning in Africa.

Wider access to agricultural financial instruments, such as crop insurance, would enable individual farmers and households to better manage climate-related risks. However, expanding crop insurances may require support, because most farmers are not able to pay the full premium.

Overall, successful adaptation may depend primarily on changes in farmers' behavior (for example, use of improved inputs such as fertilizer and better seeds), institutional improvements (for example, localized, commodity-specific forecasts), as well as the collaboration of affected stakeholders on certain adaptation measures (for example, to solve storage issues).

For additional details, download the case study, *How will African farmers adjust to changing patterns of precipitation?*

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Ryan McCullough** is a partner in the Denver office. **Tilman Melzer** is a consultant in the New York office. **Sara Boettiger** is a consultant in the San Francisco office.

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Will the world's breadbaskets become less reliable?

The COVID-19 pandemic is exposing vulnerabilities in the global food system which could be compounded by climate change risks.

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Ryan McCullough, Tilman Melzer, and Sara Boettiger

Climate change could affect food production through both continuous environmental changes—for example, increasing temperatures and changes to precipitation patterns—and more frequent episodes of acute stress, such as drought, heat waves, and excessive precipitation. The COVID-19 pandemic is exposing weaknesses in the global food system which we find is already vulnerable to climate change as a growing population depends on four key crops with high geographic concentration of production.

In this case study, we examine the changing likelihood of a harvest failure occurring in multiple breadbasket locations as well as the potential socioeconomic impact of such an event (See sidebar: "An overview of the case study analysis"). We define a breadbasket as a key production region for food grains (rice, wheat, corn, and soy) and harvest failure as a major yield reduction in the annual crop cycle of a breadbasket region where there is a potential impact on the global food system.

How vulnerable is the global food system to climate change?

A combination of factors makes the global food system more vulnerable to climate change. These include:

Dependence on a handful of grains: The human diet is highly dependent on just four grains: rice, wheat, corn, and soy. They make up almost half of the calories of an average global diet, with rice and wheat contributing 19 percent and 18 percent, respectively.

Geographic concentration of production: Sixty percent of global food production occurs in just five countries: China, the United States, India, Brazil, and Argentina (Exhibit 1). Even within these countries, food production is highly concentrated in a few regions. For example, 88 percent of Indian wheat production comes from five states in the northern part of the country and in the United States, five Midwestern states account for 61 percent of corn production, according to the Department of Agriculture. This means extreme weather events in those regions could affect a large portion of global production.

Growing dependency on grain imports: The population that relies most on these grains is growing. In particular, developing countries tend to be importers of grain, mostly because competitive disadvantages in growing grains make buying from the world markets cheaper than producing domestically. For example, Algeria, Egypt, Mexico, and Saudi Arabia are net importers of grain, and China is highly dependent on soy imports.

Limited grain storage: The amount of stored grain influences how well the food system is equipped to respond to any shortage of food production because it provides a buffer that can be built in years with low prices and released in years with higher prices. Despite historically high levels today, grain storage levels appear insufficient to withstand a large shock in production.

The likelihood of a 15% shock to grain production doubles by 2030 with possible knock on effects to prices

Our analysis suggests that a "true" multiple-breadbasket failure—simultaneous shocks to grain production through acute climate events in a sufficient number of breadbaskets to affect global production—becomes increasingly likely in the decades ahead, driven by an increase in both the likelihood and the severity of climate events. For example, a greater than 15 percent shock to grain production was a 1-in-100 event between 1998 and 2017.

This likelihood doubles by 2030 to 1 in 50, suggesting that there is an 18 percent likelihood of such a failure at least once in the decade centered on 2030. A greater than 10 percent yield shock has an 11 percent annual probability or a 69 percent cumulative probability of occurring at least once in the decade centered on 2030. This is up from 6 percent and 46 percent, respectively.

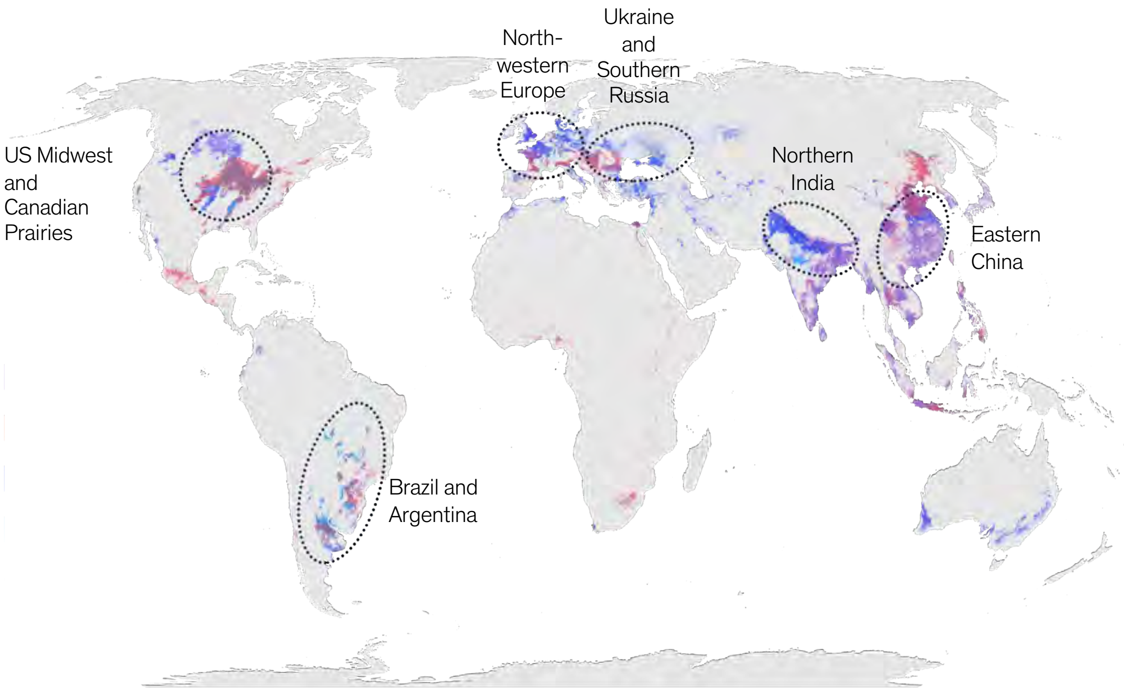
These increases are driven mainly by risks to corn, soy, and rice production, because climate change leads more frequently to weather patterns that

Exhibit 1

Production of the world's major grains is highly concentrated in a few growing regions.

Rice | Corn | Wheat | Soy[1] | Major grain production areas

Global agricultural production[2]

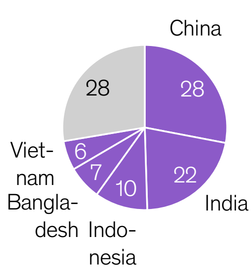


Share of grain production by country, 2015–17

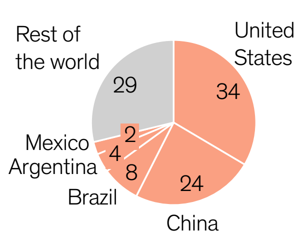
% of average annual production

Rest of world

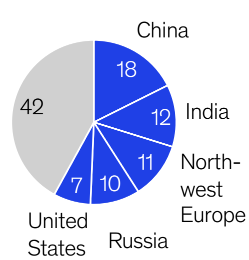
Rice



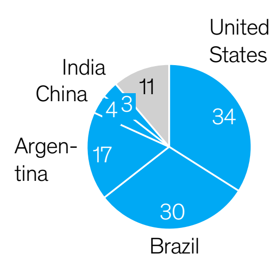
Corn



Wheat



Soy



Note: The boundaries and names shown on this map do not imply official endorsement or acceptance by McKinsey & Company.

1. Soybeans and oil.
2. Colors indicate where particular grain is produced. Darker shading within each color indicates higher density of production, lighter (more transparent) shading indicates lower density of production.

Source: FAOSTAT; Earth Stat, 2000; McKinsey Global Institute analysis (disputed boundaries) adversely affect their growing conditions. Corn, for example, has a plant physiological threshold of about 20 degrees Celsius, beyond which yields decline dramatically. Similarly, both drought and extreme precipitation (beyond roughly 0.5 meter of seasonal precipitation) lead to suboptimal yields. In the US Midwest, one of the key corn production regions globally, hotter summer temperatures and higher likelihood of excessive spring rain (as seen in 2019) drive higher likelihood of harvest failures. Wheat is the one crop that seems to benefit from the higher temperatures that climate change causes in some of the main production regions (Exhibit 2).

Since current stock-to-use ratios are historically high at 30 percent of consumption, it is virtually impossible that the world will run out of grain within any one year. However, even limited reductions in stock-to-use ratios have triggered past episodes of spiking food prices, and we have no reason to expect that this would not be the case in the event of a multiple breadbasket failure.

In our analysis, we assume stock-to-use ratios drop to about 20 percent in the event of a multiple-breadbasket failure, which would require a 15 percent drop in global supply in a given year. In that case, historical precedent suggests that prices could easily spike by 100 percent or more in the short term. 1 More broadly, negative economic shocks of this size could lead to wide-spread social and political unrest, global conflict, and increased terrorism.

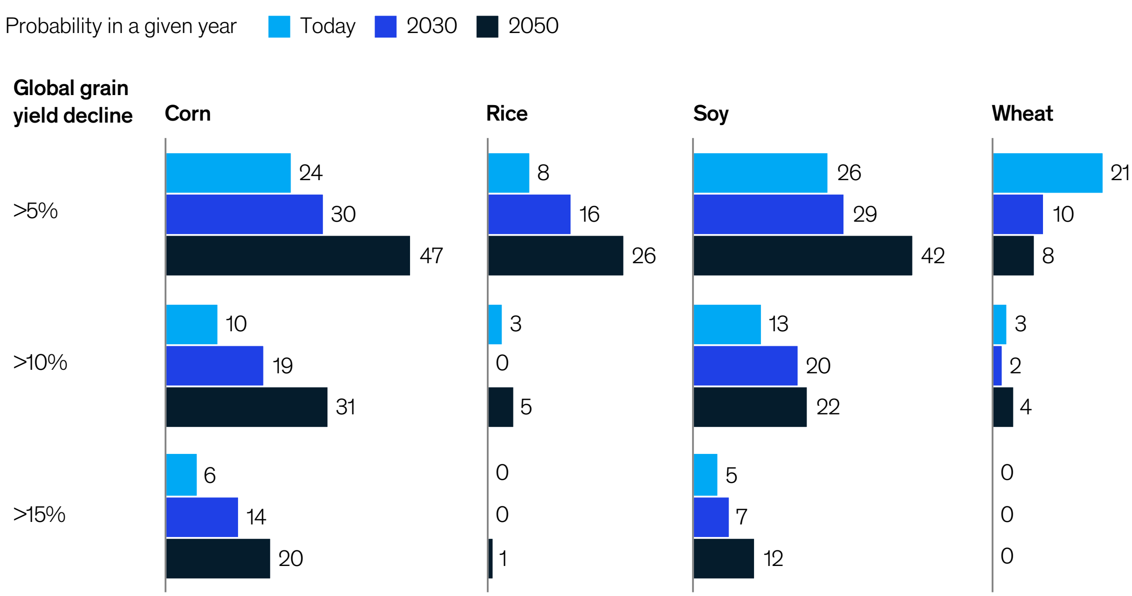
Policymakers have begun to build a more resilient food system, but more can be done

Following the food price shortages of the past decade, the G-20 developed an action plan to reduce price volatility. While we believe this is

Exhibit 2

Climate change will affect yields of each grain differently.

Based on RCP 8.5



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Source: Woods Hole Research Center

a good start, more can be done that does not require the same degree of coordination. We offer a set of actions that are in the interests of governments, agricultural trading companies, and multilateral organizations.

Governments: A relatively straightforward way to manage domestic grain prices is by keeping large amounts of stocks that are built up in times of low prices and released when prices increase, essentially creating a price ceiling. While such a policy does not require coordination with other countries, there are challenges. For example, high food stocks can drain resources during times of low prices and do not provide any immediate benefit while acquiring large amounts of grains on world markets can prove hard, and countries run the risk of paying premiums. Despite challenges, increased storage is likely to be the most straightforward and reliable tool to prevent large domestic price spikes. By introducing near-term redundancy, increased storage increases long-term resilience. In addition, governments could consider increasing the flexibility of the nonfood use of grains. For example, regulators could explicitly introduce mechanisms controlling demand for biofuels.

Agricultural trading companies: They may want to review their long-term strategies regarding storage capacity investment and utilization as well as their trading strategies in light of the revised probabilities of multiple-breadbasket failures. To the extent that governments deem food storage and the ability to ship grains quickly and reliably to consumers a positive externality, they may choose to subsidize private-sector storage, encouraging the private sector to increase storage facilities, or to invest in improved transportation infrastructure (rail lines and ports, for example). Based on annual production of 3.5 billion tons, we estimate the cost of increasing global stocks to be $5 billion to $11 billion a year, assuming the cost of stocks of $32 a ton. Such an investment would increase the current global stock-to-use ratio to 35 to 40 percent, which could offset harvest failures of the magnitude of 15 percent.

Multilateral organizations: Organizations such as the World Bank and FAO could consider the creation of virtual reserves. This would involve increasing short sales in the spot market during times of high food prices, which could help to reduce prices. However, this would work only to the extent that markets "overreact"

By introducing near-term redundancy, increased storage increases long-term resilience. In addition, governments could consider increasing the flexibility of the nonfood use of grains.

(for instance, by introducing export bans) and when there are no actual food shortages, because it does not alter supply, demand, or physical reserve levels. Organizations could also explore the design of innovative mechanisms that would lead to higher private-sector storage rates.

For additional details, download the case study, *Will the world's breadbaskets become less reliable?*

While the world today is, on average, producing more than enough food to feed the growing population, short-term price hikes from episodes of acute climate stress could have a significant impact on the well-being of 750 million of the world's poorest people, with the possibility of substantial broader knock-on impacts. Increasing production and storage in good years and increasing flexibility in the use of food crops to maximize calories consumed could go a long way to lessen that risk.

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Nicolas Denis** is a partner in the Brussels office. **Tilman Melzer** is a consultant in the New York office.

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Will mortgages and markets stay afloat in Florida?

Flood risk is rising in Florida due to climate change. How exposed is residential real estate—both directly and indirectly—and what can be done to manage the risks?

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Claudia Kampel, and Marlies Vasmel

Located in a tropical cyclone zone with low elevation and an expansive coastline, Florida faces numerous climate hazards, including exposure to storm surge and tidal flooding that are worsened by sea level rise, and heat stress due to rising temperatures and changes in humidity. Other unique features include the state's porous limestone foundation which can exacerbate flooding as water seeps into properties from the ground below and also causes saltwater intrusion into water aquifers, and makes adaptation challenging.

Much of Florida's physical and human capital is located along its vulnerable coast. Two-thirds of the state's population lives near the coastline, exposing many of them to tidal flooding, and almost 10 percent is less than 1.5 meters within sea level. At the same time, Florida's economy depends heavily on real estate. In 2018, real estate accounted for 22 percent of state GDP. Real estate also represents an important part of household wealth for the 65 percent of Floridians who are home owners: primary residences represent 42 percent of median home owner wealth in the United States.

In this case study, we focus on residential property in Florida exposed to flooding from storm surges and to tidal flooding and assess the likely impact both in terms of direct and knock-on effects, for example through housing price adjustments.

The effects of climate change could increase over the next decade and beyond

Climate change is projected to exacerbate flooding due to storm surges, precipitation intensity, and rising sea levels that increase tidal (also referred to as nuisance) flooding. For example, the frequency of tidal flooding from rising sea levels is expected to grow from a few days a year to 30 to 60 times per year in 2030 and more than 200 times per year in 2050 for stations near Florida's coast, according to First Street Foundation.

We consider two impacts from rising sea levels: increased flooding from storm surge and tidal flooding. Based on analysis conducted by KatRisk for this case study, average annual damages from storm surges in Florida's residential real estate market total $2 billion today, a figure that could increase to $3 billion to $4.5 billion, by midcentury depending on whether the exposure is expected as constant or as seeing some buildup. However, individual counties can see more extreme increases. Examples are Volusia, St. Johns, and Broward counties, which could see their average annual losses grow by approximately 80 percent by 2050.

Rising sea levels also increase the damage caused by "tail" events in all counties. Florida's real estate losses during storm surge from a 100-year event are expected to be $35 billion today and projected to grow to $50 billion to $75 billion by 2050. For Miami-Dade, the expected damages from such a tail event could be about 10 percent of total market value, about 30 percent in Lee, and about 20 percent in Collier. To put the likelihood of such a large loss into context, in the lifetime of a 30-year mortgage, a 100-year event (that is, an event with a likelihood of 1 percent) has a 26 percent chance of occurring at least once. Finally, the level of losses that are observed during today's 100-year event are projected to become more frequent; by 2050, such losses could happen approximately every 60 years, that is, almost doubling the likelihood of such an event (Exhibit 1).

Knock-on effects could be even more significant than the direct impact of flooding

While the Florida residential real estate market remains robust today, climate risk poses a potential threat to asset prices. There are several ways this could occur although it is difficult to know the timing and magnitude of impacts:

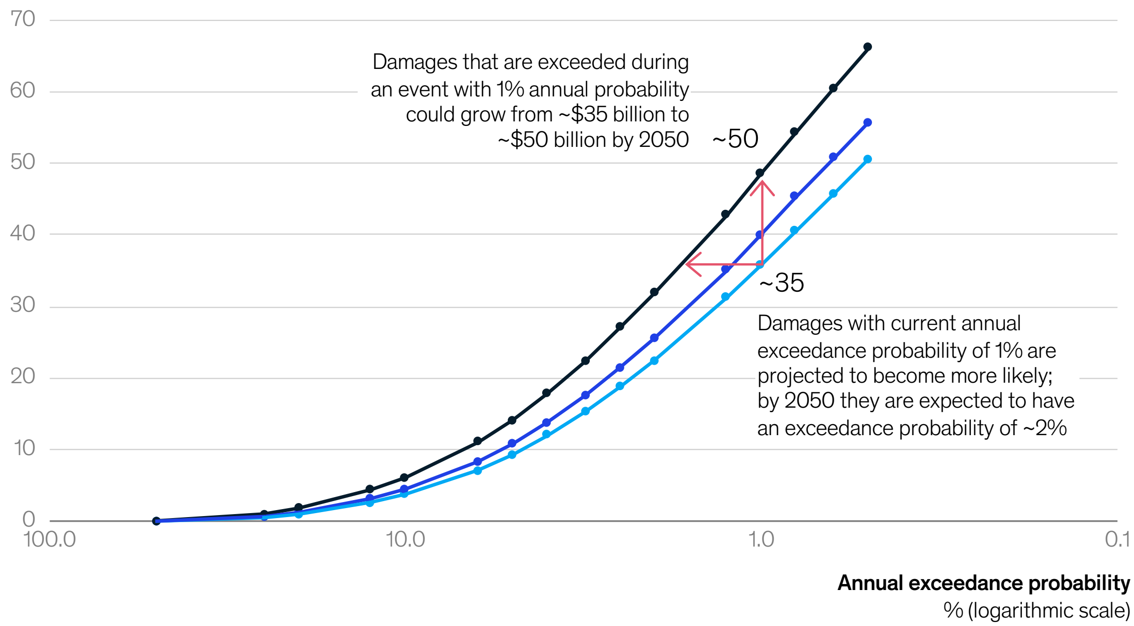
— *As buyers experience flooding, prices of affected homes may adjust:* According to First Street Foundation, properties exposed to flooding have on average seen a 3 percent price discount compared with similar unexposed properties while properties exposed to disruptive flooding—where more than 25 percent of a property lot or nearby roads are flooded—on average have lost 11 percent of their value. This has already resulted in a total devaluation today of $5 billion of affected residential properties in

Exhibit 1

"Tail" events are projected to cause more damage; losses from an event with 1 percent annual probability in Florida could grow from approximately $35 billion to approximately $50 billion by 2050.

Based on USACE high scenario

Potential damage to residential real estate in Florida from storm surge, by event probability[1]
$ billion, 2018 dollars[2]



1. Sea level rise based on USACE high curve. High curve results in 1.5 meter eustatic sea level rise by 2100 (within range of RCP 8.5 scenario; see, for example, Jevrejeva et al., 2014). Based on current exposure. Buildup of additional residential real estate in areas prone to storm surge could further increase expected damage.
2. Based on damages if event occurs; damages not adjusted for likelihood of event. Damages based on constant exposure, ie, increase in potential damages to 2030 or 2050 is due to change in expected hazards.

Note: See the Technical Appendix of the full report for why this climate scenario was chosen. We define "today" based on sea level rise in 2018.

Source: Analysis conducted by KatRisk

Florida compared with prices of unexposed homes. Going forward, more homes will be exposed to tidal flooding, and those exposed to disruptive flooding are also expected to increase. About 25,000 homes in Florida already experience flooding at frequencies of more than 50 times per year (almost once a week on average). With rising sea levels, 40,000 coastal properties representing about $15 billion of value could run this risk by 2030, and 100,000 properties worth $50 billion in 2050. These properties may see resale prices drop significantly due to severe and frequent flooding, even falling to zero if there are no prospective buyers. Putting this together, we estimate that the projected increase in tidal flooding frequency and severity could result in a $10 billion to $30 billion devaluation in exposed properties by 2030, and $30 billion to $80 billion by 2050, all else being equal (Exhibit 2). By 2050, the average impact of affected homes is expected to increase to 15 to 35 percent, up from 5 percent today.

— *Real estate buyers may price in expectations of future climate hazards:* Home prices may be influenced not just by today's level of hazard, but also by expectations of how hazards could evolve. The resale potential, maintenance costs, and comfort and convenience of a home

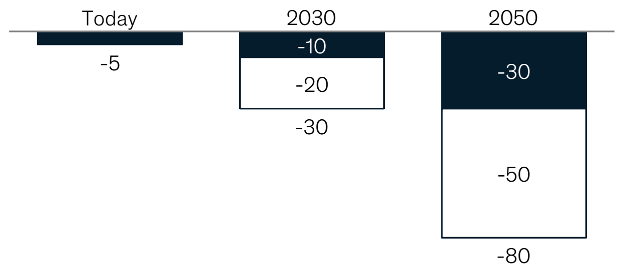
Exhibit 2

Tidal flooding has caused an estimated $5 billion devaluation in real estate, which could grow to $30 billion to $80 billion by 2050.

Projected devaluation of Florida real estate market due to tidal flooding[1]

$ billion, 2018 dollars

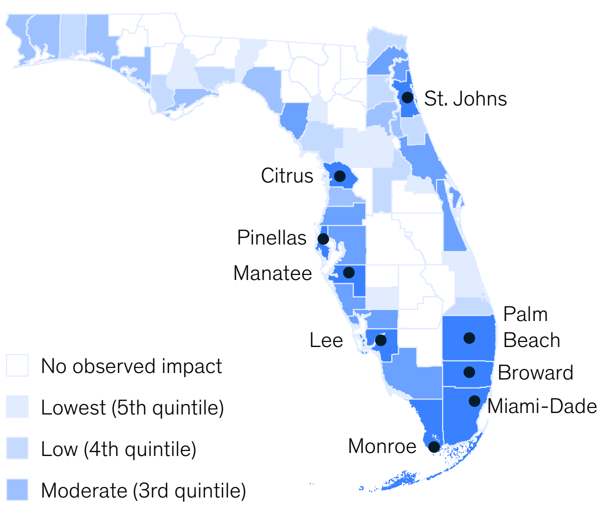
- ■ Projected devaluation of homes based on trend observed today
- □ Potential additional devaluation if homes flooding >50x per year become entirely undesirable for future buyers



	Today	2030	2050
Average devaluation compared to unexposed homes %	~5	5–15	15–35
Number of impacted homes Thousand		470	550

Level of devaluation by county by 2050

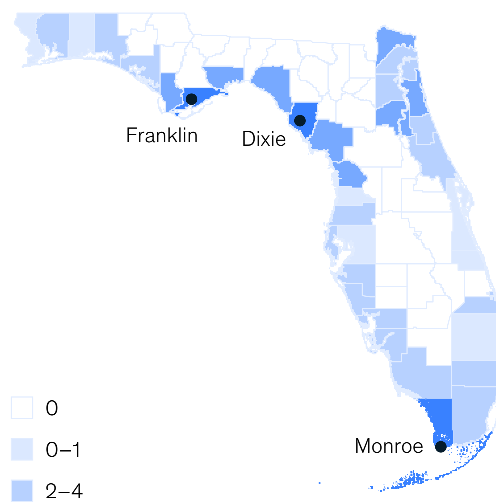
Quintile (by total value, $)



- No observed impact
- Lowest (5th quintile)
- Low (4th quintile)
- Moderate (3rd quintile)
- High (2nd quintile)
- Highest (1st quintile)
- ● Counties with highest devaluation impact

Homes exposed to tidal flooding >50x per year by 2050

Share of total number of homes in each county, %



- 0
- 0–1
- 2–4
- 5–10
- >10
- ● Counties with highest number of homes exposed to tidal flooding

1. Based on First Street Foundation's property-level analysis of relationship between real estate trends and local experience of tidal flooding events. Analysis identifies differential appreciation rates for properties that experience tidal flooding in comparison to those that do not, with the former seeing a slower rate of appreciation over study period (2005–17). Analysis relies on assumption that future relationship between flooding impact and home value devaluation equals historical relationship. Low end of rage based on historical devaluation; high end assumes homes flooded >50x per year see 100% devaluation.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060. $ figures rounded to nearest 5, % figures rounded to nearest 5%.

Source: First Street Foundation 2019; McKinsey Global Institute analysis in the future are all factors buyers consider. Once buyers become aware of and price in expectations of future hazards, home prices may adjust in advance of significant climate-induced property destruction or flooding-related inconvenience. For example, homes adjacent to properties that are frequently affected by tidal flooding or storm surges could see prices drop as prospective buyers grow concerned. Other effects could also exacerbate the price impacts described here. If public infrastructure assets are affected, for example from frequent flooding, that could reduce the desirability of entire communities.

— *Insurance premiums and availability for homes in high-risk areas may change:* Real estate prices reflect expectations of the future and often extend beyond a single decade; mortgages are typically set on 15- or 30-year time horizons. Conversely, insurance premiums are repriced annually. If premiums grow accordingly with the projected average annual loss (about 50 percent by 2050), the average annual premium could increase by about 50 percent from $800 to $1,200, with high-risk properties seeing a much higher jump. Such a hike could further affect future property values. If home buyers factor increased premium contributions into a home's current value, this could cause a decline of about $3,000 in the average value of a home, or a statewide devaluation of about $5 billion. Impacts could be much higher for homes in high-risk areas.

The impact on real estate prices would directly impact local government tax revenues, potentially affecting financial resilience. For example, if homes that flood more than 50 times per year are abandoned, that could correspond to 4 percent of forgone property tax revenues by 2050. Our estimates suggest that the price effects discussed above could impact property tax revenue in some of the most affected counties by about 15 to 30 percent (though impacts across the state could be less, at about 2 to 5 percent).

How long commercial financing and insurance provision will remain viable in parts of Florida prone to climate hazards is unresolved—but it could likely occur in advance of the physical risks themselves manifesting. One shift that could trigger changes in financing and insurance provision is if the likelihood of mortgage defaults increases with intensifying climate hazards: damages from extreme events may cause financial distress for home owners, and even home owners and buyers who are not financially distressed may depress property values through a mix of shifts in buying and selling behaviors as well as potentially strategically defaulting if their homes fall steeply in value and are not expected to recover. As lenders and insurers start to recognize these risks, they could shift their willingness to hold these risks on their balance sheets—or might reprice that risk accordingly.

While there is considerable uncertainty about the knock-on effects of intensifying climate hazards, one consequence of climate change in Florida is becoming increasingly clear: home owners and taxpayers may bear more risk than they realize. While home owners can insure against the direct damages of flooding, they cannot insure against property devaluation. Prospective home owners could also be affected, as banks may stop providing 30-year mortgages in high-risk areas. Finally, with the state and federal governments often subsidizing premiums and needing to finance adaptation measures, taxpayers could be affected.

How can Florida manage the risks from climate change?

As communities recognize the threat of climate change, this is spurring adaptation efforts across Florida. For example, in 2019, the county and the cities of Miami and Miami Beach released a strategy for the area, "Resilient305," that includes measures to bolster beaches, expand nature-based infrastructure, and identify opportunities to reduce storm surge risk. While adaptation measures should help reduce climate-related damages in the future, they still represent costs today and require funding. For example, beach nourishment has been a regular investment along the coast for decades. Since 1980, some $1.7 billion has been spent on beach nourishment in Florida, nearly three quarters of that total from federal sources. New funding measures are being implemented. For example, in Miami, a new property tax will finance the $400 million Forever Bond to help repay debt incurred on the municipal bond market.

These efforts will need to accelerate. To help Florida manage physical climate risk, policy makers, home owners, and investors should consider strategically what to protect, how to protect (for example, fortifying infrastructure and increasing financing), when to protect, and how to minimize climate risk exposure. We identify a number of steps for consideration:

— *Increase awareness and transparency of climate change risk.* For example: include flood maps as part of online real estate home searches, issue mortgages with 30-year insurance premium forecasts based on increasing flood risk, pledge a proportion of local real estate investment to "climate opportunity zones," and include climate change risk in interest rate models to both increase bank resilience and be more transparent to home owners.

— *Build resilience at the local level.* For example: strengthen community-based networks and organizations that can provide not only information but also economic and technical assistance to help with adaptation, and an emergency natural-disaster response network.

— *Accelerate adaptation investment, particularly to assist vulnerable communities.* For example, policy makers might consider: how drainage could be improved, where seawalls might be built, whether development should be restricted in vulnerable areas, whether sewers could be upgraded to prevent wastewater from contaminating streets or property, hardening and improving resiliency of existing infrastructure, installing new green infrastructure, whether to introduce incentives to encourage coastal residents to move inland, and how to preserve equity and keep communities intact while discouraging development in areas most susceptible to the effects of climate change.

— *Decide when and what to protect versus retreat.* For example, rising adaptation costs will create real choices about which infrastructure to prioritize for near-term defense. Policy makers, engineers, investors, and community-based organizations could help develop criteria.

— *Mobilize funds and assistance to vulnerable communities.* For example, possible solutions include targeted tourist taxes (as seen in New York City), usage fees for protection solutions, public-private partnerships and federal support, and encouraging private adaptation investment through tax exemptions.

While the state and communities will face hard choices in the face of rising sea levels and worsening hazards, planning today can help manage the consequences and minimize the costs of climate change in the future.

For additional details on these actions, download the case study, *Will mortgages and markets stay afloat in Florida?*

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Claudia Kampel** is a consultant in the Stuttgart office. **Marlies Vasmel** is a consultant in the Amsterdam office.

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Can coastal cities turn the tide on rising flood risk?

Coastal cities are on the front line of flooding. Two very different cities, Ho Chi Minh City and Bristol, help illustrate variations in risks and approaches to adaptation.

by Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Peter Cooper

Climate change is increasing the destructive power of flooding from extreme rain and rising seas and rivers. Many cities around the world are exposed. Strong winds during storms and hurricanes can drive coastal flooding through storm surge. As hurricanes and storms become more severe, surge height increases. Changing hurricane paths may shift risk to new areas. Sea-level rise amplifies storm surge and brings in additional chronic threats of tidal flooding. Pluvial and riverine flooding becomes more severe with increases in heavy precipitation. Floods of different types can combine to create more severe events known as compound flooding. With warming of 1.5 degrees Celsius, 11 percent of the global land area is projected to experience a significant increase in flooding, while warming of 2.0 degrees almost doubles the area at risk.

When cities flood, in addition to often devastating human costs, real estate is destroyed, infrastructure systems fail, and entire populations can be left without critical services such as power, transportation, and communications. In this case study we simulate floods at the most granular level (up to two-by-two-meter resolution) and explore how flood risk may evolve for Ho Chi Minh City (HCMC) and Bristol. Our aim is to illustrate the changing extent of flooding, the landscape of human exposure, and the magnitude of societal and economic impacts.

We chose these cities for the contrasting perspectives they offer: Ho Chi Minh City in an emerging economy, Bristol in a mature economy; Ho Chi Minh City in a regular flood area, Bristol in an area developing a significant flood risk for the first time in a generation.

We find the metropolis of Ho Chi Minh City can survive its flood risk today, but its plans for rapid infrastructure expansion and continued economic growth could be incompatible with an increase in risk. The city has a wide range of adaptation options at its disposal but no silver bullet.

In the much smaller city of Bristol, we find a risk of flood damages growing from the millions to the billions, driven by high levels of exposure. The city has fewer adaptation options at its disposal, and its biggest challenge may be building political and financial support for change.

When cities flood, in addition to often devastating human costs, real estate is destroyed, infrastructure systems fail, and entire populations can be left without critical services such as power, transportation, and communications.

How significant are the flood risks facing Ho Chi Minh City and what can the city do?

Flooding is a common part of life in Ho Chi Minh City. This includes flooding from monsoonal rains, which account for about 90 percent of annual rainfall, tidal floods and storm surge from typhoons and other weather events. Of the city's 322 communes and wards, about half have a history of regular flooding with 40 to 45 percent of land in the city less than one meter above sea level.

In our analysis, we quantify the possible impact on the city as floods hit real estate and infrastructure assets.[1] We simulate possible 1 percent probability flooding scenarios for the city for three periods: today, 2050, and a longer-term scenario of 180 centimeters of sea-level rise, which some infrastructure assets built by 2050 may experience as a worse-case in their lifetime (Exhibit 1).

— *Today:* We estimate that 23 percent of the city could flood, and a range of existing assets would be taken offline; infrastructure damage may total $200 million to $300 million. Knock-on effects would be significant, and we estimate could total a further $100 million to $400 million. Real estate damage may total $1.5 billion.

— *2050:* A flood with the same probability in 30 years' time would likely do three times the physical damage and deliver 20 times the knock-on effects. We estimate that 36 percent of the city becomes flooded. In addition, many of the 200 new infrastructure assets

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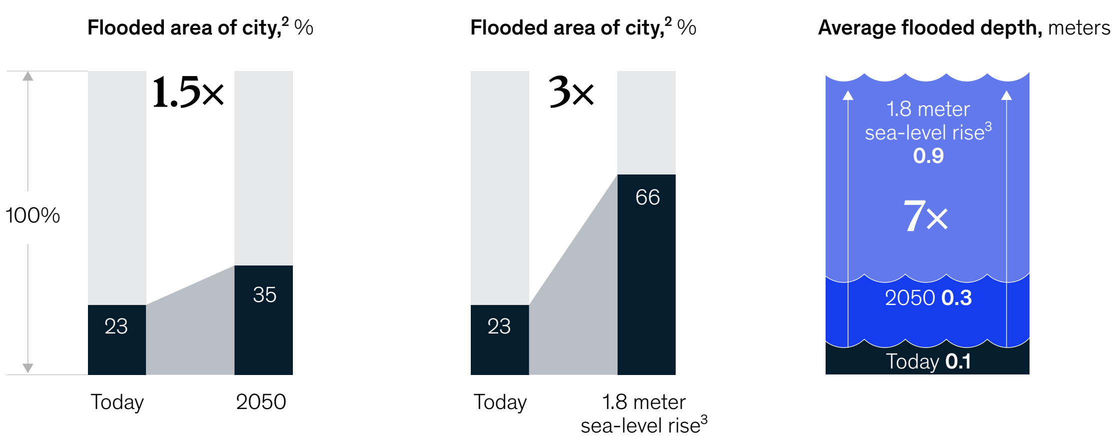
[1] Flood modeling and expert guidance were provided by an academic consortium of Institute for Environmental Studies, Vrije Universiteit Amsterdam, and Center of Water Management and Climate Change, Viet Nam National University. Infrastructure assets covered include both those currently available and those under construction, planned, or speculated. Knock-on effects are adjusted for estimates of economic and population growth.

Exhibit 1

Ho Chi Minh City could experience a sevenfold increase in flood depth within modeled area.

100-year[1] flood effects in Ho Chi Minh City



[1]One-hundred-year flood represents about 1% annual probability.
[2]Within modeled area.
[3]Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change.
Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; Economic Commission for Latin America and the Caribbean; EU Commission; HAZUS; Federal Emergency Management Agency; historical insurance data; Oxford Economics; People's Committee of Ho Chi Minh City; review of critical points of failure in infrastructure assets by chartered engineering consultants; Scussolini et al., 2017; United Nations; Viet Nam National University, Ho Chi Minh City; World Bank; McKinsey Global Institute analysis

are planned to be built in flooded areas. As a result, the damage bill would grow, totaling $500 million to $1 billion. Increased economic reliance on assets would amplify knock-on effects, leading to an estimated $1.5 billion to $8.5 billion in losses. An additional $8.5 billion in real estate damages could occur.

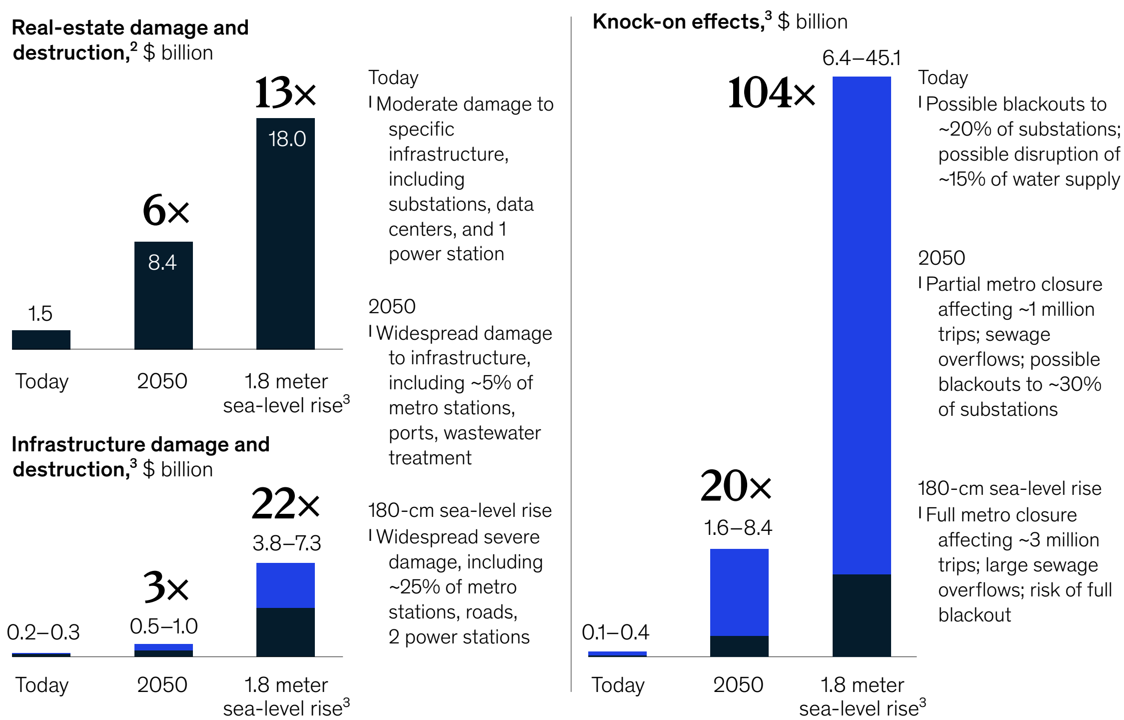
— *A 180 centimeters sea-level rise scenario:* A 1 percent probability flood in this scenario may bring three times the extent of flood area. About 66 percent of the city would be underwater, driven by a large western area that suddenly pass an elevation threshold. Under this scenario, damage is critical and widespread, totaling an estimated $3.8 billion to $7.3 billion. Much of the city's functionality may be shut down, with knock-on effects costing $6.4 billion to $45.1 billion. Real estate damage could total $18 billion.

While "tail" events may suddenly break systems and cause extraordinary impact, extreme floods will be infrequent. Intensifying chronic events are more likely to have a greater effect on the economy, with a mounting annual burden over time. We estimate that intensifying regular floods may rise from about 2 percent today to about 3 percent of Ho Chi Minh City's GDP annually by 2050 (Exhibit 2).

Exhibit 2

Ho Chi Minh City could experience five to ten times the economic impact from an extreme flood in 2050 versus today.

100-year[1] flood effects in Bristol



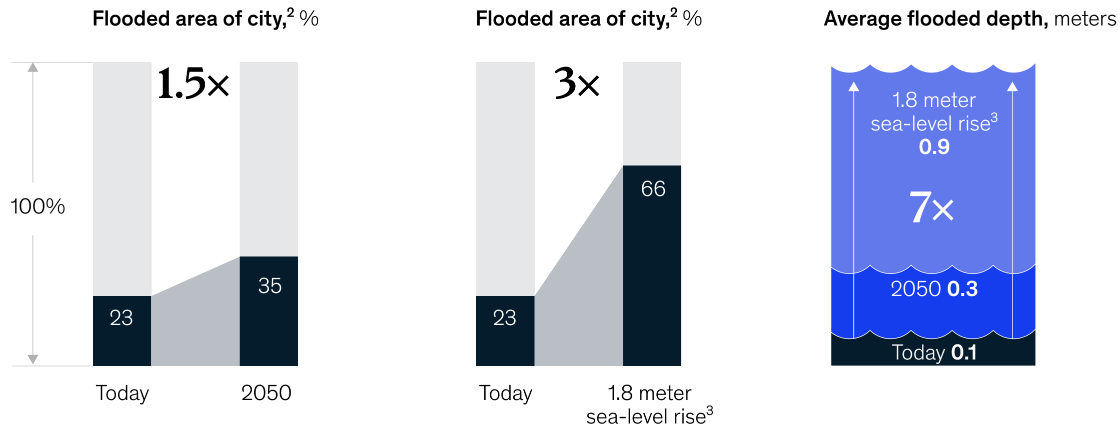
[1]One-hundred-year flood represents about of 1% annual probability. Repair and replacement costs. Qualitative descriptions of damage and knock-on effects are additional to previous scenarios. [2]Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change. [3]Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure, including loss of freight movement, lost data revenues, and lost working hours due to a lack of access to electricity, clean water, and metro services. Adjusted for economic and population growth to 2050 for both 2050 and 180-centimeter sea-level rise scenarios.

Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; Economic Commission for Latin America and the Caribbean; EU Commission; HAZUS; Federal Emergency Management Agency; historical insurance data; Oxford Economics; People's Committee of Ho Chi Minh City; review of critical points of failure in infrastructure assets by chartered engineering consultants; Scussolini et al., 2017; United Nations; Viet Nam National University, Ho Chi Minh City; World Bank; McKinsey Global Institute analysis

Exhibit 3

By 2065, a 200-year flood in Bristol, United Kingdom, could be twice as extensive compared to today.

100-year[1] flood effects in Ho Chi Minh City



[1]One-hundred-year flood represents about 1% annual probability.
[2]Within modeled area.
[3]Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change.
Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; Economic Commission for Latin America and the Caribbean; EU Commission; HAZUS; Federal Emergency Management Agency; historical insurance data; Oxford Economics; People's Committee of Ho Chi Minh City; review of critical points of failure in infrastructure assets by chartered engineering consultants; Scussolini et al., 2017; United Nations; Viet Nam National University, Ho Chi Minh City; World Bank; McKinsey Global Institute analysis

Ho Chi Minh City has time to adapt, and the city has many options to avert impacts because it is relatively early in its development journey. As less than half of the city's major infrastructure needed for 2050 exists today, many of the potential adaptation options could be highly effective. We outline three key steps:

1. Better planning to reduce exposure and risk

2. Investing in adaptation through hardening and resilience

3. Financial mobilization to mitigate impacts on lower-income populations

Could Bristol's flood risk grow from a problem to a crisis by 2065?

Bristol is facing a new flood risk. The river Avon, which runs through the city, has the second largest tidal range in the world, yet it has not caused a major flood since 1968, when sea levels were lower, and the city was smaller and less developed. During very high tides, the Avon becomes "tide locked" and limits/restricts land drainage in the lower reaches of river catchment area. As a result, the city is vulnerable to combined tidal and pluvial floods, which are sensitive to both sea-level rise and precipitation increase. Both are expected to climb with climate change. While Bristol is generally hilly and most of the urban area is far from the river, the most economically valuable areas of the city center and port regions are on comparatively low-lying land.

With the city's support, we have modeled the socioeconomic impacts of 200-year (0.5 percent probability) combined tidal and fluvial flood risk, for today and for 2065 (Exhibit 3). This considers the flood defenses in existence today; some of these were built after the 1968 flood, and many assumed a static climate would exist for their lifetime.

We find:

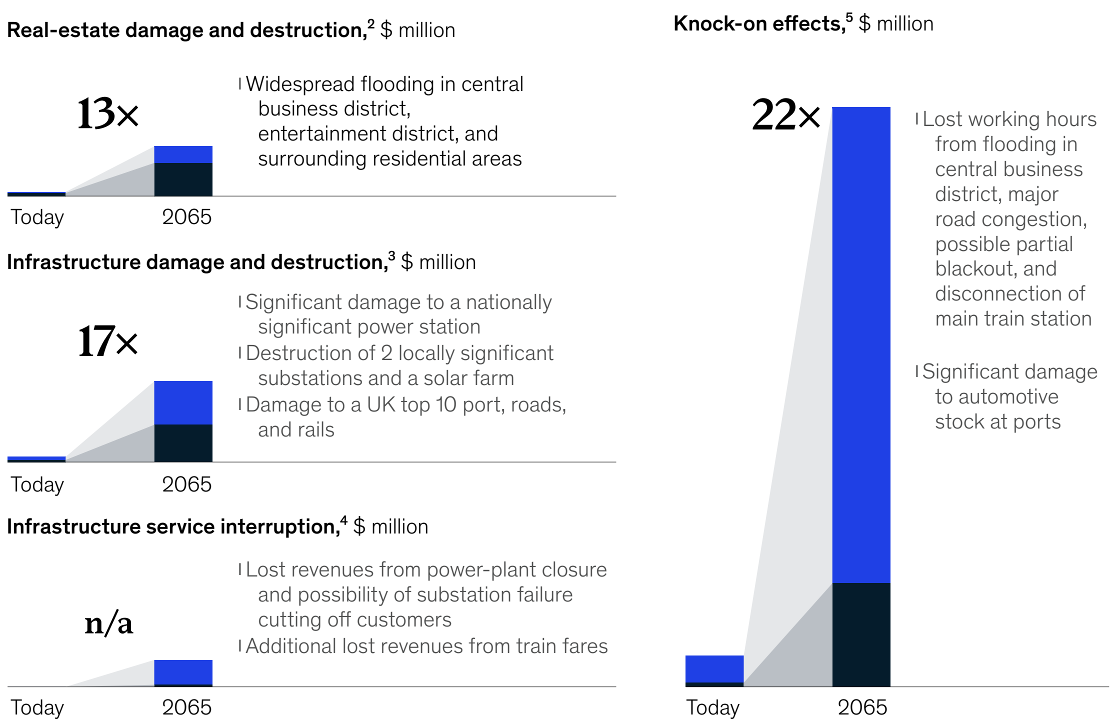
— *Today:* The consequences of a major flood today in Bristol would be small but are still material. We find that the flood area would be relatively minor, with small overflows on the edges of the port area and isolated floods in the center of the city. Our model estimates that damage to the city's infrastructure could amount to $10 million to $25 million, real estate damage to $15 million to $20 million, and knock-on effects of $20 million to $150 million.

— *2065:* In contrast, by 2065, an extreme flood event could be devastating. Water would exceed the city's flood defenses at multiple locations, hitting some of its most expensive real estate, damaging arterial transportation infrastructure, and destroying sensitive critical energy assets. Our model estimates that damages to the city's infrastructure could amount to between $180 million and $390 million. It may also cause $160 million to $240 million of property damage. Overall, considering economic growth, knock-on effects could total $500 million to $2.8 billion, and disruptions could last weeks or months (Exhibit 4).

Exhibit 4

By 2065, a 200-year flood in Bristol, United Kingdom, could produce 18 times more infrastructure damage and 30 times more knock-on effects.

200-year[1] flood effects in Bristol



Note: See the technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multimodel ensemble. Heat data bias corrected.
[1]Two-hundred-year flood represents about a 0.5% per year probability. [2]Repair and replacement costs. [3]Costs from lost infrastructure revenue. [4]Minimal energy losses in 2018 create a distorted ratio if calculated. [5]Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure; covers issues of lost customer surplus, GDP, and capital stock. Adjusted for forecast economic growth.
Source: Bristol City Council; BTE; CATDAT disaster database; CAPRA; Economic Commission for Latin America and the Caribbean; HAZUS, Federal Emergency Management Agency; historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; Western Power Distribution; McKinsey Global Institute analysis

Bristol has undertaken a detailed review of how the scale of flooding in the city will change in the future under different climate scenarios.

Unlike many small and medium-size cities, Bristol has invested in understanding this risk. It has undertaken a detailed review of how the scale of flooding in the city will change in the future under different climate scenarios. This improved understanding of the risks is an example that other cities could learn from.

However, adaptation is unlikely to be straightforward. It is difficult to imagine Bristol's infrastructure assets being in a position more exposed to the city's flood risk. Yet the center of the city, formed in the 1400s, cannot be shifted overnight, nor would its leafy reputation be the same today if the city had not oriented the growth of the past 20 years to harness its existing Edwardian and Victorian architecture. Unlike in Ho Chi Minh City, most of the infrastructure the city plans to have in place in 2065 has already been built.

In the immediate future, Bristol's hands are likely largely tied, and hard adaptation may be the most viable short-term solution. In the medium term, however, Bristol may be able to act to improve resilience through measures such as investing in sustainable urban drainage that may reduce the depth and duration of an extreme flood event.

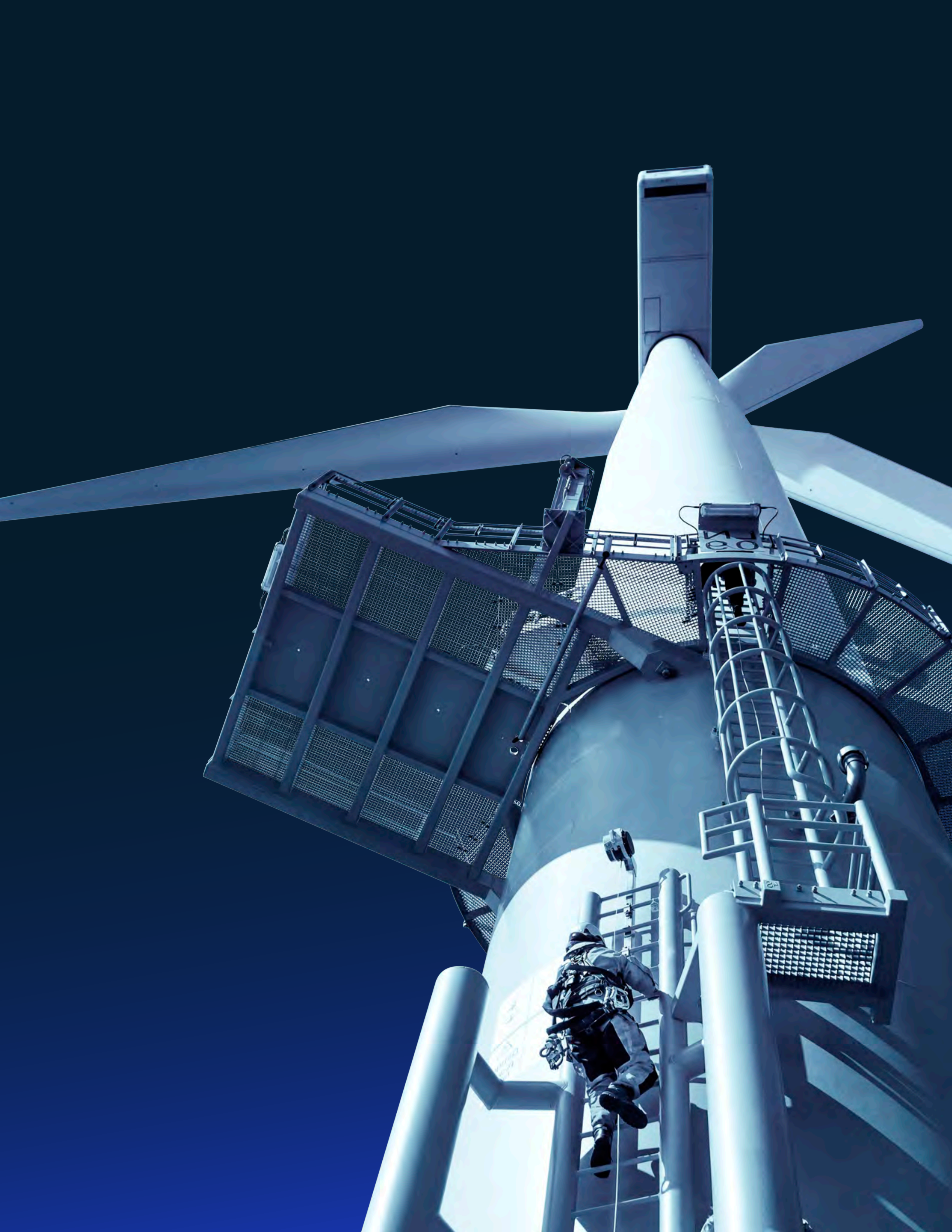
Bristol is already taking a proactive approach to adaptation. A $130 million floodwall for the defense of Avonmouth was planned to begin in late 2019. The city is still scoping out a range of options to protect the city. As an outside-in estimate, based on scaling costs to build the Thames Barrier in 1982, plus additional localized measures that might be needed, protecting the city to 2065 may cost $250 million to $500 million (roughly 0.5 to 1.5 percent of Bristol's GVA today compared to the possible flood impact we calculate of between 2 to 9 percent of the city's GVA in 2065). However, the actual costs will largely depend on the final approach.

Bristol has gotten ahead of the game by improving its own understanding of risk. Many other small cities are at risk of entering unawares into a new climatic band for which they and their urban areas are ill prepared. While global flood risk is concentrated in major coastal metropolises, a long tail of other cities may be equally exposed, less prepared, and less likely to bounce back.

For additional details, download the case study, *Can coastal cities turn the tide on rising flood risk?*

Jonathan Woetzel is a director of the McKinsey Global Institute, where **Mekala Krishnan** is a senior fellow. **Dickon Pinner** is a senior partner in McKinsey's San Francisco office. **Hamid Samandari** is a senior partner in the New York office. **Hauke Engel** is a partner in the Frankfurt office. **Brodie Boland** is an associate partner in the Washington office. **Peter Cooper** is a consultant in the London office.

The struggle to limit climate change



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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?

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)

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

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.

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

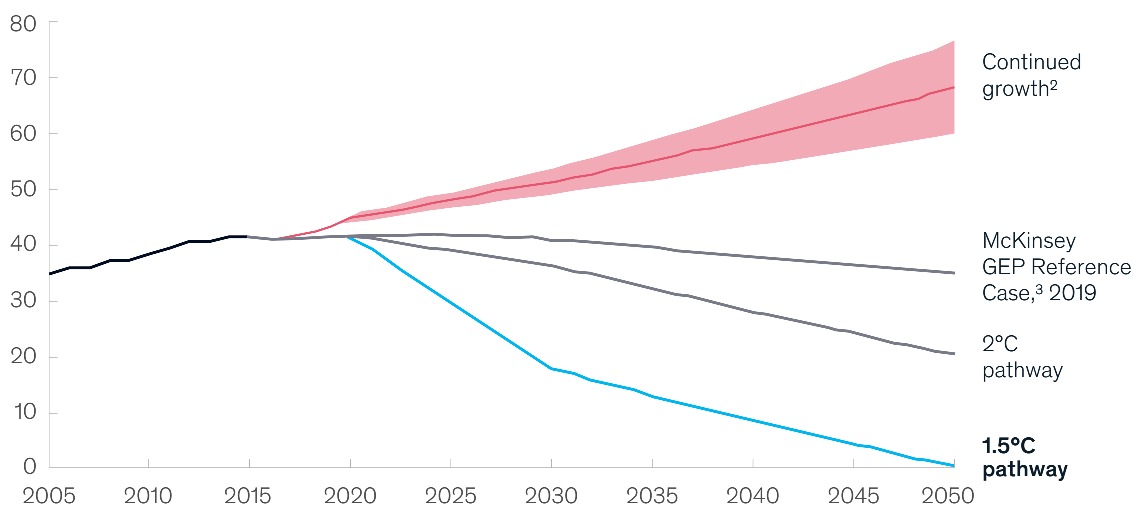
[2] See Rajat Dhawan, Russell Hensley, Asutosh Padhi, and Andreas Tschiesner, "Mobility's second great inflection point," *McKinsey Quarterly*, February 2019, McKinsey.com.

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 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 99).

Urgency amid uncertainty

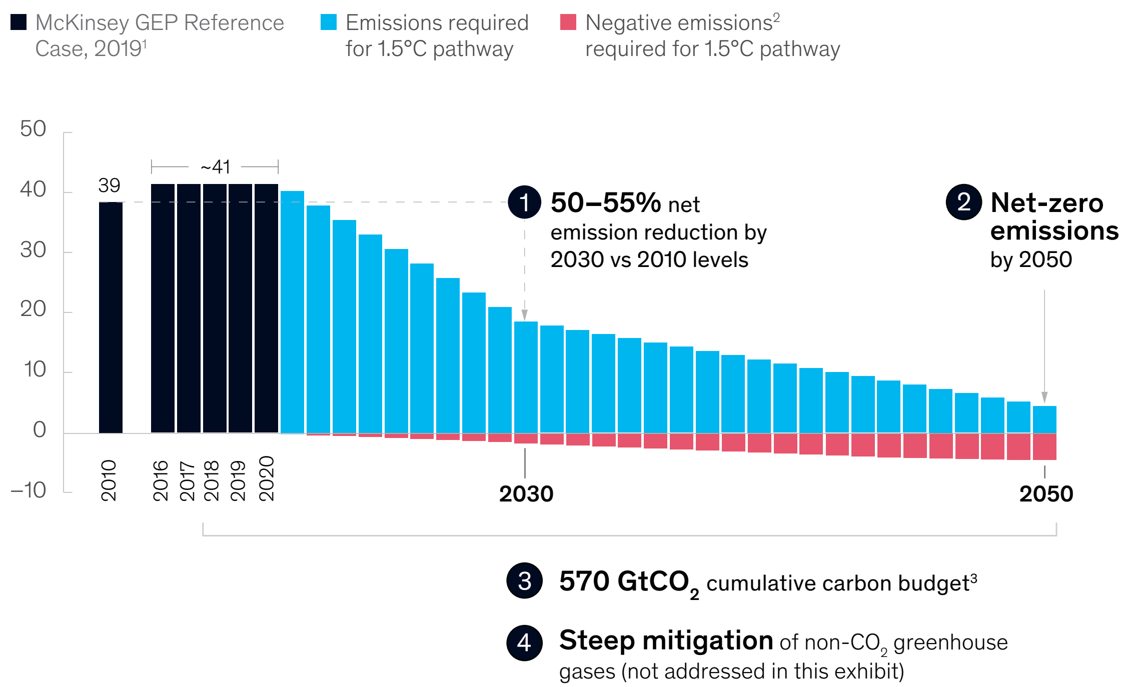
These scenarios represent rigorous, data-driven snapshots of the decarbonization challenge, not predictions; reality may play out quite differently. Still, the implied trade-offs underscore just how stark a departure a 1.5-degree pathway is from the global economy's current trajectory. Keeping to 1.5 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.

[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.

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

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).

The authors wish to thank Sophie Bertreau, Suyeon Choi, Luc Oster-Pecqueur, Diana Ostos, Andres Palacios, and Thomas Vahlenkamp for their contributions to this article.

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.

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,

[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 CO2 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.

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.

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.

Halting deforestation

Deforestation—quite often linked to agricultural practices, but not exclusively so—is one of the largest carbon-dioxide emitters, accounting

[7] Does not include land use, land-use change, or forestry. Non-CO2 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.

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 CO2 as of January 1, 2018, and a complementary reduction of non-CO2 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 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.

[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.

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.

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 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.

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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.

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

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

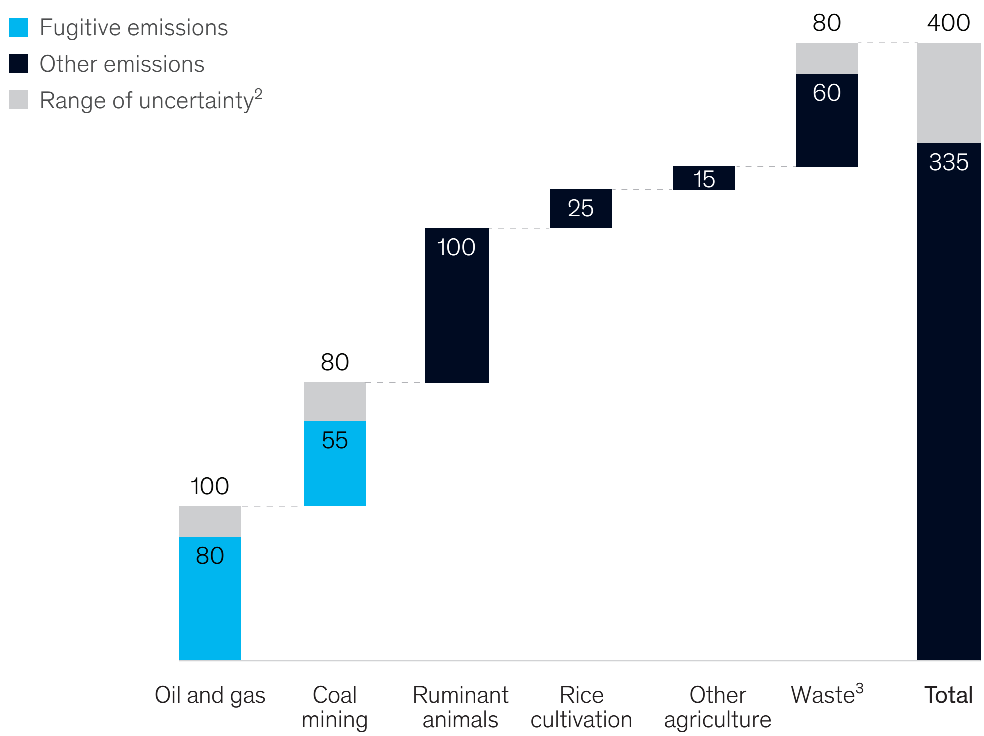
[12] In the United States, for example, the Coalbed Methane Outreach Program—part of the Environmental Protection Agency—works with the coal-mining industry to support project development and to help overcome technical and other barriers to implementation.

[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.

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

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]

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

[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*.

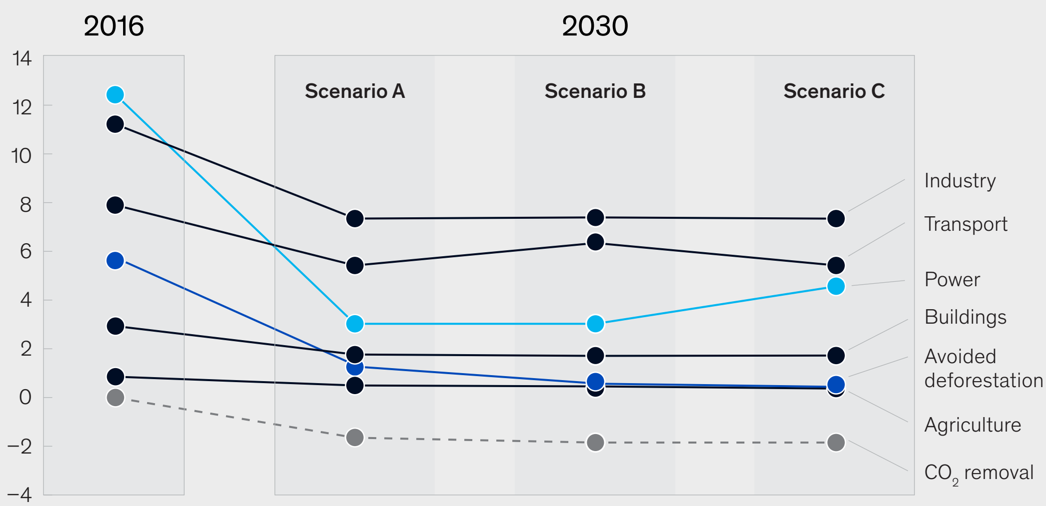
(continued on page 103)

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

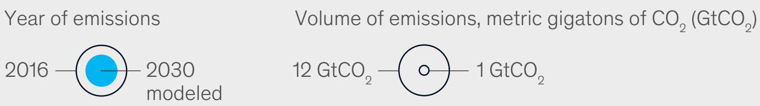
Scenario B
Oil fuels transport for longer; reforestation and curbing deforestation abate the additional emissions

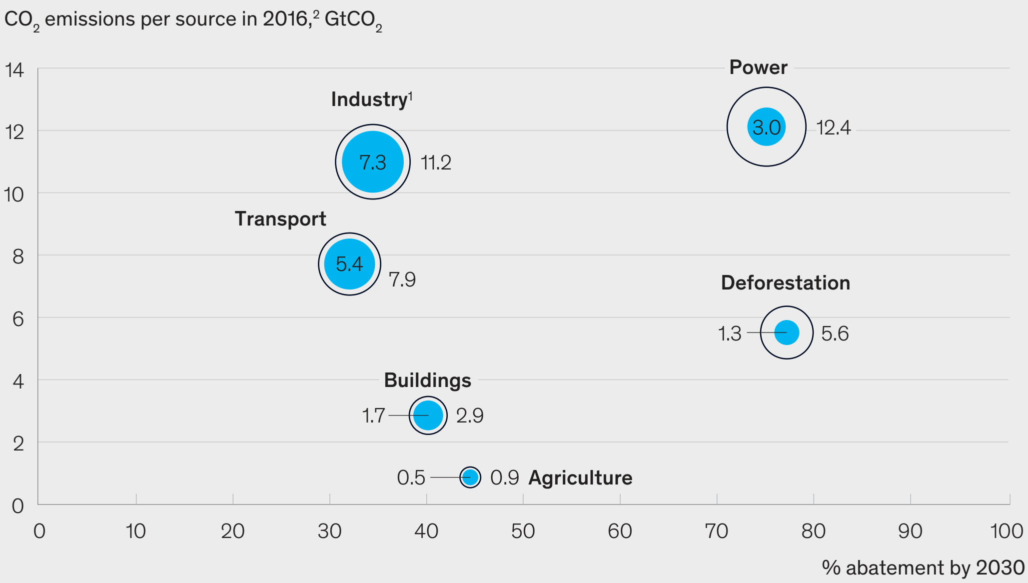
Scenario C
Coal and gas generate power for longer; reforestation and curbing deforestation abate the surplus CO_2

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

Scenario A: Significant and steady decarbonization

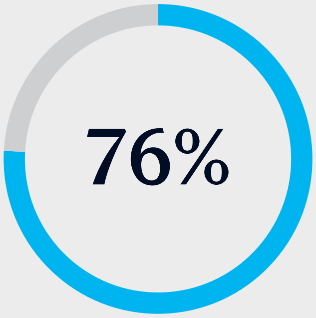
A paced transition, enabled by regulation and targeted investment, would require immediate action but would support a significant and steady decrease in emissions. By 2030, all sectors/sources would have abated at least 30% of their 2016 CO_2 emissions.



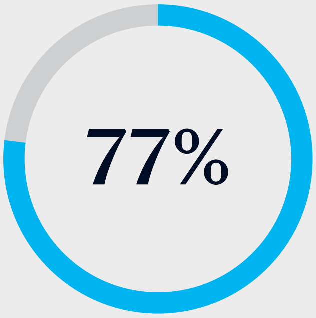


The heavy hitters

Share of category's total 2016 emissions



of the power sector's CO_2 emissions abated by 2030



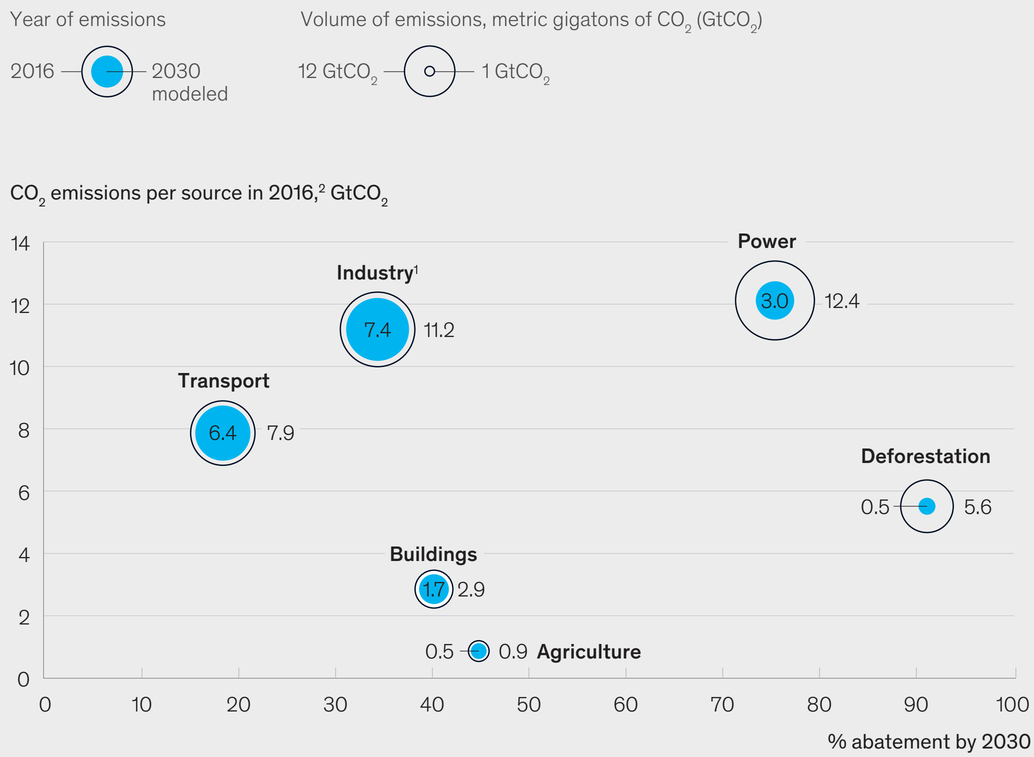
of deforestation's CO_2 emissions abated by 2030

[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

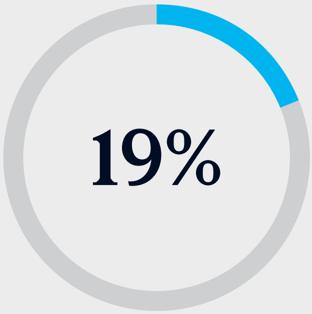
Scenario B: Oil decarbonizes more slowly

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.

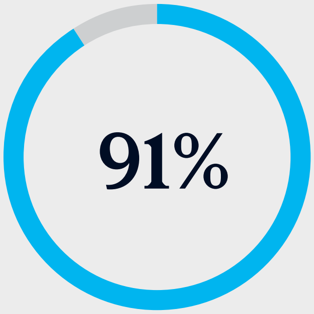


Trade-offs

Share of category's total 2016 emissions



of the transport sector's CO_2 emissions abated by 2030



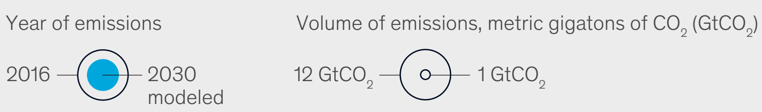
of deforestation's CO_2 emissions abated by 2030

[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.

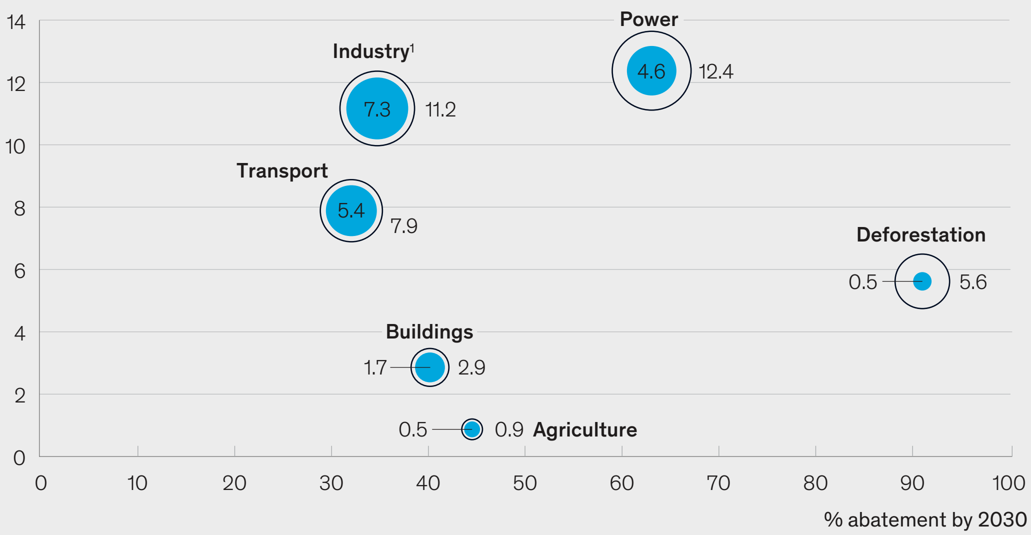
Source: McKinsey 1.5°C scenario analysis

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.

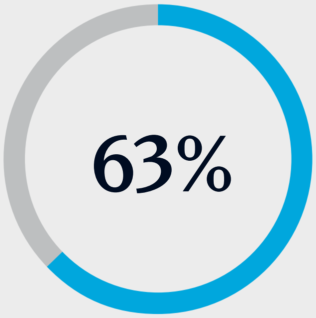


CO_2 emissions per source in 2016,[2] $GtCO_2$

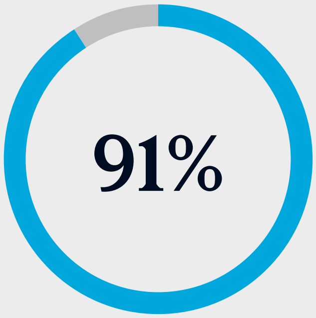


Trade-offs

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 C.

Source: McKinsey 1.5°C scenario analysis

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*.

Even in the scenario where coal and gas generate power for longer, the reduction would need to be about two-thirds by 2030.

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.

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

Over the next decade, a massive, global mobilization to reforest the earth would be required to achieve a 1.5-degree pathway.

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.

Addressing climate change in a post-pandemic world

The coronavirus crisis holds profound lessons that can help us address climate change—if we make greater economic and environmental resiliency core to our planning for the recovery ahead.

by Dickon Pinner, Matt Rogers, and Hamid Samandari

A ferocious pandemic is sweeping the globe, threatening lives and livelihoods at an alarming rate. As infection and death rates continue to rise, resident movement is restricted, economic activity is curtailed, governments resort to extraordinary measures, and individuals and corporations scramble to adjust. In the blink of an eye, the coronavirus has upended the world's operating assumptions. Now, all attention is focused on countering this new and extreme threat, and on blunting the force of the major recession that is likely to follow.

Amid this dislocation, it is easy to forget that just a few short months ago, the debate about climate change, the socioeconomic impacts it gives rise to, and the collective response it calls for were gaining momentum. Sustainability, indeed, was rising on the agenda of many public- and private-sector leaders—before the unsustainable, suddenly, became impossible to avoid.

Given the scope and magnitude of this sudden crisis, and the long shadow it will cast, can the world afford to pay attention to climate change and the broader sustainability agenda at this time? Our firm belief is that we simply cannot afford to do otherwise. Not only does climate action remain critical over the next decade, but investments in climate-resilient infrastructure and the transition to a lower-carbon future can drive significant near-term job creation while increasing economic and environmental resiliency. And with near-zero interest rates for the foreseeable future, there is no better time than the present for such investments.

To meet this need and to leverage this opportunity, we believe that leaders would benefit from considering three questions:

— What lessons can be learned from the current pandemic for climate change?

— What implications—positive or negative—could our pandemic responses hold for climate action?

— What steps could companies, governments, and individuals take to align our immediate pandemic response with the imperatives of sustainability?

What follows is our attempt at providing some initial answers to these questions, in the hope that they will inspire ideas and actions that help connect our immediate crisis response with priorities for recovery.

Potential lessons from the current pandemic

Understanding the similarities, the differences, and the broader relationships between pandemics and climate risk is a critical first step if we are to derive practical implications that inform our actions.

Fundamental similarities

Pandemics and climate risk are similar in that they both represent physical shocks, which then translate into an array of socioeconomics impacts. By contrast, financial shocks—whether bank runs, bubble bursts, market crashes, sovereign defaults, or currency devaluations—are largely driven by human sentiment, most often a fear of lost value or liquidity. Financial shocks originate from within the financial system and are frequently remedied by restoring confidence. Physical shocks, however, can only be remedied by understanding and addressing the underlying physical causes. Our recent collective experience, whether in the public or the private sector, has been more often shaped by financial shocks, not physical ones. The current pandemic provides us perhaps with a foretaste of what a full-fledged climate crisis could entail in terms of simultaneous exogenous shocks to supply and demand, disruption of supply chains, and global transmission and amplification mechanisms.

Pandemics and climate risk also share many of the same attributes. Both are *systemic*, in that their direct manifestations and their knock-on effects propagate fast across an interconnected world. Thus, the oil-demand reduction in the wake of the initial coronavirus outbreak became a contributing factor to a price war, which further exacerbated the stock market decline as the pandemic grew. They are both *nonstationary*, in that past probabilities and distributions of occurrences are rapidly shifting and proving to be inadequate or insufficient for future projections. Both are *nonlinear*, in that their socioeconomic impact grows disproportionally and even catastrophically once certain thresholds are breached (such as hospital capacity to treat pandemic patients). They are both *risk multipliers*, in that they highlight and exacerbate hitherto untested vulnerabilities inherent in the financial and healthcare systems and the real economy. Both are *regressive*, in that they affect disproportionally the most vulnerable populations and subpopulations of the world. Finally, neither can be considered as a "black swan," insofar as experts have consistently warned against both over the years (even though one may argue that the debate about climate risk has been more widespread). And the coronavirus outbreak seems to indicate that the world at large is equally ill prepared to prevent or confront either.

Furthermore, addressing pandemics and climate risk requires the same fundamental shift, from optimizing largely for the *shorter-term performance* of systems to ensuring equally their *longer-term resiliency*. Healthcare systems, physical assets, infrastructure services, supply chains, and cities have all been largely designed to function within a very narrow band of conditions. In many cases, they are already struggling to function within this band, let alone beyond it. The coronavirus pandemic and the responses that are being implemented (to the tune of several trillion dollars of government stimulus as of this writing) illustrate how expensive the failure to build resiliency can ultimately prove. In climate change as in pandemics, the costs of a global crisis are bound to vastly exceed those of its prevention.

Finally, both reflect "tragedy of the commons" problems, in that individual actions can run counter to the collective good and deplete a precious, common resource. Neither pandemics nor climate hazards can be confronted without true *global coordination and cooperation*. Indeed, despite current indications to the contrary, they may well prove, through their accumulated pressures, that boundaries between one nation and another are much less important than boundaries between problems and solutions.

Key differences

While the similarities are significant, there are also some notable differences between pandemics and climate hazards.

A global public-health crisis presents *imminent, discrete, and directly discernable dangers*, which we have been conditioned to respond to for our survival. The risks from climate change, by contrast, are *gradual, cumulative, and often distributed dangers* that manifest themselves in degrees and over time. They also require a present action for a future reward that has in the past appeared too uncertain and too small given the implicit "discount rate." This is what former Bank of England Governor Mark Carney has called the "tragedy of the horizon."[1]

Another way of saying this is that the *timescales* of both the occurrence and the resolution of pandemics and climate hazards are different. The former are

Neither pandemics nor climate hazards can be confronted without true global coordination and cooperation.

often measured in weeks, months, and years; the latter are measured in years, decades, and centuries. What this means is that a global climate crisis, if and when ushered in, could prove far lengthier and far more disruptive than what we currently see with the coronavirus (if that can be imagined).

Finally, pandemics are a case of *contagion* risk, while climate hazards present a case of *accumulation* risk. Contagion can produce perfectly correlated events on a global scale (even as we now witness), which can tax the entire system at once; accumulation gives rise to an increased likelihood of severe, contemporaneous but not directly correlated events that can reinforce one another. This has clear implications for the mitigation actions they each call for.

Broader relationships

Climate change—a potent risk multiplier—can actually contribute to pandemics, according to researchers at Stanford University and elsewhere.[2] For example, rising temperatures can create favorable conditions for the spread of certain infectious, mosquito-borne diseases, such as malaria and dengue fever, while disappearing habitats may force various animal species to migrate, increasing the chances of spillover pathogens between them. Conversely, the same factors that mitigate environmental risks—reducing the demands we place on nature by optimizing consumption, shortening and localizing supply chains, substituting animal proteins with plant proteins, decreasing pollution—are likely to help mitigate the risk of pandemics.

The environmental impact of some of the measures taken to counter the coronavirus pandemic have been seen by some as a full-scale illustration of what drastic action can produce in a short amount of time. Satellite images of vanishing pollution in China and India during the COVID-19 lockdown are a case in point. Yet this (temporary) impact comes at tremendous human and economic cost. The key question is how to find a paradigm that provides at once environmental and economic sustainability. Much more easily said than done, but still a must-do.

What could happen now?

While we are at the initial stages of a fast-unfolding crisis, we can already start seeing how the pandemic may influence the pace and nature of climate action, and how climate action could accelerate the recovery by creating jobs, driving capital formation, and increasing economic resiliency.

Factors that could support and accelerate climate action

For starters, certain temporary adjustments, such as teleworking and greater reliance on digital channels, may endure long after the lockdowns have ended, reducing transportation demand and emissions. Second, supply chains may be repatriated, reducing some Scope 3 emissions (those in a company's value chain but not associated with its direct emissions or the generation of energy it purchases). Third, markets may better price in risks (and, in particular, climate risk) as the result of a greater appreciation for physical and systemic dislocations. This would create the potential for additional near-term business-model disruptions and broader transition risks but also offer greater incentives for accelerated change.

There may, additionally, be an increased public appreciation for scientific expertise in addressing systemic issues. And, while not a foregone conclusion, there may also be a greater appetite for the preventive and coordinating role of governments in tackling such risks. Indeed, the tremendous costs of being the payor, lender, and insurer of last resort may prompt governments to take a much more

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[1] "Breaking the tragedy of the horizon—climate change and financial stability—speech by Mark Carney," Bank of England, September 29, 2015, bankofengland.co.uk.

[2] See Andrew Winston, "Is the COVID-19 outbreak a black swan or the new normal?," *MIT Sloan Management review*, March 16, 2020; and Rob Jordan, "How does climate change affect disease?," Stanford Earth, School of Earth, Energy & Environment, March 15, 2019.

active role in ensuring resiliency. As for the private sector, the tide may be turning toward "building back better" after the crisis.[3]

Moreover, lower interest rates may accelerate the deployment of new sustainable infrastructure, as well as of adaptation and resilience infrastructure—investments that would support near-term job creation. And lastly, the need for global cooperation may become more visible and be embraced more universally.

If past is prologue, both the probability of such shifts and their permanence are likely to be proportional to the depth of the current crisis itself.

Factors that may hamper and delay climate action
Simultaneously, though, very low prices for high-carbon emitters could increase their use and further delay energy transitions (even though lower oil prices could push out a number of inefficient, high-emission, marginal producers and encourage governments to end expensive fuel-subsidy regimes). A second crosscurrent is that governments and citizens may struggle to integrate climate priorities with pressing economic needs in a recovery. This could affect their investments, commitments, and regulatory approaches—potentially for several years, depending on the depth of the crisis and hence the length of the recovery. Third, investors may delay their capital allocation to new lower-carbon solutions due to decreased wealth. Finally, national rivalries may be exacerbated if a zero-sum-game mentality prevails in the wake of the crisis.

What should be done?

In this context, we believe all actors—individuals, companies, governments, and civil society—will have an important role.

For governments, we believe four sets of actions will be important. First, build the capability to model climate risk and to assess the economics of climate change. This would help inform recovery programs, update and enhance historical models that are used for infrastructure planning, and enable the use of climate stress testing in funding programs. Second, devote a portion of the vast resources deployed for economic recovery to climate-change resiliency and mitigation. These would include investments in a broad range of sustainability levers, including building renewable-energy infrastructure, expanding the capacity of the power grid and increasing its resiliency to support increased electrification, retrofitting buildings, and developing and deploying technologies to decarbonize heavy industries. The returns on such investments encompass both risk reduction and new sources of growth. Third, seize the opportunity to reconsider existing subsidy regimes that accelerate climate change. Fourth, reinforce national and international *alignment and collaboration* on sustainability, for inward-looking, piecemeal responses are by nature incapable of solving systemic and global problems. Our experiences in the weeks and months ahead could help inform new paths toward achieving alignment on climate change.

For companies, we see two priorities. First, seize the moment to decarbonize, in particular by prioritizing the retirement of economically marginal, carbon-intensive assets. Second, take a systematic and through-the-cycle approach to building resilience. Companies have fresh opportunities to make their operations more resilient and more sustainable as they experiment out of necessity—for example, with shorter supply chains, higher-energy-efficiency manufacturing and processing, videoconferencing instead of business travel, and increased digitization of sales and marketing. Some of these practices could be expedient and economical to continue, and might become important components of a company-level sustainability transformation—one that accompanies the cost-efficiency and digital-transformation efforts that are likely to be undertaken across various industries in the wake of the pandemic.

When it comes to resilience, a major priority is building the capability to truly understand,

[3] María Mendiluce, "How to build back better after COVID-19," World Economic Forum, April 3, 2020, weforum.org.

qualitatively and quantitatively, corporate vulnerabilities against a much broader set of scenarios, and particularly physical events. In that context, it will also be important to model and prepare for situations where multiple hazards would combine: it is indeed not difficult to imagine a pandemic resurgence coinciding with floods or fires in a given region, with significant implications for disaster response and recovery. The same holds true for public entities, where resilience thinking will have to take greater account of the combination and correlation of events.

For all—individuals, companies, governments, and civil society—we see two additional priorities. First, use this moment to raise awareness of the impact of a climate crisis, which could ultimately create disruptions of great magnitude and duration. That includes awareness of the fact that physical shocks can have massive nonlinear impacts on financial and economic systems and thus prove extremely costly. Second, build upon the *mindset and behavioral shifts* that are likely to persist after the crisis (such as working from home) to reduce the demands we place on our environment—or, more precisely, to shift them toward more sustainable sources.

By all accounts, the steps we take in the decade ahead will be crucial in determining whether we avoid runaway climate change. An average global temperature rise above 1.5 or 2°C would create risks that the global economy is not prepared to weather. At an emission rate of 40 to 50 gigatons of CO_2 per year, the global economy has ten to 25 years of carbon capacity left. Moving toward a lower-carbon economy presents a daunting challenge, and, if we choose to ignore the issue for a year or two, the math becomes even more daunting. In short, while all hands must be on deck to defeat the coronavirus and to restart the economy, to save lives and livelihoods, it is also critical that we begin now to integrate the thinking and planning required to build a much greater economic and environmental resiliency as part of the recovery ahead.

Dickon Pinner and **Matt Rogers** are senior partners in McKinsey's San Francisco office, and **Hamid Samandari** is a senior partner in the New York office.

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How a post-pandemic stimulus can both create jobs and help the climate

The $10 trillion in stimulus measures that policy makers have allocated could be decisive for the world's low-carbon transition. Here's how organizations can bring economic and environmental priorities together.

This article was a collaborative, global effort by Hauke Engel, Alastair Hamilton, Solveigh Hieronimus, and Tomas Nauclér, with David Fine, Dickon Pinner, Matt Rogers, Sophie Bertreau, Peter Cooper, and Sebastien Leger, representing views from the Public & Social Sector and Sustainability Practices.

The tragedy of the COVID-19 crisis has taken much attention away from the threat of climate change, as institutions devoted themselves to protecting lives and livelihoods. Sustaining an effective public-health response remains a top concern for many policy makers and business executives. Severe job losses and revenue declines in some sectors, along with the high likelihood of an economic recession, have also compelled policy makers to mount an unprecedented financial response, which already exceeds $10 trillion, according to McKinsey estimates.

Important as it is to repair the economic damage, a swift return to business as usual could be environmentally harmful, as the world saw after the 2007–08 financial crisis. The ensuing economic slowdown sharply reduced global greenhouse-gas emissions in 2009. But by 2010, emissions had reached a record high, in part because governments implemented measures to stimulate economies, with limited regard for the environmental consequences. The danger now is that the same pattern will repeat itself—and today the stakes are even higher. The period after the COVID-19 crisis could determine whether the world meets or misses the emissions goals of the 2015 Paris Agreement, which were set to limit global warming to 1.5°C to 2°C.

Achieving those goals is a distinct possibility. A low-carbon recovery could not only initiate the significant emissions reductions needed to halt climate change but also create more jobs and economic growth than a high-carbon recovery would. Our analysis of stimulus options for a European country suggests that mobilizing €75 billion to €150 billion of capital could yield €180 billion to €350 billion of gross value added, generate up to three million new jobs, and enable a carbon-emissions reduction of 15 to 30 percent by 2030. Such a package need not involve economic compromises. A recent survey of top economists shows that stimulus measures targeting good environmental outcomes can produce as much growth and create as many jobs as environmentally neutral or detrimental measures.[1] But a high-carbon recovery could make it hard to meet the goals of the Paris Agreement, and heavy relief and stimulus spending might leave governments too debt-strapped to pay later for emissions cuts.

Finding a low-carbon, high-growth recovery formula isn't easy. It requires assessing stimulus measures with respect to complex factors, including socioeconomic impact, climate impact, and feasibility. But our analysis highlights the chance for policy makers to assemble a package that quickly creates jobs and economic demand, produces steady growth, and accelerates the uptake of zero-carbon technologies. Governments can use the framework described in this article to design and carry out a low-carbon recovery agenda that could meet the immediate economic needs and improve the long-term well-being of their people.

The recovery from the COVID-19 economic crisis coincides with a pivotal time in the fight against climate change

The coronavirus pandemic has not only had tragic effects on health and lives but also taken an immense toll on livelihoods. That cost is visible in the rising unemployment figures that many countries continue to report. And the worst may be yet to come. A McKinsey analysis published in April suggests that lockdowns could make up to 60 million jobs in Europe and up to 57 million jobs in the United States vulnerable: subject to reductions in hours or pay, temporary furloughs, or permanent discharge.[2] In one McKinsey scenario for a muted world recovery, the EU-27 unemployment rate peaks at 11.2 percent in 2021 and remains unlikely to achieve 2019 levels even by 2024.[3]

[1] Cameron Hepburn et al, "Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?," *Oxford Review of Economic Policy* working paper, number 20-02, 36(S1), May 4, 2020.
[2] David Chinn, Julia Klier, Sebastian Stern, and Sahil Tesfu, "Safeguarding Europe's livelihoods: Mitigating the employment impact of COVID-19," April 19, 2020, McKinsey.com; Susan Lund, Kweilin Ellingrud, Bryan Hancock, and James Manyika, "COVID-19 and jobs: Monitoring the US impact on people and places," McKinsey Global Institute, April 29, 2020, McKinsey.com; David Fine, Julia Klier, Deepa Mahajan, Nico Raabe, Jörg Schubert, Navjot Singh, and Seckin Ungur, "How to rebuild and reimagine jobs amid the coronavirus crisis," April 15, 2020, McKinsey.com.
[3] David Chinn, Julia Klier, Sebastian Stern, and Sahil Tesfu, "Safeguarding Europe's livelihoods: Mitigating the employment impact of COVID-19," April 19, 2020, McKinsey.com.

Targeted low-carbon programs could restart growth and hiring while ushering in a more environmentally sustainable "next normal."

Although the COVID-19 crisis has brought sickness and economic hardship to countless households, the urgency of responding to the pandemic is arguably matched by the urgency of addressing climate change.[4] Already, climate change brings on storms, floods, wildfires, and other natural disasters that inflict billions of dollars in damage. Additional warming over the next decade is locked in, so it is crucial to plan for physical climate risk.[5] To avert the further buildup of physical risk and to keep temperatures below thresholds that would trigger runaway warming, significant near-term reductions of greenhouse-gas emissions must happen. Achieving them will require rapid, capital-intensive action across every part of the economy.[6]

The simultaneity of the COVID-19 crisis and the climate challenge means that the post-pandemic recovery will be a decisive period for fending off climate change. In the aftermath of COVID-19, any number of factors could slow climate action: reduced political attention (this year's UN climate summit, COP26, has been postponed to 2021), the easing or delay of environmental regulations in the interest of economic growth, depressed oil prices that make low-carbon technologies less competitive, or stimulus programs that consume funds governments might otherwise invest in a zero-carbon transition.

By contrast, a climate-smart approach to economic recovery could do much to put the world on an emissions pathway that would hold the average temperature increase to a relatively safe 1.5°C. Since recovery efforts usually involve much higher public spending than governments lay out in noncrisis years, they can bring about extensive, lasting changes in the structure of national and regional economies. As we explain in the next section, targeted low-carbon programs could restart growth and hiring while ushering in a more environmentally sustainable "next normal."

Low-carbon stimulus spending can spur economic recovery and job creation

In many countries, efforts to provide economic relief and restart growth after the pandemic are well under way. Governments around the world have devoted more than $10 trillion to economic-stimulus measures. McKinsey estimates that the G-20 nations have announced fiscal measures averaging 11 percent of GDP—three times the response to the 2008–09 financial crisis. Some countries have said they will commit up to 40 percent of GDP to their economic-stimulus packages. Preliminary reports on the European Commission's green-recovery plan indicate that it will provide some €1 trillion in economic assistance.

Support is mounting for a low-carbon recovery from the COVID-19 economic crisis. The informal green-recovery alliance, launched in April by

[4] Dickon Pinner, Matt Rogers, and Hamid Samandari, "Addressing climate change in a post-pandemic world," *McKinsey Quarterly*, April 7, 2020, McKinsey.com.
[5] Jonathan Woetzel, Dickon Pinner, Hamid Samandari, Hauke Engel, Mekala Krishnan, Brodie Boland, and Carter Powis, "Climate risk and response: Physical hazards and socioeconomic impact," McKinsey Global Institute, January 16, 2020, McKinsey.com.
[6] 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 30, 2020, McKinsey.com.

12 environment ministers from European countries, 79 members of the European Parliament, and 37 CEOs and business associations, has been joined by more than 50 banking and insurance CEOs. Top executives at upward of 150 companies signed a public statement calling for a net-zero recovery. European Commission president Ursula von der Leyen and German chancellor Angela Merkel have said that the European Green Deal should form the center of Europe's economy recovery plan. Populations around the world favor recovery policies that also address climate change (Exhibit 1).

Amid debate over how to spend stimulus funds, some have questioned whether low-carbon programs generate sufficiently strong economic returns. Yet research suggests that many such programs stimulate growth and create jobs as effectively as—or better than—environmentally neutral or harmful programs. In a survey reported in a recent working paper, more than 200 economists and economic officials said that "green" economic-recovery measures performed at least as well as others did.[7] An econometric study of government spending on energy technologies showed that spending on renewables creates five more jobs per million dollars invested than spending on fossil fuels (Exhibit 2).[8]

Faced with the COVID-19 recession, governments don't have to compromise economic priorities

[7] "Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?"
[8] Heidi Garrett-Peltier, "Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model," *Economic Modelling*, Elsevier, vol. 61(C), 439–47.

Exhibit 1

Nearly two-thirds of survey respondents say governments' economic-recovery efforts after COVID-19 should prioritize climate change.

Government actions should prioritize climate change in the economic recovery after COVID-19, % of respondents[1]

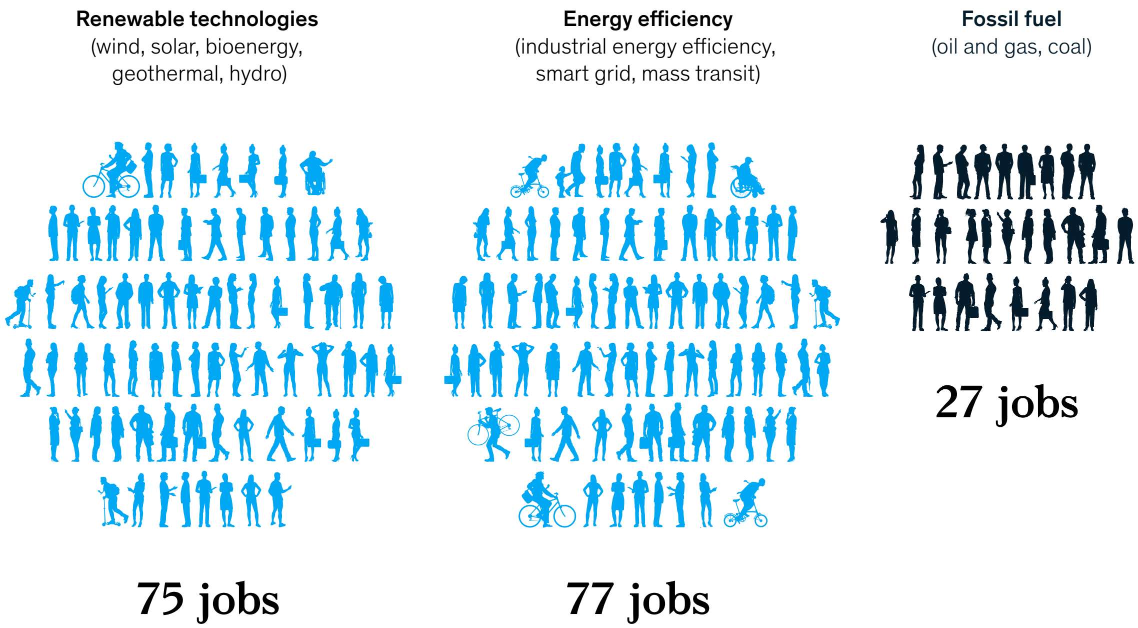
[1] Question: "To what extent do you agree or disagree with the following: In the economic recovery after COVID-19, it's important that government actions prioritize climate change." Response rates shown for "agree" include "strongly agree" and "somewhat agree"; rates for "disagree" include "strongly disagree" and "somewhat disagree." Survey conducted via online poll, April 17–19, 2020; n = 28,039; data are weighted to the profile of the population.

Source: Ipsos MORI

Exhibit 2

Government spending on renewable energy and energy efficiency has been shown to create more jobs than spending on fossil fuels.

Jobs created, directly and indirectly,[1] per $10 million in spending



[1] Excludes induced jobs.

Source: Heidi Garrett-Peltier, "Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model," *Economic Modelling*, pp. 439–47, 2017

for the sake of environmental ones. By carefully designing low-carbon stimulus packages, they can address both sets of priorities at once.

How to design and implement low-carbon stimulus programs

In assessing stimulus measures, policy makers may wish to balance several factors, such as socioeconomic benefits, climate benefits, and feasibility, before turning to implementation.

Identifying and prioritizing low-carbon stimulus options

To add climate change to post-crisis stimulus planning, policy makers might pay attention to a wide range of considerations as they evaluate programs that might receive public funds:

Socioeconomic benefits. These can be assessed by various criteria, including the number of jobs created per sum of money spent, the GDP or gross-value-added (GVA) multiplier, or the benefits to particular population segments, sectors, or geographies. The last consideration may be especially important, for COVID-19's economic fallout has landed unevenly. A McKinsey analysis of the United Kingdom and the United States shows that less-skilled workers, younger workers, lower-paid workers, and racial and ethnic minorities hold disproportionately large shares of jobs made vulnerable by lockdowns.[9]

Other areas to consider include regions and demographics affected by the low-carbon transition—for example, those exposed to phaseouts of coal mining and fossil-fuel power generation.

[9] Tera Allas, Marc Canal, and Vivian Hunt, "COVID-19 in the United Kingdom: Assessing jobs at risk and the impact on people and places," May 11, 2020, McKinsey.com.

Climate benefits. A stimulus measure's decarbonization effect can be gauged by tons of greenhouse gases prevented (or removed) per year or by the ability to enable other carbon-reducing changes. Reinforcing the energy grid, for example, promotes more distributed microgeneration, which can cut emissions.

Time frame for economic stimulus to take effect. Certain measures have a more immediate effect on job creation and GDP growth; for example, programs to construct bicycle lanes can ramp up and create jobs quickly. Other options take longer to play out. Big infrastructure projects require extensive planning before economic activity starts in earnest.

Time frame in which carbon emissions are reduced. Some stimulus measures, such as efforts to improve industrial efficiency, can lower emissions in the near term. Measures to support the development of low-carbon technologies, such as advanced batteries or carbon capture and storage (CCS), may take longer to make a difference. But that difference can become enormous when such technologies are deployed widely, as we have seen with solar power, wind power, and battery storage. The cumulative decarbonization benefits of advanced technologies can make investments in innovation a valuable element of economic-stimulus portfolios.

Feasibility. The ease of implementing stimulus measures also matters. Construction programs, for instance, might require training or reskilling large numbers of workers. Expansions of renewable-energy capacity might proceed slowly until regional supply chains are more developed. COVID-19 also introduces new feasibility issues, such as the need to maintain physical distancing.

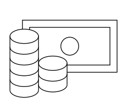
All these factors matter not only when governments assess individual stimulus options but also when they assemble them into a stimulus package. Options that quickly put people to work might be attractive, but not all boost employment for long. Sustained growth might call for projects that create jobs for years to come, even if they require extra time to ramp up. A mix may provide the best employment outcomes. Similarly, policy makers might combine some measures that cut greenhouse-gas emissions in the near term with others that reduce them after several years.

Exhibit 3

A balanced low-carbon stimulus portfolio can produce significant economic and environmental benefits.

Estimated capital mobilized and impact of a low-carbon stimulus package for a European country[1]

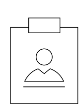
Capital mobilized



€75–€150 billion

of capital mobilized[2]

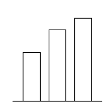
Induced employment



1–3 million

"job years" of employment created, excluding knock-on effects[3]

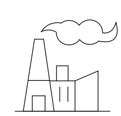
Gross value added



€180–€350 billion

in GVA created[4]

Decarbonization



15–30 percent

reduction in CO_2 by 2030[5]

[1] Population of 50 million to 70 million. Low-carbon stimulus package includes 12 stimulus measures.
[2] Includes direct government spend and "crowded-in" private-sector capital; exact cost to state is dependent on funding mechanism.
[3] Job years correspond to 1 job for 1 year; job multipliers measure only employment created during spend. In practice, economic stimulus could create jobs that become self-sustaining, resulting in more job years than shown here.
[4] Based on gross-value-added multiplier at a sector level for a typical European country of 50 million to 70 million people.
[5] Reduction is relative to current emissions and estimated based on potential; actual reduction will depend on multiple societal factors.

Creating a low-carbon stimulus program: A European example

Our analysis of stimulus options across four sectors in one European country illustrates the possibility of assembling a balanced, effective low-carbon stimulus program. By our estimates, deploying €75 billion to €150 billion would produce €180 billion to €350 billion of gross value added, create up to three million new jobs—many in sectors and demographic categories where jobs are highly vulnerable—and support a 15 to 30 percent reduction in carbon emissions by 2030 (Exhibit 3).

These outcomes rest on a careful selection of stimulus measures from an initial menu of nearly 50 options. We based estimates of the GVA multipliers of each potential measure on those observed for similar activities in major EU economies. Job-creation potential was estimated through a regression analysis that considered direct, indirect, and induced employment with respect to the features of various economic activities. (Since it is difficult to be precise when making such estimates, we have given them as wide ranges.) To gauge each measure's

Exhibit 4

Analysis highlights 12 low-carbon stimulus measures with strong socio-economic and decarbonization benefits.

Estimated capital mobilized and impact of low-carbon stimulus measures for a European country[1]

Stimulus measure by sector	**Capital mobilized,[2]** € billion	**Jobs per € milllion,[3]** number	**Jobs created,[3]** thousand	**GVA created,[4]** € billion	**GVA multiplier**
Industry					
Improve industrial energy efficiency	1–5	~14–20	15–100	2–11	2.1
Build carbon-capture-and-storage infrastructure	1–4	~15–20	30–80	4–9	2.2
Buildings					
Retrofit houses for energy efficiency[5]	50–80	~16–21	800–1,700	110–180	2.2
Install smart-building systems	0.1–2.0	~14–19	2–40	0.2–4.0	1.9
Energy					
Reinforce the electricity-distribution grid	5–10	~15–20	75–200	10–22	2.2
Expand energy storage	1–5	~14–19	15–95	3–18	3.4
Accelerate build-out of wind and solar power	10–20	~13–18	130–360	35–70	3.4
Accelerate rollout of LED street lighting	0.1–0.2	~15–21	2–5	0.2–0.4	2.2
Transport					
Expand electric-vehicle charging networks	3–5	~13–18	40–90	6–10	1.9
Create bus rapid transit and urban rail schemes	2–8	~20–25	40–200	4–18	2.2
Scale up electric-vehicle manufacturing	1–2	~14–19	20–40	2–4	2.1
Develop active-transport infrastructure[6]	0.5–5.0	~20–25	10–130	1–10	2.2

[1] Population of 50 million to 70 million. [2] Includes direct government spend and "crowded-in" private-sector capital; exact cost to state dependent on funding mechanism. [3] Estimated related to main economic activity based on OECD country data and McKinsey analysis, includes direct, indirect, and induced jobs. Job years correspond to 1 job for 1 year; job multipliers measure only employment created during spend. In practice, economic stimulus could create jobs that become self-sustaining, resulting in more job years than shown here. [4] Based on gross-value-added (GVA) multiplier at a sector level for a typical European country of 50 million to 70 million people. [5] Estimate of deep retrofit (including heat pumps) of 2 million homes. Exact quantity of homes highly flexible. [6] For example, bicycle lanes.

decarbonization impact, feasibility, and fit with the skills of the workforce and the needs of individual sectors, we drew on expert interviews and academic research.

This approach yielded a list of 12 feasible stimulus measures with strong socioeconomic benefits (including multiregional job creation) and decarbonization effects in the near, medium, and long terms (Exhibit 4):

— Improve industrial energy efficiency through such means as replacing equipment and upgrading waste-heat technologies

— Build carbon-capture-and-storage infrastructure around large industrial clusters

— Retrofit houses to increase energy efficiency—for example, by installing heat pumps

— Install smart-building systems, particularly in commercial property, to better manage heating, ventilation, air conditioning, lighting, and security

— Reinforce the electricity-distribution grid (including interconnections) to support widespread electrification

— Expand large- and community-scale energy storage

— Accelerate the build-out of wind- and solar-power generation capacity

— Accelerate the rollout of street lights using light-emitting diodes (LEDs)

— Expand electric-vehicle (EV) charging networks

— Create major bus rapid transit and urban rail projects

— Scale up EV manufacturing

— Develop infrastructure for active transport (such as bicycling lanes)

According to our analysis, this stimulus package would deliver substantial economic and environmental returns. For this example, we assumed that the capital mobilized would range from €75 billion to €150 billion. The exact cost to a government would depend on how the measures were funded—for instance, whether the government invested directly or private-sector capital provided some funding. In any case, we estimate that half of the money would be spent in the first two years and the vast majority within five. Our analysis suggests that every €1 spent would generate some €2 to €3 of GVA.

The employment boost from this stimulus package would also be substantial: 1.1 million to 1.5 million new "job years" of employment at the low end of the spending range and 2.3 million to 3.0 million at the high end.[10] These are conservative estimates, accounting only for jobs created as money is disbursed; additional self-sustaining employment could also be created. By design, most of the jobs would be low- or medium-skill jobs, for which demand will be greatest, and many are in sectors (for example, industry) that have large numbers of jobs at risk. Some are in categories with enough labor flexibility to concentrate hiring in regions with the highest unemployment rates. Hiring for these stimulus measures would begin on a range of dates, from the near term to the medium to long term.

All of this spending and labor ought to help the country's transition to a low-carbon economy move forward. By our estimates, these measures could help cut CO_2 emissions 15 to 30 percent, from current levels, by 2030. Such a decrease would account for a good portion of the 50 percent emissions reduction that is considered necessary to achieve a 1.5°C warming pathway by 2030.

Implementing low-carbon stimulus measures

Policy makers can use various mechanisms to deliver stimulus measures. We classify these in two main groups: pushes and pulls. Pushes are regulatory interventions or backstops that give companies more certainty about future regulations and thereby encourage forward planning. Building

[10] Job years correspond to one job for one year.

Many stimulus measures produce the greatest benefit if delivered through a combination of pushes and pulls.

codes are one kind of push, target dates for phasing out technologies another.

Pulls—financial interventions that compel companies to take particular actions—generally fall into one of four main groups:

— *Tax credits and subsidies* are suited to stimulus measures targeting active markets. For example, these might help accelerate improvements in industrial energy efficiency, since many companies are making them and capital is available.

— *Loans and loan guarantees* tend to work best when they target a few beneficiaries, because their administrative costs are relatively high. Loans can fill gaps in private lending, and loan guarantees can bring down interest rates for projects that private lenders see as risky. Loans and loan guarantees could support EV-charging infrastructure, for example, by diminishing the risk for charging-network operators, which must make large capital outlays without knowing when EVs will become widely used.

— *Grants* can deliver stimulus funding to many parties (such as the small contractors that retrofit homes) because their administrative costs are comparatively low. They are also useful to fund projects, such as research and development, that generate no short-term revenues.

— *Direct government ownership* can be appropriate for projects that lack a revenue stream reliable enough to interest the private sector or that inspire a political interest in outright ownership. Such projects might include grid upgrades or CCS systems, depending on regulations.

In addition to direct regulatory pushes and financial pulls, policy makers can also implement indirect "nudges" of both kinds, such as high-occupancy vehicle lanes. At modest cost, these nudges can complement and reinforce more direct measures.

Many stimulus measures produce the greatest benefit if delivered through a combination of pushes and pulls (Exhibit 5). Since stimulus packages often target a variety of companies, policy makers can create delivery mechanisms that allow wide access to funds by designing each measure to reach its intended beneficiaries. CCS network build-outs, for example, could require negotiations with just a few companies, while home retrofit programs might engage thousands of small businesses. The sequencing of pulls and pushes can also make a big difference. To foster new hiring and growth before regulations begin to restrict certain economic activities, policy makers might consider funding ahead of new regulations.

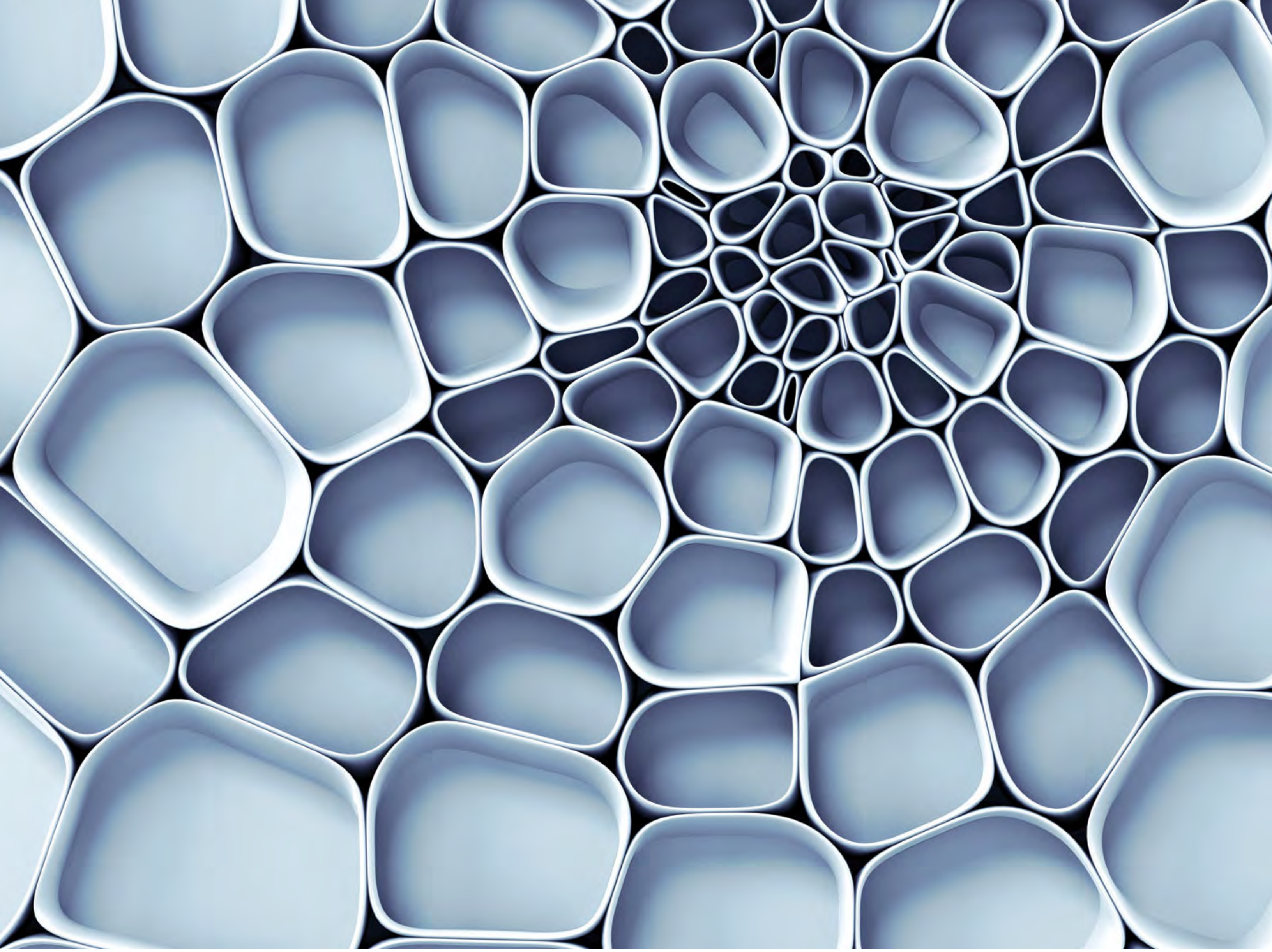
Exhibit 5

Some stimulus projects can be more effective if delivered using a balanced combination of mechanisms.

Illustrative examples	**The push** (regulation)		**The pull** (funding)
Building energy efficiency	Require residential properties to have a certain minimum energy rating, (eg, when renting or selling the property) and ban the use of oil boilers from a targeted date	+	Provide direct funding to retrofit residential property (eg, grants for heat pumps)
Electric vehicles	Restrict the use of internal-combustion-engine vehicles in urban areas (eg, with clean-air zones)	+	Introduce substantial tax breaks for the installation of electric-vehicle charging stations
Carbon capture and storage (CCS)	Mandate that industrial emitters over a certain threshold in specific regions adopt CCS technologies	+	Fund CCS infrastructure (eg, storage and transport network) in major industrial hubs

It now appears that recovery from the COVID-19 economic crisis will require stimulus programs lasting for months or even years. Those coming months and years will also be a decisive time for efforts to keep global warming within 1.5°C to 2°C. Low-carbon stimulus measures can help policy makers fulfill both needs at once—but the clock is ticking. This is the pivotal moment for policy makers to unite their economic and environmental priorities to improve and sustain the well-being of individual citizens and of the planet as a whole.

Hauke Engel is a partner in McKinsey's Frankfurt office. **Alastair Hamilton** is an associate partner in the London office. **Solveigh Hieronimus** is a senior partner in the Munich office. **Tomas Nauclér** is a senior partner in the Stockholm office. **David Fine** is a senior partner in the London office. **Dickon Pinner** is a senior partner in the San Francisco office. **Matt Rogers** is a senior partner in the San Francisco office. **Sophie Bertreau** is a consultant in the Paris office. **Peter Cooper** is a consultant in the London office. **Sebastien Leger** is a partner in the Paris office.



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Driving CO_2 emissions to zero (and beyond) with carbon capture, use, and storage

Any pathway to mitigate climate change requires the rapid reduction of CO_2 emissions and negative-emissions technologies to cut atmospheric concentrations. Technology and regulation will be the key.

by Krysta Biniek, Kimberly Henderson, Matt Rogers, and Gregory Santoni

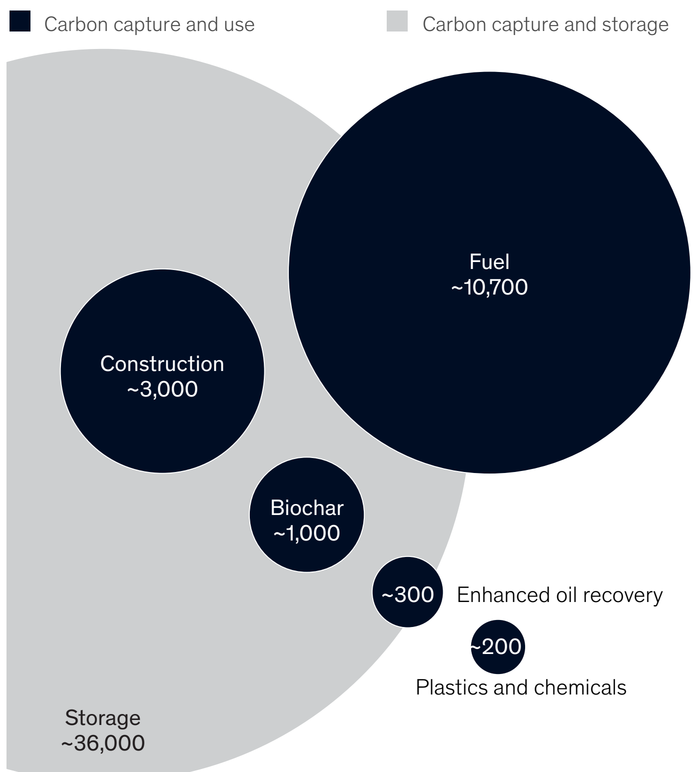
Growing concerns about climate change are intensifying interest in advanced technologies to reduce emissions in hard-to-abate sectors, such as cement, and also to draw down CO_2 levels in the atmosphere. High on the list is carbon capture, use, and storage (CCUS), the term for a family of technologies and techniques that do exactly what they say: they capture CO_2 and use or store it to prevent its release into the atmosphere. Through direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS), CCUS can actually draw down CO_2 concentrations in the atmosphere—"negative emissions," as this is called. In some cases, that CO_2 can be used to create products ranging from cement to synthetic fuels.

To better understand the possible role of CCUS, we looked at current technologies, reviewed current developments that could accelerate CCUS adoption, and assessed the economics of a range of use and storage scenarios. The short- to medium-term technical potential for CCUS is significant (Exhibit 1). CCUS doesn't diminish the need to continue reducing CO_2 emissions in other

Exhibit 1

Applications for captured CO_2 cover a wide range of materials.

Technical potential of CCUS in 2030, metric megatons of CO_2 per year[1]



Selected examples

Fuel	Synfuel and macro- or microalgae fuel
Enhanced oil recovery (EOR)	Conventional or unconventional CO_2 EOR and CO_2 EOR in residual oil zones
Construction materials	Cement and aggregates
Plastics and chemicals	Polyethylene, polypropylene, carbon fiber, and methanol
Biochar	A charcoal derived from burning organic agriculture- and forestry -waste products
Storage	Saline aquifers and depleted oil and gas reservoirs

[1] CCUS = carbon capture, use, and storage. Excludes small amounts of CO_2 used for other applications, such as decaffeination, dry ice, food and beverages, fire extinguishers, and greenhouses.

ways—for instance, by using more renewable energy, such as wind and solar power. But it offers considerable potential for reducing emissions in particularly hard-to-abate sectors, such as cement and steel production. What's more, CCUS, along with natural carbon capture achieved through reforestation, would be a necessary step on the pathway to limiting warming to 1.5 degrees Celsius above preindustrial levels.[1]

However, to reach CCUS's potential, commercial-scale[2] projects must become economically viable. In the short to medium term, CCUS could continue to struggle unless three important conditions are met: (1) capture costs fall, (2) regulatory frameworks provide incentives to account for CCUS costs, and (3) technology and innovation make CO_2 a valuable feedstock for existing or new products. This article surveys the state of a portfolio of CCUS technologies, the underlying economics, and the changes needed to accelerate progress.

The value chain of carbon capture, use, and storage

The potential of CCUS can be tracked along an intuitive value chain. Many industrial processes generate CO_2, most prominently when hydrocarbons are burned to generate power, but also less obviously—for example, when limestone is heated to produce cement. Driving your car or heating your home also releases CO_2. Carbon dioxide can be captured at the source of the emissions, such as power plants or refineries, or even from the air itself.

A range of technologies—some using membranes, others using solvents—can perform the capture step of the process. Once captured, concentrated CO_2 can be transported (most economically by pipeline) to places where it can be used as an input—for example, cured in concrete or as a feedstock to make synthetic jet fuel—or simply stored underground.

While these options all help stabilize levels of CO_2 in the atmosphere, the challenge is economics. Storage would seem the obvious choice, as the geologic-storage-reservoir potential is vast, and the technology involved is mature. But storing CO_2 at scale is a pure cost, and related investments have (understandably) been limited, given the absence of regulatory incentives to defray the installation of capture technology and a storage infrastructure. There are also tricky legal issues, such as liability for potential leaks and the jurisdictional complexities associated with underground property use.

The economics of CCUS

To clarify these dynamics, we modeled the expected alternative CO_2 uses in 2030—from the already proven technologies, such as enhanced oil recovery (EOR), to more speculative ones, such as CO_2-derived substitutes for carbon fiber. We also included an estimate for CO_2 storage.

From now to 2030, our research and modeling suggest, CCUS *could* expand from 50 million tons of CO_2 abatement per year (Mtpa) today, mostly for enhanced oil recovery and beverage carbonation,[3] to at least 500 Mtpa (0.5 gigatons a year, or Gtpa)—just over 1 percent of today's annual emissions (41 Gtpa). Such an expansion would be possible only with a supportive regulatory environment. Exhibit 2 offers a view of where the economic payoff is close and where more incentives would be needed to enable CCUS technologies to scale and reach their full potential. (For additional background on the relationship between CCUS and climate-abatement potential, see sidebar, "For further reading.")

High potential

Despite the challenging economics, there is a wave of creative energy gathering around a number of CCUS bets.

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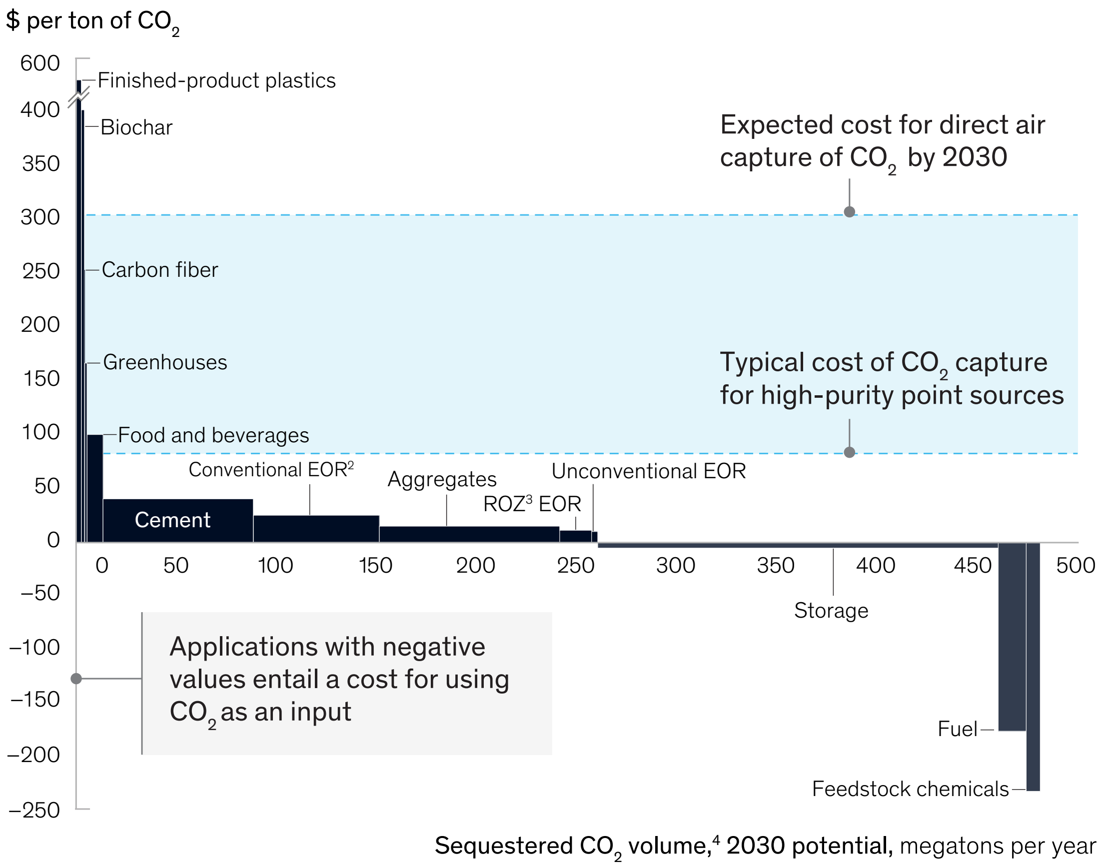
[1] See "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020, McKinsey.com.
[2] Commercial scale projects are those with at least 0.5 Mtpa of capacity.
[3] National Energy Technology Laboratory, US Department of Energy, netl.doe.gov.

Exhibit 2

The demand for CO_2 varies across applications, depending on cost and value.

Manufacturers' maximum willingness to pay for CO_2 as an input in 2030[1]



[1]While keeping their CO_2-based products cost competitive with traditional products.
[2]EOR = enhanced oil recovery.
[3]ROZ = residual oil zone.
[4]Amount stored in product through manufacture; excludes avoided emissions or those created through use of product.

For further reading

There is ongoing discussion about the level of abatement through carbon capture, use, and storage (CCUS) needed to avoid catastrophic climate change. Some key sources for insights and estimates include the following:

— *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use, and storage*, National Petroleum Council, 2019, dualchallenge.npc.org

— *Global status of CCS 2019: Targeting climate change*, Global CCS Institute, globalccsinstitute.com

— "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020, McKinsey.com

Today’s leader: Enhanced oil recovery

Among CO_2 uses by industry, enhanced oil recovery leads the field. It accounts for around 90 percent of all CO_2 usage today (mostly in the United States)[4] and benefits from a clear business case with associated revenues. Typical recovery processes leave anywhere from 40 to more than 80 percent of oil unrecovered, depending on factors such as reservoir depth, porosity, and type of oil. In some cases, the additional oil recovered is substantial (5 to more than 15 percent), and, if a nearby industrial source of CO_2 can be found (say, a power plant or refinery), the use of emitted CO_2 could be economically attractive. Our model estimates that by 2030, CO_2 usage for EOR could account for more than 80 Mtp[5] of CO_2 annually across conventional reservoirs, residual oil zones (ROZ), and unconventional oil fields[6]—an enabling step along the journey to reduced emissions through CCUS.

Cementing in CO_2 for the ages

New processes could lock up CO_2 permanently in concrete, “storing” CO_2 in buildings, sidewalks, or anywhere else concrete is used. This could represent a significant decarbonization opportunity (see “Laying the foundation for zero-carbon cement,” on McKinsey.com). For example, consider precast structural concrete slabs and blocks. They could potentially be made with new types of cement that, when cured in a CO_2-rich environment, produce concrete that is around 25 percent CO_2 by weight. There’s a CO_2 bonus available here as well: cement used in this curing process has a lower limestone content. That’s significant, since baking limestone (calcination) to make conventional Portland cement releases around 7 percent of all industrial CO_2 emissions globally. A second concrete process involves combining the aggregates with cement to make concrete (think cement mixers). Synthetic CO_2-absorbing aggregates (combining industrial waste and carbon curing) can be formed to produce this type of concrete, which is 44 percent CO_2 by weight. We estimate that by 2030, new concrete formulations could use at least 150 Mtpa of CO_2.

Carbon-neutral fuels for jets and more

Technically, CO_2 could be used to create virtually any type of fuel. Through a chemical reaction, CO_2 captured from industry can be combined with hydrogen to create synthetic gasoline, jet fuel, and diesel. The key would be to produce ample amounts of hydrogen sustainably. One segment keen on seeing synthetics take off is the aviation industry, which consumes a lot of fuel and whose airborne emissions are otherwise hard to abate. By 2030, we estimate, this technology could abate roughly 15 Mtpa of CO_2.

Turning the dial negative?

Other interesting applications seem further out. While several are novel enough to be worth keeping an eye on, their abatement potential is often uncertain. Estimating their cost and scalability is also difficult.

Capturing CO_2 from ambient air—anywhere

Direct air capture (DAC) could push CO_2 emissions into negative territory in a big way. DAC does exactly what it suggests—capture CO_2 directly from the atmosphere, where it exists in very small ambient concentrations (400 parts per million, or 0.04 percent by volume). It has been put there in a variety of ways, including both industrial point sources and more diffuse emissions, such as those from vehicles, airplanes, ships, buildings, and agriculture. DAC facilities could be located at storage or industrial-use locations, bypassing the need for an expensive CO_2-pipeline infrastructure. The challenge is that it takes a lot of energy—and money—to capture CO_2 at very low atmospheric concentrations. Costs are high, running more than \$500 per ton of CO_2 captured—five to ten times the cost of capturing CO_2 from industrial or power-plant sources. There are plans to scale this technology

[4] Ibid.
[5] CO_2-abatement estimates for CO_2 uses in this section are based on McKinsey demand-curve modeling.
[6] Around three million barrels of daily oil production use enhanced-oil-recovery techniques with approximately 30 percent of that oil produced using injected CO_2.

and reduce unit costs substantially, but the pathway to competitive economics remains unclear.

The biomass-energy cycle: CO_2 neutral or even negative

Bioenergy with carbon capture and storage relies on nature to remove CO_2 from the atmosphere for use elsewhere. Using sustainably harvested wood as a fuel renders the combustion process carbon *neutral.* (Other CO_2-rich biomass sources, such as algae, could be harvested, as well.) Biomass fuel combustion could become carbon negative if the resulting CO_2 emissions were then stored underground or used as inputs for industrial products, such as concrete and synthetic fuel. The degree to which BECCS can yield negative emissions, however, depends on a number of intermediate factors across the life cycle. These factors include how the biomass is grown, transported, and processed—all of which may "leak" CO_2. (For more on the role of forests in sequestering CO_2, see "Climate math: What a 1.5-degree pathway would take," on McKinsey.com.)

Next horizons

Three other opportunities to capture and use carbon—in carbon fiber, plastics, and agricultural "biochar"—are also worth watching.

Carbon fiber

Superstrong, superlight carbon fiber is used to make products from airplane wings to wind-turbine blades, and its market is booming. The price of the component carbon is high ($20,000 a ton), so manufacturers would love to have a cheaper, CO_2-derived substitute. Moreover, the volume of CO_2 used could become significant if cost-effective carbon fiber could be used widely to reinforce building materials. A number of pilot projects in the works focus on cracking the tough chemistry involved, but a commercially viable process appears to be perhaps a decade or more away. By 2030, we believe, the contribution to CO_2 abatement would be 0.1 Mtpa of CO_2.

Storing carbon in your mattress?

CO_2 could substitute for fossil fuel–based inputs in plastics production. The combination of technical feasibility and high interest from environmentally aware consumers has attracted the attention of major chemical companies, which are testing a range of CO_2-based plastics for widespread use. Green polyurethane—used in products such as textiles, flooring for sports centers, and, yes, mattresses—is in the early stages of commercial rollout. Storing carbon in green plastics would sequester it indefinitely. By 2030, we estimate, plastics could abate a modest but growing 10 Mtpa of CO_2.

Biochar, anyone?

Farms produce enormous amounts of biomass waste. When this is heated in an oxygen-poor environment, it creates what's called "biochar"—a charcoal-like soil amendment that today is used by a modest number of small farmers and gardeners, mostly in the United States. Producing biochar captures 50 percent of the CO_2 that would otherwise escape during waste decomposition—and retains most of it for up to 100 years. We estimate that biochar technology is more than a decade away from the point when it could start having a real impact: by 2030, it could sequester roughly 2 Mtpa of CO_2.

The road ahead: Obstacles and enablers

Moving toward an economy where CCUS plays a meaningful role would require overcoming challenges across three areas of the value chain, as well as changes in the regulatory environment to expand incentives.

Capture

About half of CO_2 emissions are generated by factories, refineries, power plants, and the like.

Some emissions, such as those from ethanol plants, are purer than others and can be captured relatively cheaply, for around $25 to $30 a ton. For less pure sources (such as emissions from cement and steel-making facilities or coal and natural-gas power plants), the costs get steeper, ranging from $60 to more than $150 a ton.[7] What remains, of course, is the other half of CO_2 emissions—widely dispersed or mobile. A look at four tiers of CO_2 sources in the United States offers a perspective on the challenges of scaling CO_2 capture (Exhibit 3).

CO_2 transportation

Today, CO_2 transportation—a necessity for CCUS to scale—is a weak link in the value chain. In the United States, some 5,000 miles of pipeline transport CO_2, compared with 300,000 miles of natural-gas pipelines. Outside the United States, pipelines for moving CO_2 are rare.

Storage

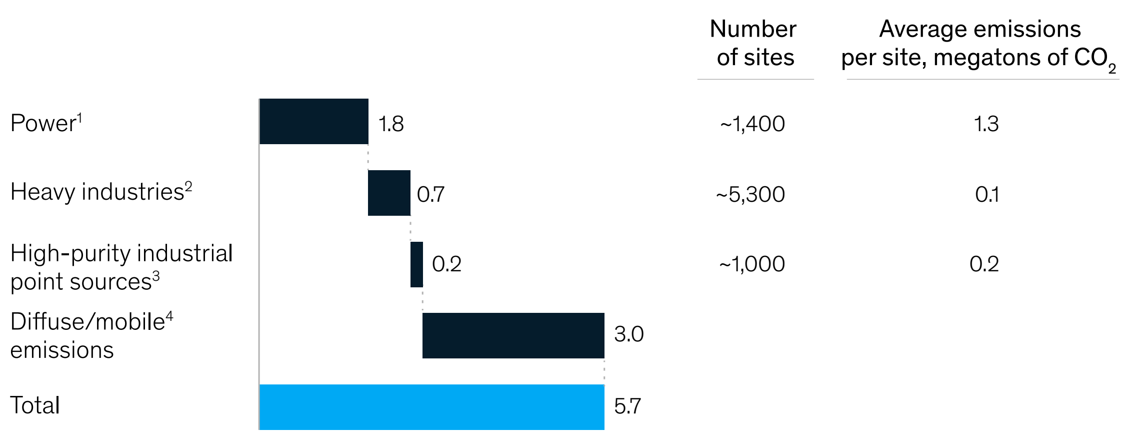
The challenges for CO_2 storage are primarily nontechnical—a function of economic, legal, and regulatory challenges. By some estimates, the United States could geologically store 500 years of its current rate of CO_2 emissions; globally, the number is around 300 years. This potential is constrained by the fact that carbon storage (without use) is largely a cost, as we have noted, and thus attracts relatively little project investment and innovation, particularly in the absence of regulatory support or incentives. Moreover, there are also complex legal issues that must be resolved, such as liability for potential leaks, as well as

[7] For data used in this section, see "CCUS supply chains and economics," in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use, and storage*, National Petroleum Council, December 2019, dualchallengenpc.org.

Exhibit 3

In the United States alone, potential industrial sources for carbon capture, use, and storage are plantiful, though they vary in terms of CO_2 concentration.

Total CO_2 emissions in United States, 2018, metric gigatons of CO_2



[1] Includes gas and coal.
[2] Includes oil and gas production, storage and distribution, refining, cement, iron/steel, and chemical production (except as noted in high-purity sources).
[3] Includes natural-gas processing, ethanol, ammonia, hydrogen, and pulp and paper production.
[4] Diffuse/mobile sites number in the millions, with average emissions per site of ~0.001 megatons of CO_2; includes transportation (eg, cars, trucks, aircraft, ships), residential/commercial use, and agriculture.

Source: "Greenhouse Gas Reporting Program (GHGRP)," US Environmental Protection Agency, epa.gov the jurisdictional complexities associated with underground property ownership and use. Still, by 2030 we estimate that storage could account for 200 Mtpa of CO_2 abatement—a small but meaningful slice of the full potential for storage.

Regulation

Anywhere you look in the CCUS value chain, projects to jump-start progress are costly. One avenue of government support is tax credits. In the United States, a tax credit (Internal Revenue Code, Section 45Q) offers $35 a ton for CO_2 use and $50 a ton for geologic storage (the higher incentive accounts for the lack of revenue potential). An alternative would be a market price for carbon.

In some sense, the CCUS opportunity is a natural extension of something that occurs every day in the global economy: the collection and disposal of waste and the transformation of some of it into higher-value products and materials. For a wide variety of players in the oil, gas, and chemical industries, this also represents a natural extension of core capabilities—such as operating pipelines, managing reservoirs, and synthesizing new materials—and could therefore be a major opportunity. To make the economics work and to encourage further technological innovation, incentives and supportive regulatory frameworks will be necessary. If they come, CCUS can help support the transition to a low-carbon economy. Without CCUS, the transition would become much more challenging—because every scenario to stabilize the climate depends on investment in negative-emissions technologies.

Krysta Biniek is an associate partner in McKinsey's London office; **Kimberly Henderson** is a partner in Washington, DC, office; **Matt Rogers** is a senior partner in the San Francisco office; and **Gregory Santoni** is an associate partner in the Houston office.

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How the fashion industry can urgently act to reduce its greenhouse-gas emissions

by Achim Berg, Anna Granskog, Libbi Lee, and Karl-Hendrik Magnus

As the need to address climate change becomes more urgent, industry sectors are working to reduce their carbon emissions. Fashion makes a sizeable contribution to climate change. McKinsey research shows that the sector was responsible for some 2.1 billion metric tons of greenhouse-gas (GHG) emissions in 2018, about 4 percent of the global total. To set that in context, the fashion industry emits about the same quantity of GHGs per year as the entire economies of France, Germany, and the United Kingdom combined.

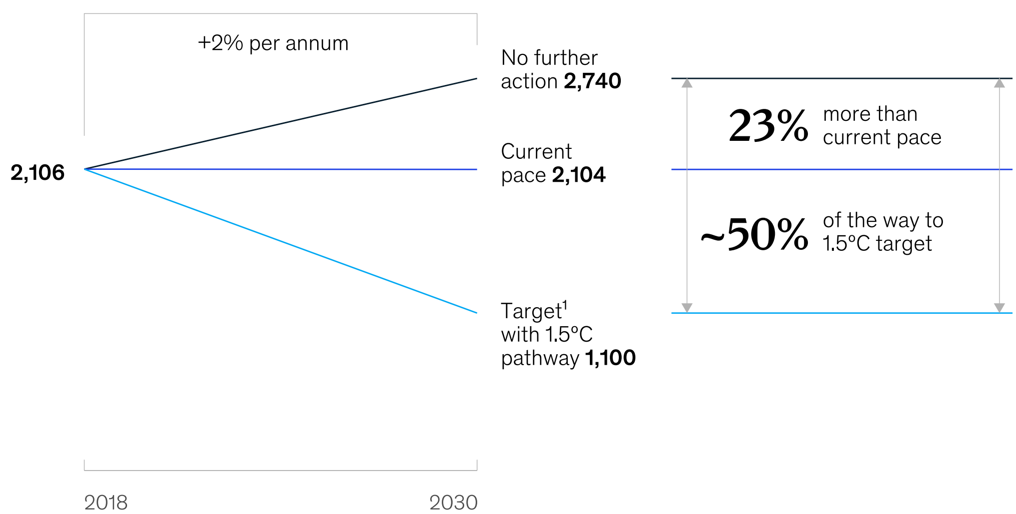
Despite efforts to reduce emissions, the industry is on a trajectory that will exceed the 1.5-degree pathway to mitigate climate change set out by the Intergovernmental Panel on Climate Change (IPCC) and ratified in the 2015 Paris agreement. To reach this pathway, fashion would need to cut its GHG emissions to 1.1 billion metric tons of CO_2 equivalent by 2030. But our growth calculations, adjusted to take into account the likely impact of COVID-19, show that the industry is set to overshoot its target by almost twofold, with emissions of 2.1 billion metric tons of CO_2 equivalent in 2030, unless it adopts additional abatement actions (Exhibit 1).

To gain a deeper understanding of fashion's carbon emissions and identify additional abatement efforts the industry could pursue, we examined the entire value chain from farms and factories to brands and retailers to policy makers, investors, and consumers (see sidebar, "Our methods and assumptions"). Our findings show that all participants in all parts of the value chain have a role to play in driving decarbonization and bringing about real and lasting change for the better in the fashion industry.

Exhibit 1

Under the current trajectory, the fashion industry misses the 1.5°C pathway by 50 percent and abates only emissions from incremental growth.

Emissions abatement assuming the industry decarbonization continues at current pace, million tons of CO_2 equivalent



[1]Calculation: half of available 1.5°C pathways indicate 25 billion to 30 billion tons of CO_2 equivalent a year by 2030 (IPCC). 4% of 27.5 billion tons of CO_2 equivalent equals 1.1 billion tons of CO_2 equivalent.
Source: Consolidated model as of June 19, 2020

Our methods and assumptions

To arrive at an emission baseline for the fashion industry, we calculated the volume of garments manufactured, used, and disposed in 2018, taking into account the fibers used to meet garment demand and the energy consumption and emission intensity of the raw materials and processes involved.

Exhibit

In assessing abatement potential, we focused on levers across the value chain.

Levers by garment life stage

Stage			Levers
Upstream value chain	Raw-material production	1	**Decarbonized material production** Improvements across the production and cultivation of key current materials
		2	**Improved material mix** Decarbonization through the use of alternative or new materials
	Material preparation and processing	3	**Decarbonized material processing** Improvements in energy efficiency, transition to renewable energy and reduced chemical use
		4	**Minimized production wastage** Reducing waste generated in the processing stages
	Product manufacturing	5	**Decarbonized garment manufacturing** Improvements in energy mix and efficiency across garment-manufacturing countries
Transport and distribution		6	**Minimized manufacturing wastage** Reducing waste generated in the manufacturing stages
Retail	Operations	7	**Increased use of sustainable transport** Changes in modes of transportation and improvements in fuel mix
		8	**Improved packaging** Decarbonization through material-mix improvements and minimized material usage (manufacturing through retail)
		9	**Decarbonized retail operations** Improvements in energy mix and efficiency
	New business models	10	**Minimized returns** Decarbonization by limiting wastage as a result of retail returns
		11	**Minimized stock wastage** Reducing waste generated as a result of unsold retail stock
		12	**Increased use of rental models** Promotion of subscriptions or one-time rental offerings
		13	**Increased use of re-commerce models** Promotion of second-hand sales (direct or through platforms)
		14	**Introduction of refurbished/upcycled products** Promotion of refurbished/upcycled product offerings
		15	**Introduction of product-repair services** Promotion of repair services to extend product life
Product use life		16	**Reduced washing and drying** Decarbonization through reduced washing and improved care
End of life		17	**Increased recycling and collections** Decarbonization through increased recycling and minimized incineration without recovery and landfill

Our methods and assumptions (continued)

Our analysis considered a range of possible trajectories for the fashion industry post COVID-19, and was based on a scenario in which a 30 percent drop in demand in 2020 is followed by a rebound in 2021, with sales some 3 percent higher than in 2019.

We calculated the fashion industry's target 2030 pathway of 1.1 billion metric tons of GHG emissions by combining the 1.5-degree scenario in the Intergovernmental Panel on Climate Change (IPCC) report with our bottom-up calculation of the industry's emission baseline. In assessing abatement potential, we focused on 17 levers across the value chain (Exhibit), ranging from improving the production and cultivation of materials to increasing recycling and collections for garments at the end of their life. For each lever, we assessed the level of decarbonization that could be achieved under two scenarios: the industry's current trajectory and an accelerated abatement program to meet the target 2030 pathway.

To calculate abatement costs, we estimated the net annualized cost of applying a specific decarbonization lever and divided this cost by the amount of abatement achieved per year, to arrive at a unit cost per metric ton of abated CO_2. This calculation includes the additional annual operating costs and potential cost savings of replacing a lever, but excludes transaction costs, subsidies, explicit CO_2 costs, taxes, and impact on the economy. We stress-tested our findings with experts, constructed an abatement cost curve, and identified the contributions different sets of stakeholders could make to carbon reduction across the value chain.

More detail on our methodology can be found be downloading the full report.

Accelerated abatement

One of the challenges fashion faces in reducing its GHG footprint is the likelihood that shifting population and consumption patterns will drive continuing industry growth. A predicted rise in volumes could push carbon emissions to around 2.7 billion metric tons a year by 2030 if no abatement actions are taken. However, if the industry continues to embrace decarbonization initiatives at its current pace, it will cap emissions at around 2.1 billion metric tons a year by 2030, roughly the same as they are today. Yet even with these efforts, emissions would reach almost twice the maximum level that would allow the fashion industry to follow the 1.5-degree pathway.

To reach the 1.5-degree pathway, the industry would need to intensify its abatement actions and scale up existing decarbonization efforts to reduce annual emissions to around 1.1 billion metric tons in 2030, roughly half of today's figure. Some 60 percent of the additional emission reduction under this accelerated abatement scenario could be achieved in upstream operations, through initiatives such as energy-efficiency improvements and a transition to renewable energy, with support from brands and retailers. Another 18 percent of emissions could be saved through operational improvements by fashion brands, and a further 21 percent through changes in consumer behavior. Together, these efforts could reshape the fashion landscape.

The good news for the fashion industry is that many of the actions required for accelerated abatement can be delivered at modest cost. Almost 90 percent of the measures we identified would cost less than $50 per metric ton of GHG emissions abated. What's more, around 55 percent of the measures would lead to net cost savings for the industry.

The remaining actions would require incentives to shape consumer demand or regulations to deliver abatement. Up-front capital would be needed to fund 60 percent of the abatement measures.

Given their potential to act as the main drivers of accelerated abatement, brands and retailers face a call to collaborate with others in the value chain to invest for long-term social and environmental benefits. Not only can they effect change in their own operations but they can also support decarbonization efforts elsewhere in the industry and help consumers make more sustainable purchasing choices.

Priorities for industry participants

Our analysis identified a need for concerted action in three key areas:

Reducing emissions from upstream operations. Manufacturers and fiber producers could deliver 61 percent of the accelerated abatement we identified by decarbonizing material production and processing, minimizing production and manufacturing waste, and decarbonizing garment manufacturing. Improvements in energy efficiency and a transition from fossil fuels to renewable-energy sources could deliver about 1 billion metric tons of emission abatement in 2030 across the fashion value chain.

Reducing emissions from brands' own operations. The main contributions brands could make to emission abatement are to improve their material mix (for instance, through greater use of recycled fiber), increase their use of sustainable transport, improve their packaging (with recycled and lighter materials), decarbonize their retail operations, minimize returns, and reduce overproduction (only 60 percent of garments are currently sold without a markdown). If brands followed the measures we have identified, they could achieve 308 million metric tons of CO2-equivalent abatement in 2030.

Encouraging sustainable consumer behavior. The adoption of a more conscious approach to fashion consumption, changes in consumer behavior during use and reuse, and the introduction by brands of radically new business models could contribute 347 million metric tons of emission abatement in 2030. The main levers in this effort are an increase in circular business models promoting garment rental, resale, repair, and refurbishment; a reduction in washing and drying; and an increase in recycling and collection to reduce landfill waste and move the industry toward an operating model based on closed-loop recycling.

Policy makers and investors also have important parts to play in these efforts. Governments and regulators should promote sustainable practices and conscious consumption, and provide incentives to support decarbonization measures with high abatement potential. Investors can make their contribution by encouraging decarbonization initiatives, emission transparency, and sustainability-focused innovation among the companies in their portfolios.

Stepping up

Accelerating emission abatement through the actions identified in our analysis calls for bold commitments from stakeholders across the value chain. These commitments need to be supported by equally bold actions, greater transparency, increased collaboration, and joint investment.

After 2030, the challenge becomes still greater. To stay on the 1.5-degree pathway, fashion will need to go beyond the accelerated abatement envisaged in our analysis and deploy all its ingenuity and creativity to decouple value creation from volume growth.

The report on which this article is based is part of a multiyear strategic-knowledge partnership between the Global Fashion Agenda and McKinsey & Company. The partnership aims to present research and a fact base on the priorities of CEOs and to guide and mobilize industry players in taking bold action on sustainability. Download the full report.

Achim Berg and **Karl-Hendrik Magnus** are senior partners in McKinsey's Frankfurt office, **Anna Granskog** is a partner in the Helsinki office, and **Libbi Lee** is an associate partner in the London office.

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How airlines can chart a path to zero-carbon flying

The coronavirus crisis will transform aviation, giving airlines their best chance yet to address climate change. Sustainable fuels are a key part of that strategy.

by Alex Dichter, Kimberly Henderson, Robin Riedel, and Daniel Riefer

The airline industry is understandably focused on the coronavirus pandemic's impact on growth, along with the health and livelihoods of its millions of workers.

This year now represents the biggest retrenchment in the history of aviation, with airline capacity down roughly 75 percent as of early April. That means an industry with a predictably steady growth rate has suddenly shrunk to a fraction of its size. It is unclear how protracted the decline will be, though demand is likely to bottom out in 2020 before returning to pre-crisis levels several years from now. The timing will depend on many factors outside the industry's control.

In the longer term, aviation is likely to undergo structural changes with regard to demand and the degree of industry consolidation, along with unprecedented government support. That transition provides an opportunity to rebuild the industry for a low-carbon future, something that airlines have been grappling with for some time.

Even before the coronavirus pandemic began, the industry was facing the challenge of reducing its carbon emissions in line with international goals to reach net-zero emissions by 2050. Forces that have buoyed the case for sustainability—including customers and regulators worried about emissions and unpredictable future carbon policies—have shifted with the pandemic, as airlines' survival seems to be at stake.

The industry has a solid record on fuel efficiency: fuel burn per passenger-kilometer has dropped by half since 1990, according to the International Air Transport Association. The current crisis could provide forward-thinking airlines with a chance to emphasize their fuel-efficiency programs and justify the retirement of older, less-fuel-efficient aircraft (see sidebar, "Ten questions airline executives should be asking"). Modernizing fleets and improving operational efficiency are important; however, in the best case, annual industry growth counters the emissions that they save. Carbon offsetting holds more promise, and it can help serve as a bridge while the industry takes action needed to reduce its own emissions over time.

The option that could be transformative, aligning the industry's growth ambitions with Paris Agreement targets, is sustainable aviation fuel (SAF). Compared with fossil kerosene, SAF could mean a reduction in carbon emissions of 70 percent to almost 100 percent. While SAF has drawbacks, including high prices and supply concerns, airline CEOs should view it as a promising tool in their decarbonization toolkits. To help push options forward, airlines can make targeted investments and purchase commitments that would increase SAF use (currently at less than 1 percent of total consumed jet fuel) while reducing costs.

Because of the scale of the challenge, any solution will require a multistakeholder approach that also includes governments, tech players, and suppliers. The trick is to create a suitable regulatory framework and supporting incentives so that no single player is penalized for going it alone.

The case for action

The aviation industry has taken steps to address rising emissions. In 2009, it set ambitious targets that include carbon-neutral growth from 2020 onward and halving its net emissions from 2005 levels by 2050.

We don't know what the pandemic will mean for emissions growth over time. But the target for all industries, companies, and countries is to reach net-zero carbon emissions by 2050, as laid out in the Intergovernmental Panel on Climate Change goals of limiting global warming to no more than 1.5°C above preindustrial levels. As the energy and transportation industries create a path to decarbonize, sectors in which climate effects are hard to abate are coming under more pressure, and aviation is no exception. McKinsey recently developed a set of

Consumers have said they are worried about the impact flying has on climate change. Public movements, such as #flygskam and Fridays for Future, reflect this sentiment, particularly among millennials.

1.5°C scenarios that would see reductions in aviation emissions of 18 to 35 percent compared with a business-as-usual pathway by 2030.[1]

Nations excluded aviation and international shipping when setting carbon targets because emissions are difficult to allocate to a particular country. But airlines shouldn't risk the perception that they aren't doing enough about CO_2, especially amid mounting scrutiny from the flying public, the media, investors, and regulators. With half of industry growth coming from Asia, including China, India, and Southeast Asia, decarbonization can work only if airlines from those nations are on board.

Despite the convenience of flying, consumers have said they are increasingly worried about the impact it has on climate change. Public movements, such as #flygskam ("flight shaming") and Fridays for Future, reflect this sentiment, particularly among millennials.

Investors, for their part, are concerned about the effects of climate risk on airline valuations, with climate-related financial disclosures becoming more common. The frequency of climate-related discussions in European earnings calls with investors increased nearly sevenfold since 2017, according to HSBC data. At the same time, corporate customers turn to airlines for ways to reduce scope-3 emissions[2] incurred from their employees' business travel.

Institutions and governments are announcing policies on CO_2 or SAF. Norway has mandated that 0.5 percent of aviation fuel in the country must be sustainable this year, growing to 30 percent by 2030. It wants all short-haul flights to be 100 percent electric by 2040. And Canada implemented a carbon tax of 30 Canadian dollars (around $21) per metric ton of CO_2 in most of its regions, based on the amount of loaded fuel for domestic travel.

Much of the pressure is rooted in consumer unease. Last summer, McKinsey conducted a survey of roughly 5,300 fliers in 13 aviation markets to get their views on flying and climate change. Although the survey took place well before the coronavirus essentially shut down air travel, more than 50 percent of respondents said they were "really worried" about climate change. Those feelings were higher among women than men and most pronounced among people aged 34 and younger, suggesting that these perceptions aren't going away (Exhibit 1).

[1] The scenarios include assumptions about improvements in energy efficiency (driven by operational improvements and fleet modifications), the share of zero-emission sustainable aviation fuel in the fuel mix, and reduced travel demand and modal shifts. 2016 was the baseline used for all scenarios, and the business-as-usual outlook is based on McKinsey's 2019 Global Energy Perspective.

[2] Scope-3 emissions are all indirect emissions that occur in the value chain of a reporting company. For an airline, they would include the emissions involved in manufacturing the plane and in preparing the food that people eat in flight, for example.

Exhibit 1

Younger airline customers are more concerned about climate change, our survey showed.

Attitudes toward carbon-neutral flying, by age group, % of respondents

	Really worried about climate change	Aviation plays a major role in carbon footprint	Have a bad conscience when flying	Aviation should definitely become carbon neutral	Plan to reduce own air travel	Willing to pay ≥$20 for carbon-neutral flight[1]
18–24 years	52	41	34	59	40	55
25–34 years	62	46	40	62	38	56
35–44 years	56	42	34	56	34	47
45–54 years	49	34	21	44	24	37
55–64 years	46	33	14	39	20	35
≥65 years	44	30	13	42	18	34
Total	54	40	30	53	31	46

[1] For a $1,000 flight.

Source: McKinsey CleanSky Survey, July 2019

Roughly a third of respondents said they were planning to reduce their air travel because of climate concerns (Exhibit 2), and most respondents said they were willing to pay somewhat more for carbon-neutral tickets, with fliers aged 18 to 34 willing to pay the most. At the same time, respondents felt that airlines and government subsidies should cover the costs before corporate customers or fliers themselves did. When asked about feasible ways to decarbonize aviation, they ranked carbon offsetting as the least appropriate option.

In the short term, the coronavirus pandemic and the resulting demand shock have reduced carbon emissions. We don't know what the aviation industry will look like after the coronavirus pandemic, but we believe that customer preferences for environmental flying will continue.

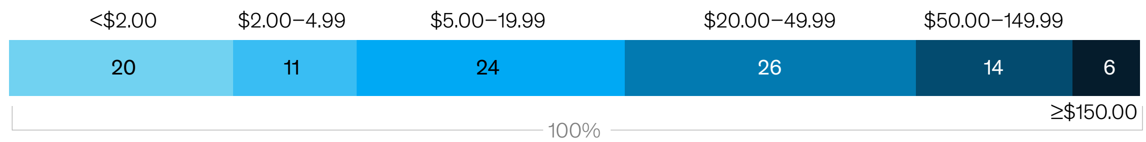
Tech and efficiency gains

Airlines are already working to align emissions cuts with their bottom-line interests. They have encouraged operational efficiency and optimal air-traffic management (ATM) and invested billions of dollars to modernize aircraft with more efficient aerodynamics and engines using lighter-weight materials. However, these actions get the industry only so far, cutting emissions by no more than 20 to 30 percent compared with the do-nothing alternative.

Exhibit 2

Many respondents say they are planning to fly less and are willing to pay more for carbon-neutral tickets.

Willingness to pay for carbon-neutral flight, by added cost,[1] % of respondents



33%
of respondents believe (other) people should fly less because of climate change

31%
of respondents are at least "likely" planning to fly less because of climate change

8%
of respondents are "definitely" planning to fly less because of climate change

Note: Figures may not sum to 100%, because of rounding
[1] Based on a $1,000 flight.
Source: McKinsey CleanSky Survey, July 2019

Operational efficiency
Fuel typically accounts for 20 to 30 percent of operational costs—one of the largest single cost items. Every kilogram of kerosene produces 3.15 kilograms of CO_2.[3] Airlines therefore have an intrinsic motivation for adopting more fuel-efficient flying, taxiing, and airport operations. They are also eking out fuel-efficiency gains by decreasing the extra fuel loaded onto aircraft and introducing lighter materials to reduce aircraft weight.

In a recent survey of airlines, we learned that, despite these efficiency gains, carriers capture only around 50 percent of their full potential. Only a few airlines address their employees' behaviors and mindsets related to fuel. This is a crucial area, since pilots, dispatchers, and other airline employees have considerable discretion in preparing and conducting safe flights, with direct implications for fuel consumption.

To increase fuel efficiency, airlines should identify the areas needing improvement with the help of analytics and systematically drive behavioral change with their frontline employees. For example, in a behavioral-science project, Virgin Atlantic Airways successfully demonstrated how nudging, or using subtle interventions to change behavior, can make pilots use less fuel.

The airline randomly placed all 335 of its pilots into four groups. It informed the members of one group (the control group) that they were part of a fuel-use study, with no further information. It provided the experimental groups with feedback on their fuel use, including monthly assessments on fuel loading, optimized flying, and efficient taxiing. According to the researchers, all three experimental groups saved more fuel than the control group did, and pilots in the "prosocial" group—those told that the company would make a charitable donation if they

[3] "Aviation Carbon Offset Programme: Frequently asked questions," International Air Transport Association, April 30, 2020, iata.org.

reached their targets—reported the highest level of job satisfaction.

Airlines also consume additional fuel from zigzagging through nations' ATM sectors that require predefined handovers. Other inefficiencies include limits on air-traffic-control capacity and a lack of automation in air-navigation services. Eliminating those inefficiencies requires a joint effort from a large group of stakeholders, including governments, regulators, and militaries, which makes the process painfully slow.

New aircraft technology

Airlines invested almost $120 billion in new aircraft in 2018 alone, according to Teal data. New models have highly efficient engines, and modern long-haul twin-engine aircraft are replacing four-engine aircraft, which enables up to 20 percent fuel-efficiency improvement per passenger.

Regarding commercial-fleet strategy, executives should consider not just fuel-price predictions but also the future cost of carbon. Applying carbon emissions as a fuel-cost premium could lead to an accelerated fleet rollover and faster adaption of future aircraft technology, including some electrification.

Alternative propulsion (such as via electricity and hydrogen) could one day replace conventional turbine-powered planes, especially smaller aircraft on shorter flights. However, the use of fully electric aircraft carrying more than 100 passengers appears unlikely within the next 30 years or longer. Given the lower energy density of batteries compared to fuels, aircraft would need to carry more than 50 kilograms of battery weight (with today's technology) to replace one kilogram of kerosene. Because battery weight wouldn't burn off the way fuel does, carrying that weight for an entire flight would require energy, creating a penalty for longer flights in particular.

Electric propulsion could start with hybrid- or turboelectric flying, enabling further improvements in fuel efficiency as jet engines become smaller and lighter, using less fuel. For example, Ampaire, a Los Angeles–based start-up, is working with Mokulele Airlines, an interisland carrier in Hawaii, on hybrid-electric flights for aircraft with around ten passengers.

Aircraft could also be powered by hydrogen, either from direct combustion (hydrogen turbine) or via a fuel cell. Hydrogen emits no CO_2 during the combustion process and allows for significant reduction of other elements that drive global warming, such as soot, nitrogen oxides, and high-altitude water vapor. (Hydrogen can also be a feedstock for SAF; more on that in a later section.)

However, liquified hydrogen would require four times the volume of kerosene, so its use would reduce space for customers or cargo. Also, airports would need new parallel refueling infrastructures, including fuel trucks able to store liquified hydrogen. Refueling time would grow for longer-range aircraft, affecting gate and aircraft utilization. Smaller aircraft powered with hydrogen could become feasible in the next decade. For aircraft with more than approximately 100 passengers, significant aircraft-technology development would be required, and infrastructure constraints would need to be overcome.

Intermodal shift

Trains and buses generate less CO_2 on a per-passenger basis than planes do (and rail freight can be a lower-emission alternative for air cargo). Airlines can work with rail and bus companies to offer a more integrated service for short connections and when alternative means of transport are available. Examples abound, often in Europe, such as the rail link between the United Kingdom and Europe that cut back the need for flying. But carbon savings here don't make a large

[4] McKinsey analysis shows that only 4 percent of worldwide emissions result from flights of fewer than 500 kilometers; 13 percent are from flights of fewer than 1,000 kilometers.

dent in overall airline emissions,[4] nor are they a great option for airlines' bottom lines.

Carbon offsetting

Carbon offsetting, or CO_2 compensation, provides a large-scale and industry-agnostic means of compensating for CO_2 emissions by reducing emissions elsewhere. Airlines are on board with offsetting; indeed, the industry is expected to be a key sponsor for global reforestation. Offsetting is also the basis for such market-based measures as Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the International Civil Aviation Organization's carbon-reduction initiative.

Offsetting allows worldwide investment in projects to compensate for emissions, independent of buyers' own efforts to reduce their footprints. Planting trees and letting them grow to capture CO_2 can cost as low as $5 to $10 per metric ton of CO_2 captured. That translates into a ticket-price increase of less than $1 per passenger on a short-haul flight. Besides nature-based solutions such as planting trees, offsetting projects can be related to resource recovery (such as methane capture from landfills), renewable energy, energy efficiency, and fuel switching, among other areas.

Yet offsetting as a longer-term solution is controversial. Some critics view it as an attempt at greenwashing. Many also worry that offsetting might relieve the pressure on buyers to reduce their emissions in other ways: they might feel better by offsetting and not consider enacting other emission-cutting measures. A credible environmental-footprint strategy includes reducing emissions through renewable fleets, fuel efficiency, and other measures as the role of SAF grows over time, in addition to offsetting emissions that remain.

Many airlines have made large offset commitments that go beyond CORSIA and offer their customers the option to pay offsetting costs themselves. Overall, however, only about 50 percent of airlines offer customers an opportunity to offset flight emissions, and the process to do so can be cumbersome, with customers redirected to a separate website to opt-in. As our survey showed, very few fliers—less than one percent—make use of voluntary carbon offsetting.

Sustainable aviation fuel

SAF is a solution that can achieve full decarbonization, but it comes with challenges on both the supply and demand fronts. When burned, SAF creates the same amount of CO_2 emissions as conventional jet fuel. The improvement results from the fact that its production process absorbs CO_2, leading to a reduction in CO_2 emissions of 70 to 100 percent on a life-cycle basis.

In a 1.5°C pathway, our analysis found that SAF would have to account for 20 percent of jet fuel by 2030, or, at a minimum, 10 percent in a scenario in which transportation lags in decarbonization compared with other sectors.

Use of advanced biofuels is a likely near-term solution. The technical feasibility of fuel made from vegetable or waste oils is proven, the product is certified, and some airlines use the fuel in daily operations. But getting the appropriate feedstock and supply chain in place is difficult; building production facilities and refineries is costly. Used cooking oil, a popular ingredient for biofuel, has fragmented availability and is expensive to collect. Other vegetable oils have high costs of production, collection, transportation, and conversion to fuel.

Feedstock resources also involve other environmental risks, such as deforestation and the creation of monocultures. Feedstock sources for biofuels must be selected thoughtfully to limit "food versus fuel" challenges.

Some airlines, including Cathay Pacific Airways and United Airlines, have invested in facilities to demonstrate how municipal household waste could be gasified and subsequently turned into jet fuel. In some regions, the fermentation of wood residues into sustainable kerosene has shown potential as a viable path.

Alternatively, the use of synfuels derived from hydrogen and captured carbon emissions could become a scalable option. Such synfuels require water, renewable electricity to produce hydrogen, and CO_2. Today, these power-to-liquid fuels are several times the cost of conventional kerosene, though we expect a significant cost reduction for green hydrogen (via reduced costs of renewable electricity and "electrolyzers") in the coming years. In a first step, CO_2 could be captured as waste gas from carbon-intensive industries, such as steel, chemicals, and cement.

Long term—and to become net-zero CO_2—the required CO_2 needs to be extracted from the carbon cycle (taken from the air with direct air capture). While this is costly today, the process benefits from cheaper renewable-electricity generation in the future.

While synfuels could become an answer to cutting emissions over the long run, it is unclear, at this point, which SAF sources will emerge as winners.

A McKinsey analysis suggests that while current SAF costs are high in relation to kerosene cost, they will come down over time and could reach breakeven between 2030 and 2035, in an optimistic scenario (Exhibit 3).

In effect, SAF presents a classic chicken-and-egg problem. Airlines don't yet have a viable business case for buying SAF; therefore, its production volume is small, with little economies of scale and insufficient funding (Exhibit 4).

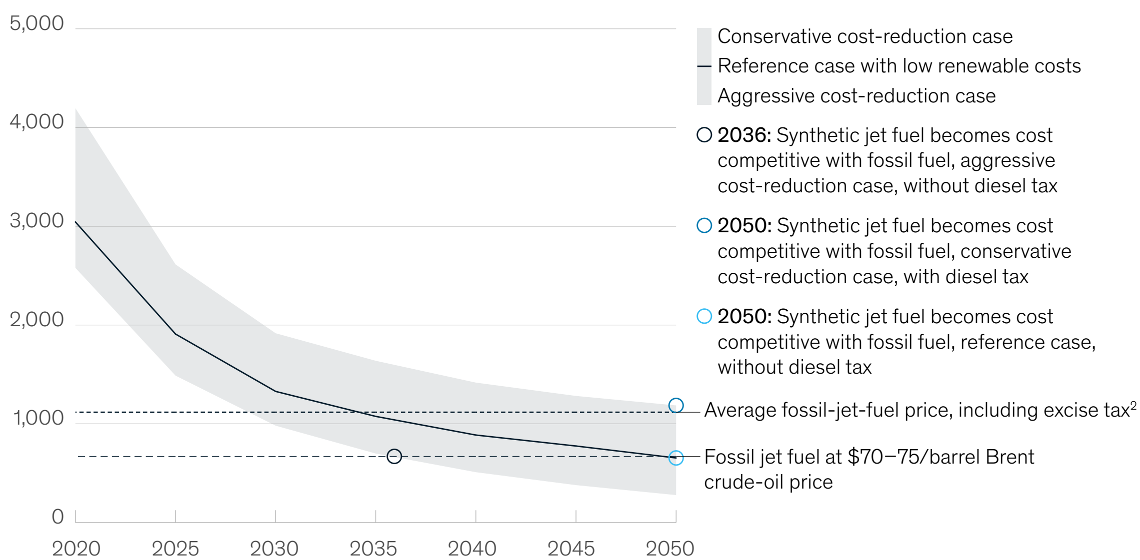
Wanted: More stakeholders for sustainable aviation fuel

Breaking through the which-comes-first problem with SAF would involve a number of groups, each doing its part to put the puzzle together. First, airlines could build and orchestrate a consortium of stakeholders that includes technology providers and oil companies to drive demand and help bridge the cost gap. For example, airlines could commit to buying SAF at a predefined price, or at a price

Exhibit 3

With low renewable costs or regulation, synthetic jet fuel could become cost competitive with fossil jet fuel.

Cost of synthetic-jet-fuel production, $/metric ton, 2019[1]



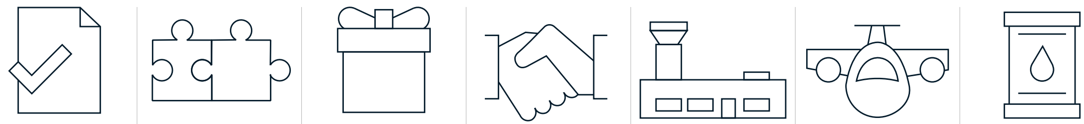
[1] Costs of synthetic fuel produced in a facility built in the corresponding year. 1 metric ton = 2,205 pounds.
[2] Assumed similar to EU diesel tax for road use ($0.50/liter).

Source: Energy Insights by McKinsey

Exhibit 4

How to overcome sustainable aviation fuel's chicken-and-egg problem.

Potential measures for spurring sustainable-aviation-fuel (SAF) production and growth



Policy and regulation	B2B contracts	B2C incentives	Demand and scale	Airports and fee structures	Prioritized aviation	Accelerated R&D
Apply effective policy measures, such as blending mandates (eg, policy in Norway)	Negotiate corporate-customer deals that involve SAF financing	Use airline-loyalty programs to incentivize customers to compensate for CO_2 through SAF	Build clusters of like-minded peers and create large-scale off-take agreements	Involve airports with suitable infrastructure and use fee structures to increase SAF uptake	Accelerate transition to alternative energy sources for road transport to make biofuels available for aviation	Motivate companies, particularly in oil and gas, to increase R&D

Ten questions airline executives should be asking

The coronavirus pandemic has created uncertainty for every industry. Airline executives should be asking themselves ten questions about what the crisis means for decarbonization and the possible responses and actions they can take:

1. Will the industry and its emissions shrink in the long run because of a fundamental shift in travel behavior?

2. Will customers become even more serious about demanding sustainable travel, with growing awareness of climate change?

3. What will governments ask in return for state support?

4. Could the coronavirus crisis lead to further industry consolidation, resulting in larger average aircraft capacity, improved seat-load factors, and improved fuel efficiency?

5. Could the crisis present an opportunity to accelerate fleet replacement or renewal?

6. How much upside is left in fuel-efficiency programs to reduce both cost and carbon emissions?

7. Could the crisis be an opportunity to harmonize air-traffic control and reduce on-the-ground and in-flight delays?

8. What does the demand shock from the coronavirus pandemic mean for CORSIA and "cap and trade" systems, such as the European Union's Emissions Trading System?

9. What will a lasting low kerosene price mean for the economic viability of SAF?

10. Could the industry accelerate innovation—for example, into production of SAF?

differential to traditional jet fuel, which would eliminate market risks for fuel suppliers.

Second, financial institutions could provide venture capital for building SAF-production facilities and new infrastructure that allows for the anticipated cost savings. Building a coalition of airlines could increase the required volume, resulting in scale effects.

Third, airlines could work with B2B customers willing to pay a premium for the opportunity to decarbonize their employees' footprints. Microsoft committed to reducing its environmental footprint by promoting SAF and paying for the cost premium. For individual customers, airlines could use loyalty-program rewards as incentives to offset CO_2 through SAF use.

Fourth, policy makers at domestic and regional levels could play a critical role by creating incentives for SAF production and setting appropriate targets. Countries such as Canada and Norway that are willing to apply blending mandates are moving forward on this front. Policy makers could also reallocate aviation taxes back to the industry to fund decarbonization, closing the remaining cost gap between conventional kerosene and SAF.

The coronavirus pandemic has hit aviation hard. Yet as the industry emerges from this painful period, there is an opportunity to move closer to low-carbon goals.

The aviation industry has made great strides in fuel efficiency and operational advancements. But to reach global emission-reduction targets, it will need to move to the next level of decarbonization, and SAF is an option that could get it there. Bolder moves and much deeper collaboration among stakeholders are necessary to build financial structures and programs that can help funnel capital into SAF production.

Because the aviation industry has such long-lived assets, making decisions now is crucial. Finding solutions that bring the industry in line with global emission goals will help ensure that future generations won't feel the flight shaming of today.

Alex Dichter is a senior partner in McKinsey's London office; **Kimberly Henderson** is a partner in the Washington, DC, office; **Robin Riedel** is a partner in the San Francisco office; and **Daniel Riefer** is an associate partner in the Munich office.

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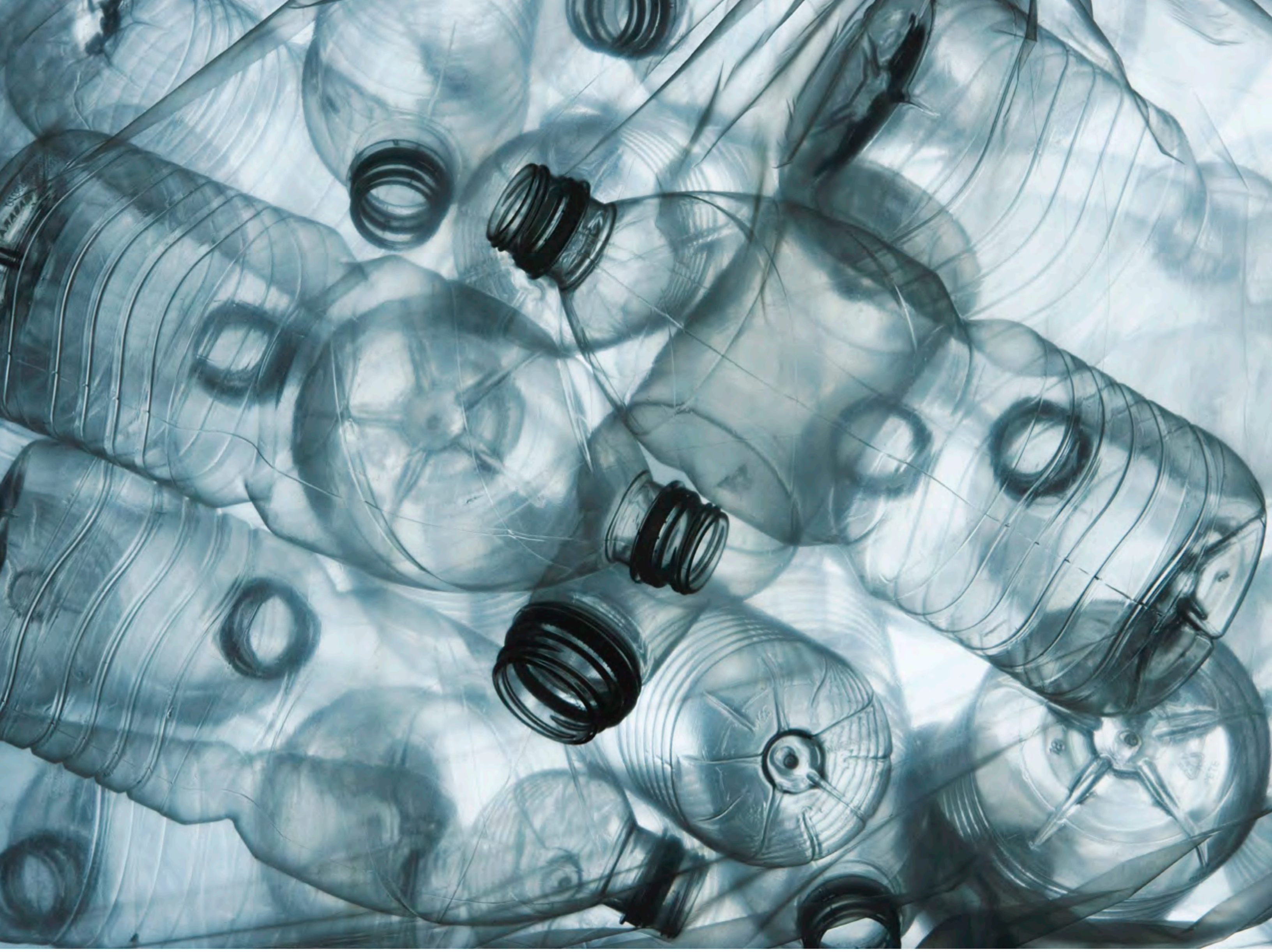

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Plastics recycling: Using an economic-feasibility lens to select the next moves

The Plastics Recovery and Reuse model helps identify the most effective moves to boost plastics recycling, using analysis of fully integrated economics across the value chain.

by Wenting Gao, Thomas Hundertmark, Theo Jan Simons, Jeremy Wallach, and Christof Witte

The worldwide crisis of plastics-waste pollution is leading to calls for action from a wide range of stakeholders, from consumers to regulators to brand owners to plastics producers. The desire to see action is easy to understand, but identifying the most effective approaches to current waste problems—and those of the future—represents a complex challenge spanning the entire plastics value chain.

The elements that could provide the foundations of a successful recycling system—a circular economy for plastics—are well recognized. The first is to design or redesign plastic products to be recyclable. Next is putting in place effective systems to recover end-of-life plastics. The third element is to reuse the recovered plastics by recycling them, turning them into new products that will create value. Our recent research has shown substantial value-creation potential in capturing plastic waste and using existing technologies to process it to make new plastics and other chemicals.[1] To date, however, investments to translate this potential into reality have been relatively small. Globally, only around 15 percent of plastics produced each year get recycled.

What explains that paradox? The contributing factors to the plastics-waste problem are complex and include issues ranging from consumer choice to food-supply safety to entrenched manufacturing systems. Not least is plastics' seemingly inexhaustible potential to meet consumer demands more cost effectively than other materials, especially in packaging.[2] This has fueled plastics' strong growth trajectory, averaging 6 percent per year since 1965. But it has also allowed the use of plastics to get well ahead of society's ability to handle waste-plastic volumes, despite the clear potential for economically viable ways to reuse the material.

The need for a way to sort through the options

This is not the kind of challenge that will be solved with a single stroke. A wide range of approaches tailored to the recycling needs of different plastics, applications, and regional waste-management systems will be necessary. And while plastics waste has become a particularly acute environmental problem in geographies where waste is largely unmanaged, our research shows that implementing these approaches in developed markets has the potential to improve recycling rates there too.[3]

But the large number of possible approaches—and the difficulty in evaluating the options—is likely contributing to the slow progress. It's been challenging to identify what would make a circular economy for plastics economically feasible, not least because of the different economics of recycled plastics and virgin resins. Nor has there been a fully integrated value-creation assessment of these elements across each of the thousands of different resins, applications, and geographical combinations.

Our research shows that the current fragmentation of the value chain and the regional nature of waste-management systems represent a further barrier to progress. This is holding back dialogue among potential value-chain partners about what needs to be fixed to speed the development of a circular economy for plastics and about trying out different approaches to achieve higher-value-creating

[1] 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; Thomas Hundertmark, Chris McNally, Theo Jan Simons, and Helga Vanthournout, "No time to waste: What plastics recycling could offer," September 2018, McKinsey.com.
[2] Peter Berg, David Feber, Anna Granskog, Daniel Nordigården, and Suku Ponkshe, "The drive toward sustainability in packaging—beyond the quick wins," January 2020, McKinsey.com
[3] Thomas Hundertmark, Manuel Prieto, Andrew Ryba, Theo Jan Simons, and Jeremy Wallach, "Accelerating plastic recovery in the United States," December 2019, McKinsey.com.

outcomes. Uncertainty continues about future regulations—for example, CO_2 taxation—while overly simplistic proposals for solving the plastics-waste problem continue to circulate, confusing the issue even further.

Building a granular and integrated understanding of the challenge

In response to these challenges, we have developed the first fact-based economic-feasibility perspective on the potential for recovery and reuse across the full plastics value chain.[4]

As part of our research, we investigated more than 1,000 combinations of used resins, applications, and geographies to estimate the costs of recovery and reuse for each. These have been incorporated into our Plastics Recovery and Reuse model. The analysis is based on current "as is" economics to provide a sound basis for capital-investment decisions (see sidebar, "Understanding the Plastics Recovery and Reuse model").

The model reflects nearly all the complexity of the plastics-waste universe and identifies the approaches that will create the most value. How the recycling economics compare for resins in different applications and in different geographies can be shown in a cost curve (Exhibit 1).[5]

An important capability of the model is that it can provide guidance on future steps. For example, by making transparent the value-creating potential of the many different combinations of resin, application, recovery systems, and geography, this analysis can help guide policy makers as they develop regulation to encourage plastics reuse.

At the same time, players across the value chain will likely benefit from moving up the learning curve as the plastics-recycling industry gains momentum—and as plastics-recycling systems and their costs evolve. The model has therefore been designed to have a high degree of flexibility so it can incorporate a range of target costs, as well as assumptions about how debottlenecking and efficiencies derived from continuous operational improvements could reduce costs. It can also be used to help reimagine process flows and work with a range of unit costs to inform decisions on future investments best.

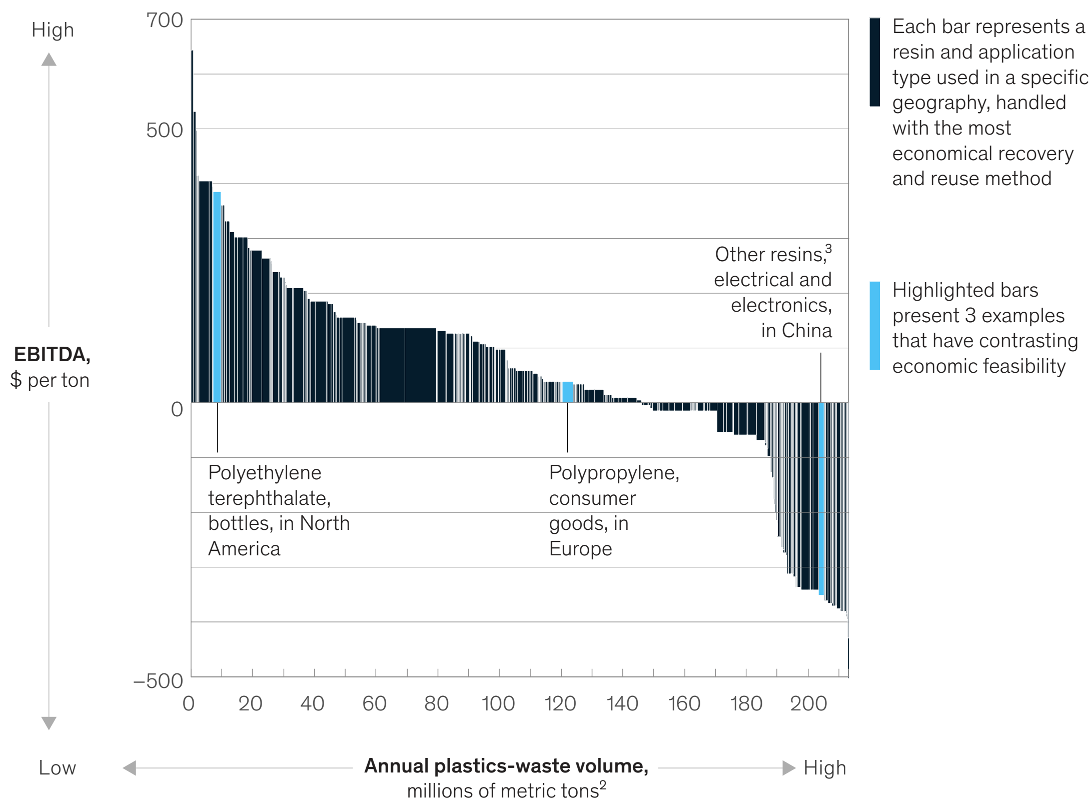
[4] The model is built to show the economics of a system under a single owner, with an integrated end-to-end cost structure. This approach makes it possible to identify the total margin pool available that could be distributed among the different participants.
[5] The curve covers the plastics-waste volumes that can realistically be collected today and assumes that a certain volume will be "lost," particularly in economies at an early stage of development in their waste-management systems and those in which informal collection systems represent a large share. We have considered in our modeling a volume of approximately 210 million metric tons per year out of a total of 270 million metric tons per year of plastics waste (one metric ton equals 2,205 pounds). This volume represents waste volumes that currently go to landfill/incineration after collection and sorting.

Players across the value chain will likely benefit from moving up the learning curve as the plastics-recycling industry gains momentum

Exhibit 1

The Plastics Recovery and Reuse model's cost curve ranks the economic feasibility of recycling initiatives at a highly granular level, across geographies.

EBITDA of waste volumes to recovery and reuse[1]



[1] EBITDA: earnings before interest, taxes, depreciation, and amortization. EBITDA of waste volumes to recover and reuse, including full system-operating-expenditure costs (eg, collection, sorting, reprocessing) and revenue from sales of core projects and byproducts (eg, fuel, energy, monomer, polymer). The calculations are based on an oil price of $60/barrel, and all other costs are taken as of Nov 25, 2019. The chart only includes volumes that currently go to landfill/incineration after collecting and sorting.
[2] Metric tons: 1 metric ton = 2,205 pounds.
[3] Plastics categorized as "other" under the Resin Identification Code and indicated as "7" (ie, the category that covers ABS, polyamide, polycarbonate, rubbers, and all other resins not covered by the six major resin families).

Understanding the Plastics Recovery and Reuse model

Plastics waste is a global problem, but the waste is generated locally, and dealing with the problem will require granular, local-level solutions. The research behind our Plastics Recovery and Reuse model is based on detailed analysis and modeling of plastic usage and waste flows, and of their economics across four dimensions: resin, application, geography, and recovery and reuse route. Each of the dimensions is built up from its detailed components (exhibit).

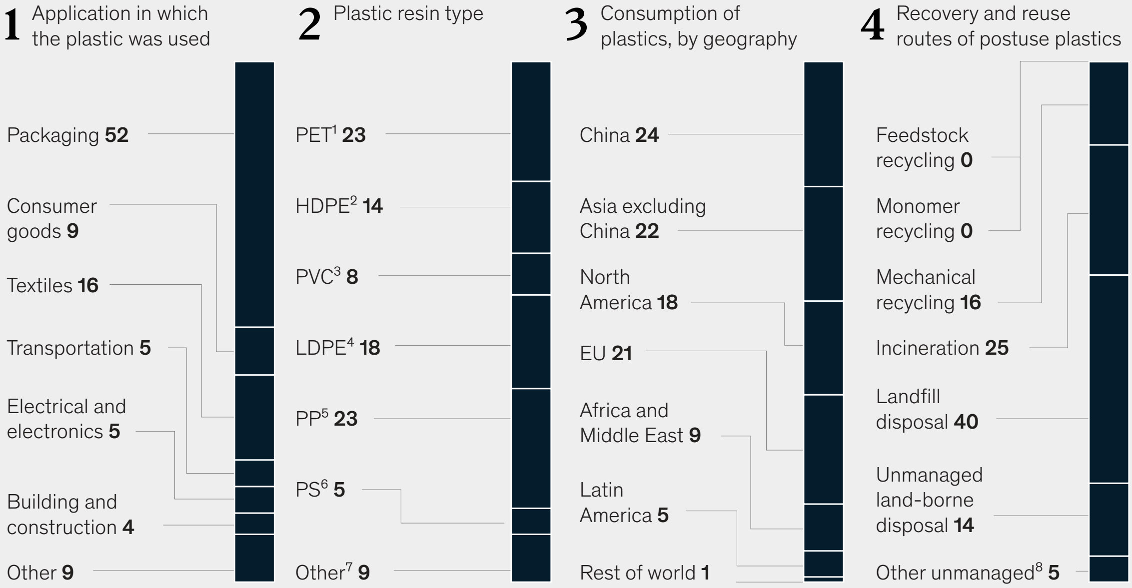
The seven components for the resin dimension cover the major-volume resins—polyethylene terephthalate (PET), polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), and polyvinyl chloride (PVC)—with a final category covering acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), polyamides (PA), and the large-volume synthetic rubbers. For the applications dimension, we included 86 applications based on the following categories: building and construction, consumer goods, textiles, transportation, electrical and electronic systems, and multiple types of packaging (including bottles, caps and closures, packaging for food, flexible packaging, industrial packaging, and miscellaneous other packaging).

The seven geographies covered are Africa and the Middle East, Asia excluding China, China, the European Union, Latin America, North America, and the rest of the world. For the recovery and reuse dimension, we modeled seven routes to provide a comprehensive picture of the options now in play. Five of these represent managed approaches—mechanical recycling, monomer recycling, feedstock recycling (with the pyrolysis process frequently referenced), incineration, and landfill disposal—and two represent unmanaged waste flows—unmanaged land-borne disposal and other unmanaged volumes, including leakage to marine biosystems.

Exhibit

The model incorporates analysis of global plastics flows across four dimensions—applications, resins, geography, and recovery and reuse route.

4 dimensions of global postuse plastics flows, state of play in 2018, %

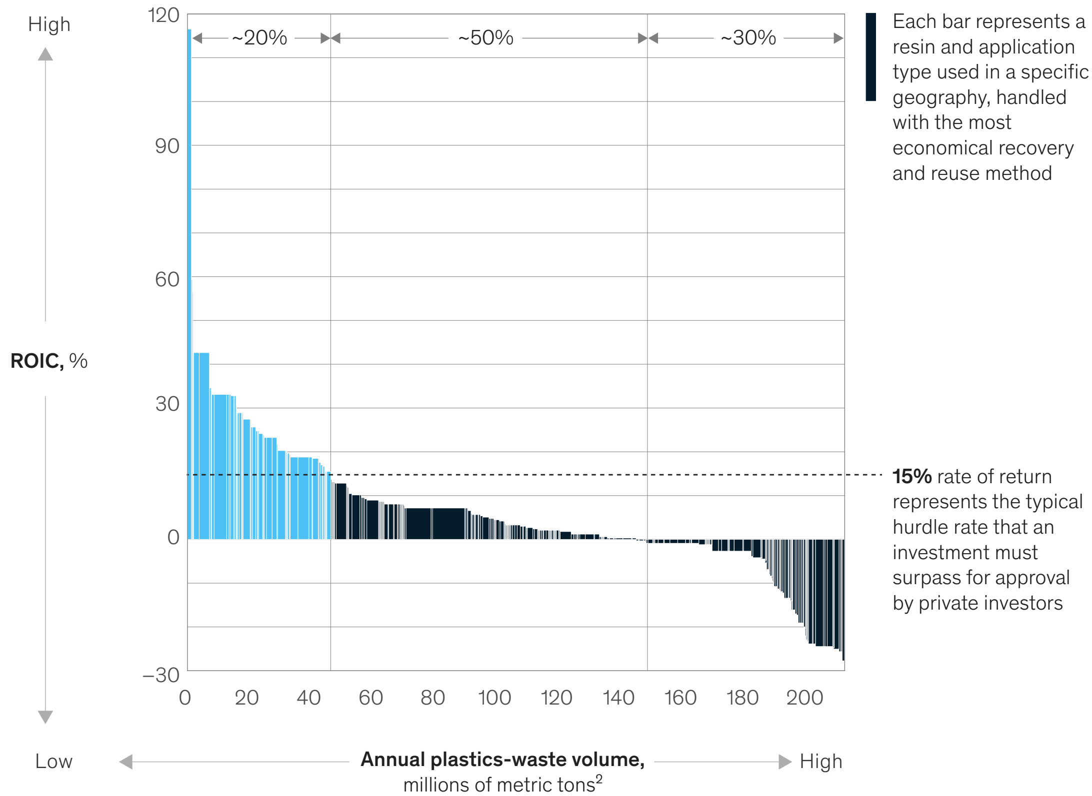


[1] Polyethylene terephthalate. [2] High-density polyethylene. [3] Polyvinyl chloride. [4] Low-density polyethylene. [5] Polypropylene. [6] Polystyrene. [7] Plastics categorized as "other" under the Resin Identification Code and indicated as "7" (ie, the category that covers ABS, epoxy resins, polyamide/nylon, polycarbonate, PMMA, EVA, SAN, and other resins not covered by the six major resin families). [8] Other unmanaged volumes, including leakage to marine biosystems.

Exhibit 2

Recovery and reuse opportunities with high enough return on invested capital to cover investment hurdles represent about one-fifth of plastics-waste volume.

Simplified ROIC of waste volumes to recovery and reuse[1]



[1] ROIC: return on invested capital. Simplified ROIC (based on calculation of earnings before interest, taxes, depreciation, and amortization divided by capital expenditures) of waste volumes to recovery and reuse, including full system cost and revenues (ie, operating and capital costs of collection, sorting, and
reprocessing and revenue from sales of core products and byproducts, including fuel, energy, monomer, and polymer). The chart only includes volumes that currently go to landfill/incineration after collection and sorting.
[2] Metric tons: 1 metric ton = 2,205 pounds.

These kinds of capabilities should help facilitate the new discussions that value-chain partners need to have about how they could adjust requirements and specifications to improve the economic feasibility of different segments of plastics recovery and reuse activity—and help get past the fragmentation and lack of dialogue that holds back the industry now.

Showing how the recovery and reuse options compare

If we add in capital costs as well as operating costs, our analysis shows that, at an oil price of $60 per barrel, only a limited number of plastics-recycling opportunities are currently value creating in themselves. We define “value-creating opportunities" as those that provide a positive return on the capital invested in all three elements (collection, handling, and processing) at a level sufficient to satisfy what private investors typically seek. These kinds of value-creating initiatives account for only around 20 percent of volumes (Exhibit 2). The analysis also suggests that, for many combinations, the initial capital investment required creates a major disincentive to potential investors.

The majority of plastics-recycling activities are in the middle, where recovery and reuse generate positive earnings before interest, taxes, depreciation, and amortization but do not create value. This category accounts for around 50 percent of cases. Investors are in effect showing good sense by not investing yet in these plastics-recycling initiatives.

The final category—around 30 percent of volumes—consists of a range of resins and applications that do not offer attractive economics for recycling or reuse under most market conditions. This is because of factors such as that the capture of the used materials and their reprocessing are prohibitively expensive.

What can be done to improve these applications' recycling economics? Combining the efforts of the recycling and petrochemical industries is still at an early stage on the learning curve, and simply gaining scale could significantly improve the overall economics.

More cost-effective collection systems could help, and there could be scope to redesign products in this category to improve their recyclability—for example, through making them out of different resins when possible. But there are also applications for which the cost incurred in recycling, with no possibility of earning a profitable return, could be deemed acceptable because the plastic used there simply does the most economical, as well as the most carbon-efficient, job. The model can make these additional factors transparent and include them in the integrated economics.

Identifying the major hurdles to progress and ways to overcome them

The Plastics Recovery and Reuse model can be used in a number of ways, including assessments of economic viability on regional, resin, and application bases. It can also identify the main bottlenecks to economically feasible recovery and reuse, such as a lack of economically attractive recycling capacity. The model is flexible; it can accommodate a wide variety of real-world situations—for example, an analysis of municipal-waste streams with a broad mix of resins and applications. In this way, it can provide a detailed and powerful approach to understanding the status quo and to simulating future scenarios, such as the removal of specific resins or applications.

Combining the efforts of the recycling and petrochemical industries is still at an early stage on the learning curve, and simply gaining scale could significantly improve the overall economics.

For investors within the value chain or infrastructure investors, the model can show how different oil-price scenarios and petrochemical-cycle phases are likely to affect the economics of plastics reuse and recycling so that ventures can be made resilient to shifts in economic conditions. For regulators, the cost curve can help guide policy decisions that improve the economic feasibility of plastics-recovery and-reuse systems across municipalities, regions, and countries.

Resolving the plastics-waste problem is a complex challenge that will require choosing from the large number of possible approaches and tailoring them to the recycling needs of different plastics, applications, and regional waste management systems. But despite evidence that recovering and reusing plastics waste could generate substantial value, investments have been held back by a lack of clarity about the economic feasibility of the various approaches. Bringing an economic-feasibility lens to bear on the possible approaches can guide choices about which moves to prioritize, opening the way to investments that can help resolve the challenge worldwide.

Wenting Gao is a consultant in McKinsey's Houston office, where **Thomas Hundertmark** is a senior partner; **Theo Jan Simons** is a partner in the Cologne office; **Jeremy Wallach** is a partner in the Boston office; and **Christof Witte** is a consultant in the Berlin office.

The authors wish to thank Mikhail Kirilyuk, Mirjam Mayer, Andrew Ryba, and Marie Seeger for their contributions to this article.

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The European recycling landscape—the quiet before the storm?

Before plastics recycling in Europe can scale up, the industry needs to overcome sizable obstacles. Our survey helps illustrate what companies can do to achieve their aspirations.

by Mikhail Kirilyuk, Mirjam Mayer, Theo Jan Simons, and Christof Witte

Plastics recycling in Europe is expected to grow significantly in the next five to ten years, particularly in response to increased pressure from regulators and consumers. Governments and major brands are continuously discussing and refining targets to reduce waste and improve the circularity of the plastics value chain. And while players in the chemicals industry aspire to expand access to recycling, adopt new technologies, and grow sustainability efforts, many existing European recyclers that have pursued these goals for years have made little progress.

To better understand the reasons why—and to assess the readiness of the EU recycling industry to accommodate the necessary scale-up—we conducted interviews with 57 recycling companies in 12 European countries (see sidebar "About the survey").[1] Our findings confirm our hypotheses: despite positive boundary conditions, plastics recycling is not (yet) thriving as an industry; and many recyclers struggle to overcome a lack of product standardization, volatile customer demand, and inefficient sortation processes. These challenges have been exacerbated by the COVID-19 pandemic, which has introduced both short-term liquidity challenges and the potential for additional regulations.

This article provides context for the current state of Europe's recycling industry as well as our perspectives on how it can overcome its hurdles and increase levels of plastics recycling. On this point, we offer four recommendations that could help the segment realize its potential.

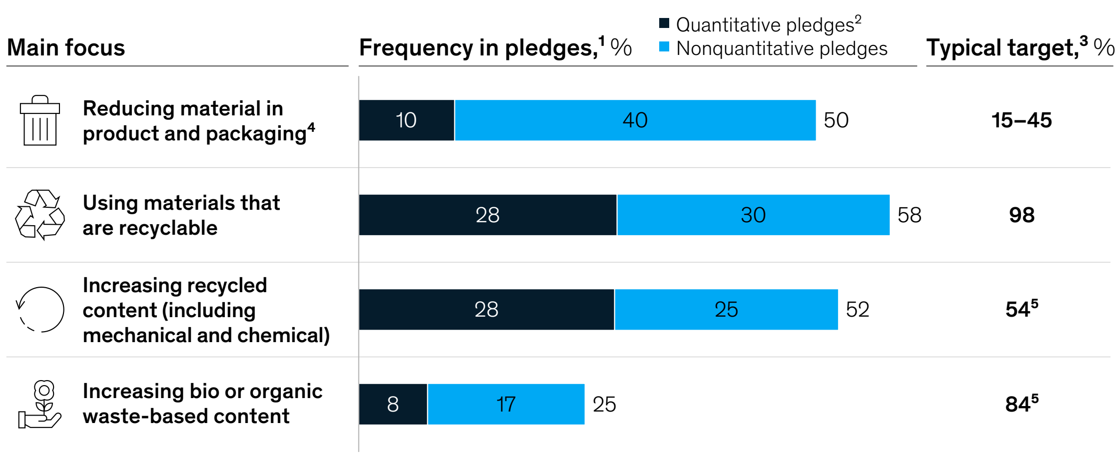
The European recycling industry today

In 2017, the European Union set a target for recycling 50 percent of plastic packaging by 2025 and 55 percent by 2030.[2] Brand owners across a variety of industries have also pledged to improve plastics usage and recycling through four main areas of focus, some committing to bold quantitative targets during this same period (Exhibit 1).[3]

[1] For more on plastics recycling in the United States, see Thomas Hundertmark, Manuel Prieto, Andrew Ryba, Theo Jan Simons, and Jeremy Wallach, "Accelerating plastic recovery in the United States," December 20, 2019, McKinsey.com.
[2] "Questions & Answers: A European strategy for plastics," European Commission, January 16, 2018, ec.europa.eu.
[3] For more on plastics wastes recycling and chemicals, see Thomas Hundertmark, Mirjam Mayer, Chris McNally, Theo Jan Simons, and Christof Witte, "How plastics waste recycling could transform the chemical industry," December 12, 2018, McKinsey.com.

Exhibit 1

Most brand owners have announced plans to increase plastics recycling, while only a few have committed to quantitative targets by 2025–30.



[1] By companies across 14 consumer segments; n = 252.
[2] Commitments associated with a defined numerical target and timeline.
[3] Mean quantitative target of quantitative pledges across broad sample.
[4] Determining typical reduction targets is complicated by the fact that many companies provide absolute volumes or different base years, or seek to eliminate specific applications or resins.
[5] Mean for recycled and renewable content slightly inflated, as pledges for 100% recycled or renewable content were counted as 100% for each category.

About the survey

We interviewed representatives from 57 companies across 12 countries in Europe, representing 20 to 30 percent of installed mechanical recycling capacity (around 2.6 million tons per year across all major resins). An analysis of publicly available data from a broader sample set of 358 European recycling companies in 22 countries validated several parameters, including relative company size (median of 30 thousand tons per year), business tenure (median of 29 years), and the primary resin types that were processed (a majority process polyolefins, the most common type of polymer).

For example, Unilever announced it will use at least 25 percent of recycled plastic in its packaging by 2025,[4] by which time Coca-Cola aims to source 50 percent of its plastic bottles from recycled content.[5] These efforts are representative of significant tailwinds to increase recycling and improve recyclers' business performance.

An overview of European plastics recyclers

The European plastics recycling industry began long before the current targets were defined and was, from the start, a vital part of valorizing plastics waste, providing economically attractive alternatives to virgin plastics for selected, primarily lower-value applications, such as flower pots. Among our sample of 57 European recyclers, a large majority have been in the business for decades. Of these companies, 47 percent are considered small (capacity of up to ten kta[6]), 25 percent are medium size (ten to 50 kta), and 28 percent are large (more than 50 kta). Overall, these operations are of modest scale compared with producers of virgin plastics or the capacity of large packaging companies. Most European recyclers in our sample process polyolefins, but many other resins are also recycled in Europe today (Exhibit 2).

While most public attention focuses on plastics waste discarded by consumers, most European recyclers in our sample, surprisingly, collect plastics waste from industrial sources—primarily the automotive, construction, agriculture, and industrial packaging industries. Often, the collection and supply of these raw materials is based on self-negotiated agreements or preexisting relationships—for example, recyclers rely on clients or other industrial partners. Sixty percent of companies use industrial plastic waste as input material, while only 16 percent rely exclusively on municipal solid waste (MSW), and the remainder uses both industrial and MSW sources (Exhibit 3).

Recyclers' dependence on industrial sources suggests that the flow from MSW (the largest stream of plastic waste) to the recycling industry is not yet working well.[7] A range of reasons could help explain why this might be the case, including lower feedstock quality or higher contamination compared to industrial plastic waste, as well as existing alternative waste treatment routes with less complexity, such as waste-to-energy or incineration.

A future for chemical recycling?

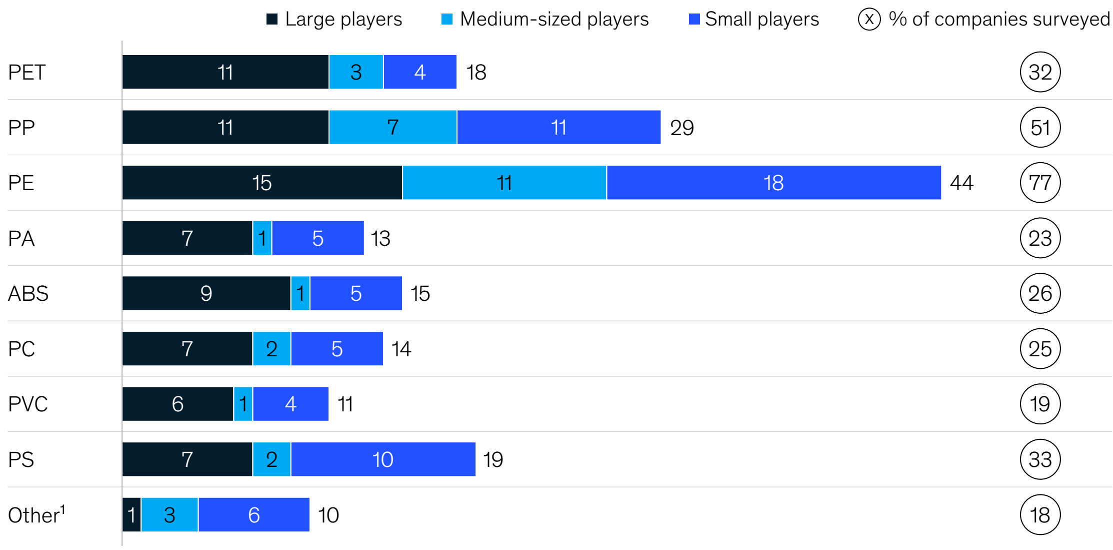
Our survey focused on companies that practice mechanical recycling, which leaves polymer chains intact, as it is the most established method to process raw materials. However, recent years have seen a surge of interest in chemical-recycling technologies, which break plastic polymers down either to their building blocks (monomerization) or to

[4] "Waste & packaging," Unilever, unilever.com.
[5] "Coca-cola sets ambitious new sustainable packaging goals for Western Europe," Coca-Cola EU dialogue, coca-cola.eu.
[6] Kta refers to thousand tons per year.
[7] For more, see Thomas Hundertmark, Chris McNally, Theo Jan Simons, and Helga Vanthournout, "No time to waste: What plastics recycling could offer," September 21, 2018, McKinsey.com.

Exhibit 2

Polyolefins are the most-commonly handled plastic resins.

Number of companies processing specific plastic resins, (n = 57)

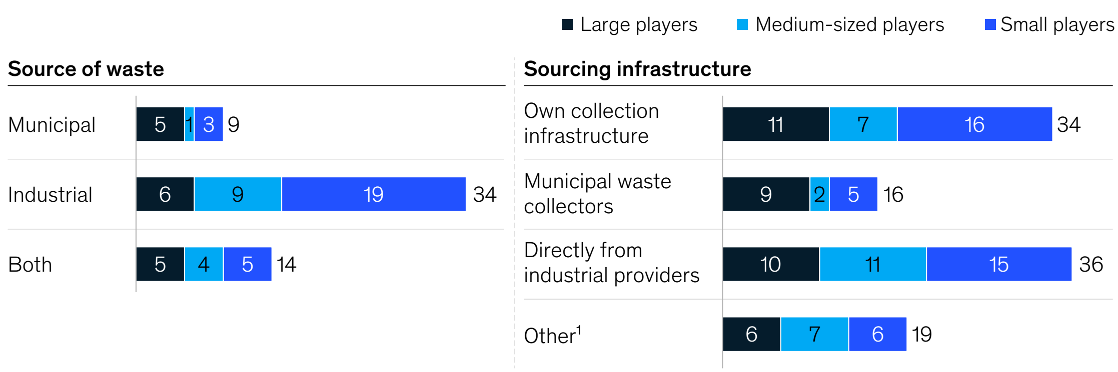


[1]Includes PMMA, PPS, PTA, PTFE, PO copolymers, PPMA, and combination plastics.

Exhibit 3

Plastics waste is typically sourced from industrial waste rather than municipal solid waste.

Number of companies, (n = 57)



[1]Includes parent company, waste-selection platforms, collection centers, external service providers, client-run collection schemes, junkyards, direct delivery, and mobile recycling.

a mix of cracked liquid polymers (pyrolysis). These substances can then be processed in refining or petrochemical plants and converted to new plastic resins or other petrochemical products, such as fuels. Chemical recycling can also prove useful as an outlet for low-quality plastic waste that cannot be mechanically processed.

One-quarter of the surveyed mechanical recyclers consider chemical recycling as potential competition for raw materials, while 35 percent view chemical-recycling technologies as adjacent players or potential partners that can complement the recycling landscape. Another 23 percent see chemical recycling as an interesting area for business growth, but a majority remains skeptical of its ecological footprint and economic viability, especially in the short to medium term. Indeed, chemical-recycling technologies are still nascent and have only recently been pursued at commercial scale.

Challenges for the European recycling industry

While some companies indicated promising growth over the past five years, more than half stated that their business had grown at a rate below GDP, stagnated, or even shrunk. Thus, significant challenges limit any tailwinds, resulting in a lack of perceptible uplift to recyclers' businesses—a scenario that has only intensified amid the COVID-19 pandemic. With this in mind, we followed up with a subset of companies from our original survey and interviewed them on their perspectives (see sidebar "The impact of COVID-19 on recycling").

The impact of COVID-19 on recycling

An additional survey conducted in April 2020 largely supports our perspectives and recommendations, even as the pandemic has continued to unfold.

While 80 percent of representatives interviewed the second time felt affected by the COVID-19 crisis, the magnitude varied considerably by individual businesses. Sixty percent of recyclers interviewed said business slowed because of the crisis but was not threatened in the long term, while 33 percent felt it was on hold or in danger. A majority (73 percent) saw a decline in demand, while supply issues (20 percent) or price drops (33 percent) were less of a concern overall.

Surprisingly, recyclers seemed less concerned about the secondary effects of the crisis, such as the recent drop in the price of oil. Even though oil prices substantially affect the recycling industry (via cheaper virgin plastics), less than half of interviewees (47 percent) were concerned about them—though respondents also indicated that it might be too early to tell. In other words, negative effects could materialize later and would mostly be associated with declining prices resulting from cheaper virgin plastics.

Furthermore, 67 percent of respondents expected their operations to go back to normal in the medium term, and the biggest crisis-induced challenges were perceived to be business uncertainty (27 percent), additional regulations, and short-term liquidity. Pre-crisis challenges related to end-industry dynamics, demand volatility (especially in the automotive sector), and competition were felt to be exacerbated, but not induced, by the current crisis. And technological challenges continued to be top of mind but were considered largely unrelated to the pandemic.

Overall, recyclers do not expect any long-lasting negative effects on circularity. In fact, 87 percent of companies interviewed do not expect consumers and customers to de-emphasize sustainable products or recycled content due to either the crisis or a looming recession.

The top two challenges named by respondents—before the pandemic but also persisting through the crisis—are unstandardized and poor product recyclability and the volatility of markets and customer demands (Exhibit 4).

Compelling meaningful change requires investment by both the recyclers themselves and other entities—which begs the question of how to improve overall business attractiveness. When companies were asked which factors could improve the attractiveness of the recycling business, the top answer was government incentives, such as mandates for recycled content, followed by public awareness and a shift in mindset to increase the acceptance of recycled material and remove any stigma associated with waste as a raw material. A further important requirement is competitive pricing with virgin plastics—for example, through taxes levied on virgin materials or subsidies for the use of recyclates.

Meeting the European aspiration for a step change in recycling

Equipped with a deeper understanding of the European recycling industry's current reality, our study also yielded several recommendations that, when effectively implemented, could support the industry in achieving its collective growth aspirations.

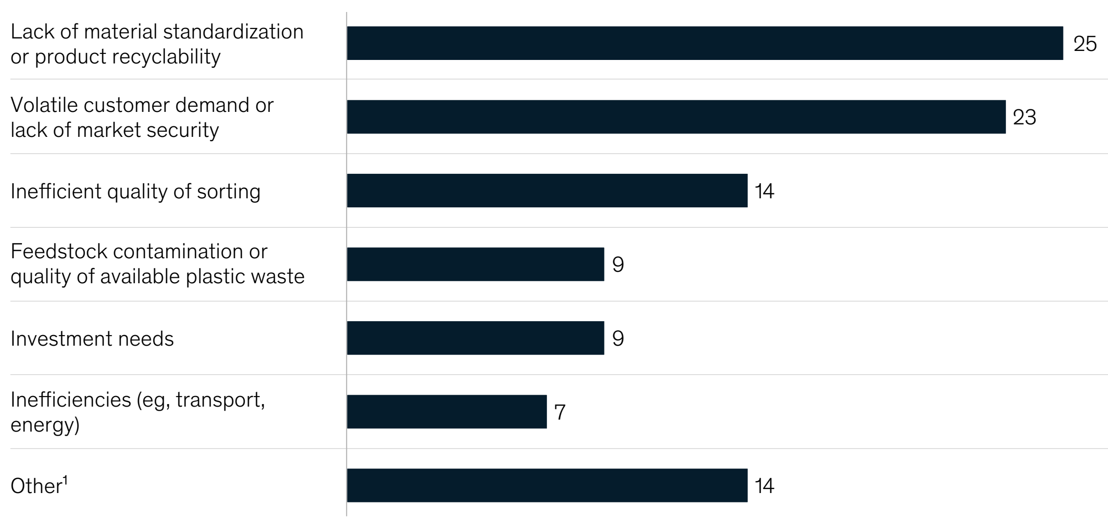
Improve the quality and availability of feedstock for recycling. Specifically, recyclers can establish a more effective way to recover plastic from MSW. This will require a combination of better collection and sorting, the use of standardized materials (such as flexible or rigid packaging), and improved product designs to facilitate recyclability.

Several approaches can help promote the use of standardized materials. One is packaging differentiation, which allows consumers to identify resin types more easily. Another is furthering the

Exhibit 4

Respondents see significant challenges to improving plastics recycling.

Current hurdles to the recycling business, % answers provided



[1]Includes competition with players in low-cost regions, bidding process, etc.

use of flexible packaging in the circular economy—which is the goal of CEFLEX, a collaborative initiative of companies and associations in Europe. Both approaches have the shared objective of harmonizing design to increase the recyclability of materials. In addition, as changing regulations may eventually require such efforts anyway, standardizing materials in the short term will likely save money in the long term (and avoid last-minute scrambles).

Target incentives to enable closed-loop recycling. Today, most recyclers practice open-loop recycling, as closed-loop systems are not yet economically feasible. That may change, however, as customers' attitudes continue evolving and new regulations take effect. The best incentive for companies to use recycled materials in their products might be from a reputational standpoint, rather than through increased regulation.

Regulators can draw from a variety of mechanisms to foster recycling, such as deposit refund systems, extended producer-responsibility schemes, recycling mandates, separate collection infrastructure, and levies or subsidies. In addition, extending appropriate incentives to increase the number of resin types recycled and their application both in the packaging and in the industrial realm could significantly increase the supply of high-quality plastic waste for mechanical recycling.

Make the industry economically more attractive and investable. We know that each step of the recycling chain must be improved, particularly collection and sorting. Economically speaking, for recyclers, the best way to improve collection is for consumers to separate their plastic waste from other forms of waste and to separate within types of plastics; empowering the consumer to reduce contamination and mixing can essentially pay for itself. In addition, investing in technologies such as AI and higher-quality washing systems can incrementally improve sorting and the quality of recycled materials, making them more competitive with virgin plastics.

Create a common marketplace for feedstock and products. One idea to help unlock the segment's potential and address the challenge of poor market liquidity is creating a common marketplace for both raw materials and recyclates, thereby creating more liquidity and providing more supply and demand security for recyclers and their customers. The voluntary commitments submitted to the Circular Plastics Alliance in the European Union provide a first attempt at creating more transparency, but their first assessment published

The best incentive for companies to use recycled materials in their products might be from a reputational standpoint, rather than through increased regulation.

in 2019 illustrates the gap between committed supply and demand and falls significantly short of formulated ambitions by stakeholders along the entire value chain, highlighting the need for more actionable mechanisms.

While some uncertainty remains around how to scale plastics recycling, the pressure to adapt to sustainability and ever-evolving customer expectations is here to stay. Brand owners, recyclers, and players in chemicals each have a role to play. Those that respond quickly and decisively will drastically increase their chances of remaining competitive in the years to come.

Mikhail Kirilyuk is a knowledge expert in McKinsey's Moscow office, **Mirjam Mayer** is an alumna of the Vienna office, **Theo Jan Simons** is a partner in the Cologne office, and **Christof Witte** is an associate partner in the Berlin office.

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McKinsey Electric Vehicle Index: Europe cushions a global plunge in EV sales

McKinsey's recent analysis of global electric-vehicle markets shows both challenges and opportunities ahead.

This article was written collaboratively by members of McKinsey's Automotive and Assembly Practice: Thomas Gersdorf, Patrick Hertzke, Patrick Schaufuss, and Stephanie Schenk.

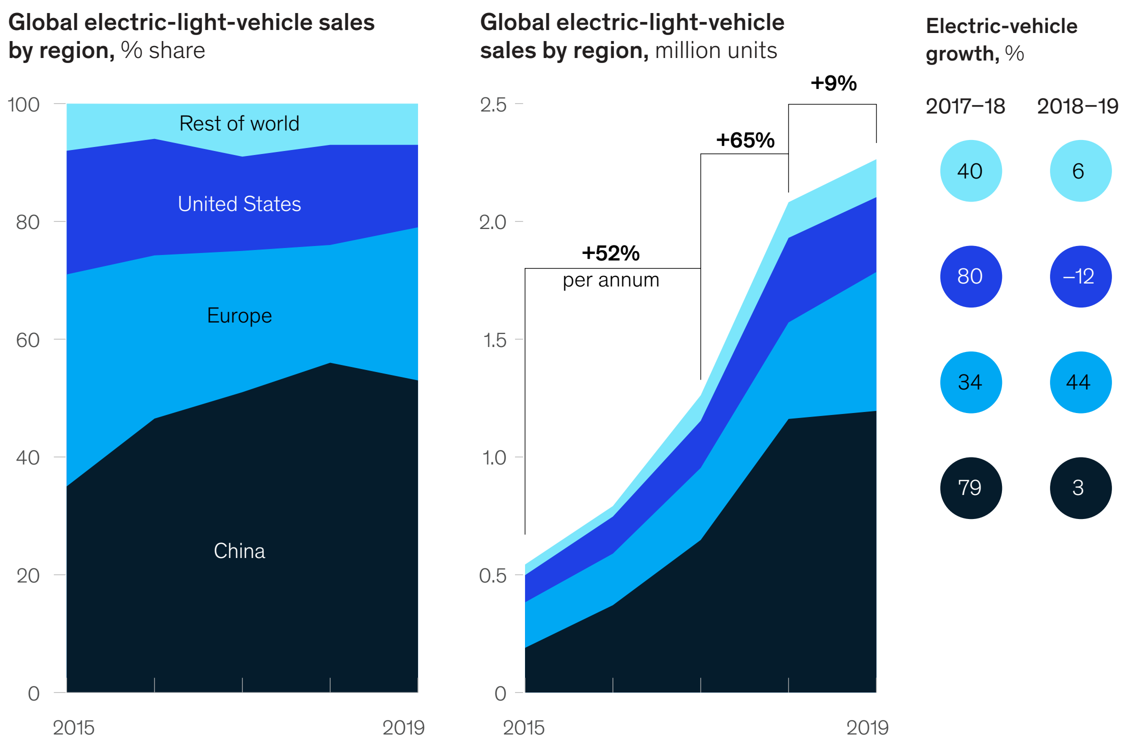
McKinsey's proprietary Electric Vehicle Index (EVI) assesses the dynamics of the e-mobility market in 15 key countries worldwide (for more information on the metrics evaluated, see sidebar "What is the Electric Vehicle Index?"). EVI results for 2019 and the first quarter of 2020 provide important insights about market growth, regional demand patterns, market share for major electric-vehicle (EV) manufacturers, and supply-chain trends.

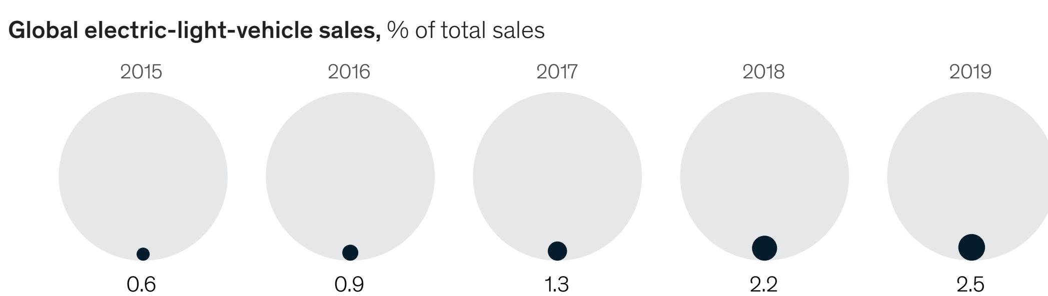
Growth in the electric-vehicle market has slowed

EV sales rose 65 percent from 2017 to 2018 (Exhibit 1). But in 2019, the number of units sold increased only to 2.3 million, from 2.1 million, for year-on-year growth of just 9 percent. Equally sobering, EV sales declined by 25 percent during the first quarter of 2020. The days of rapid expansion have ceased—or at least paused temporarily. Overall, Europe has seen the strongest growth in EVs.

Exhibit 1

In contrast to a slowdown of EV sales globally in 2019 and in the first quarter of 2020, Europe expanded its market share to 26 percent, growing by 44 percent.





Source: Ev-volumes.com; Light Vehicle Sales Forecast, May 2020, IHS Markit

What is the Electric Vehicle Index?

McKinsey's proprietary Electric Vehicle Index (EVI) focuses on battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Since we created the EVI, several years ago, it has given organizations in the automotive, mobility, and energy sectors a detailed view of the electric-vehicle (EV) market, while highlighting potential future trends.

The EVI explores two important dimensions of electric mobility:

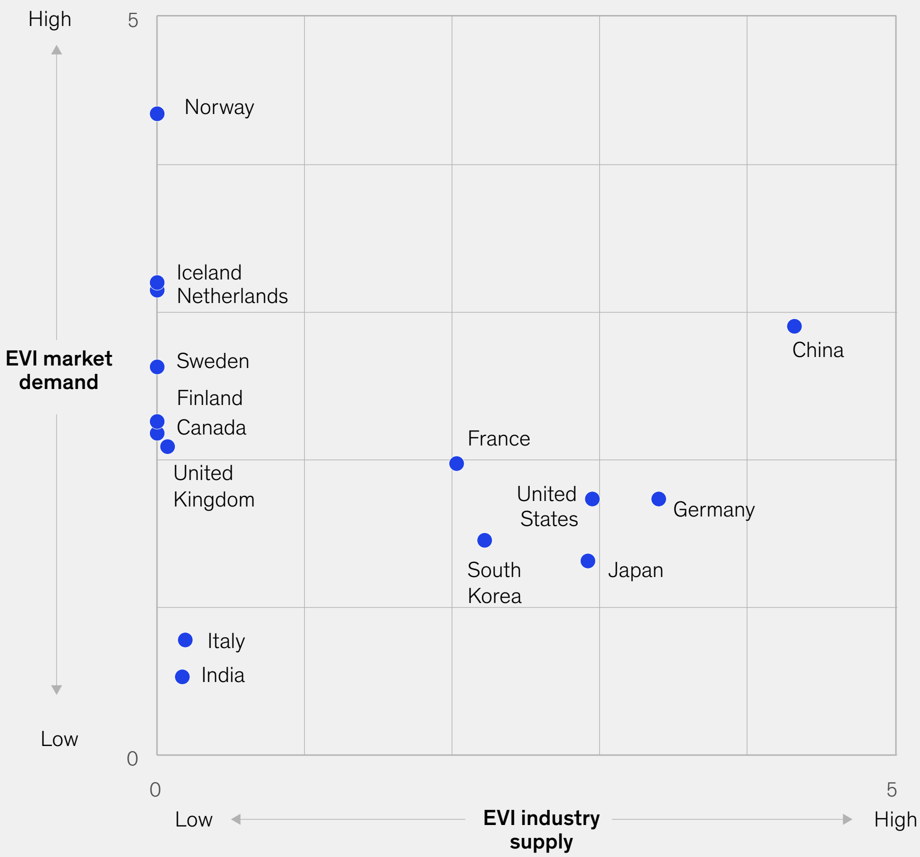
1. *Market demand* analyzes the share of EVs in the overall market, as well as factors affecting EV penetration in each country, such as incentives (for instance, subsidies), existing infrastructure, and the range of available EVs.
2. *Industry supply* explores the share of a country's OEMs in the production of EVs and EV components, such as e-motors and batteries, looking at both current and projected numbers.

The EVI assesses the key performance indicators in each country and rates them on a scale from 0 to 5 for every dimension. These scores serve as the basis for the final country ranking (exhibit).

Exhibit

The Electric Vehicle Index for 2020 shows that Nordic countries lead for market demand, while China and Germany dominate industry supply.

Overall Electric Vehicle Index (EVI) results, score (range from low of 0 to high of 5)



Market ranking
1 Norway
2 Iceland
3 Netherlands
4 China
5 Sweden
6 Finland
7 Canada
8 United Kingdom
9 France
10 United States
11 Germany
12 South Korea
13 Japan
14 Italy
15 India

Industry ranking
1 China
2 Germany
3 United States
4 Japan
5 South Korea
6 France
7 Italy
8 India
9 United Kingdom

Source: McKinsey Center for Future Mobility

Although these developments are disappointing, they largely reflect the decline of the overall light-vehicle market, which fell by 5 percent in 2019 and by an additional 29 percent in first-quarter 2020. Despite the overall drop in sales, global EV market penetration increased by 0.3 percentage points from 2018 to 2019, for a total share of 2.5 percent. With additional growth in the first quarter of 2020, EV penetration is now at 2.8 percent.

To gain different perspectives on the EV industry's growth and other topics, we interviewed various McKinsey experts (see sidebar, "Expert views on the electric-vehicle sector's future development"). The remainder of this section explores regional market variations.

Expert views on the electric-vehicle sector's future development

How will the global electric-vehicle (EV) market develop over the short to mid term? Many uncertainties persist, so we asked some McKinsey experts about their views on pressing issues.

China's declining EV sales, resulting from the government's subsidy cuts, raise concerns about the sustainability of customer demand in the country. How will sales develop, especially considering the COVID-19 crisis, and what is the government's strategy to achieve its 25 percent sales target for new-energy vehicles (NEVs) by 2025?

Ting Wu (partner, Shenzhen): NEVs are still a top priority for the Chinese government and take center stage in its postcoronavirus stimulus plan. The government recently decided to extend NEV subsidies by two years, to the end of 2022. In addition, RMB 10 billion ($1.4 billion) will be invested to expand the charging network for electric vehicles (EVs) this year. Overall, increased government purchases will probably drive the market. Nevertheless, achieving the 25 percent target by 2025 will be a challenge and probably require additional policy instruments and new business models to spur sufficient consumer demand.

Automakers are relying on EVs to achieve Europe's upcoming carbon-dioxide emissions limits for 2020 and 2021. Although we have seen strong dynamics across countries, will the industry sell enough EVs to avoid looming penalty payments, and what might be the impact of the COVID-19 crisis?

Patrick Schaufuss (associate partner, Munich): OEMs have invested more than €30 billion in EVs over the past two years to meet Europe's upcoming carbon-dioxide regulations. OEMs plan to make a spot landing on the targets. Every gram these companies miss costs the industry about €1.5 billion, but overachieving would tighten their 2030 targets.

In the first quarter of 2020, we saw increased momentum on the consumer side for buying EVs, despite the COVID-19 pandemic. Other signs also suggest that the momentum of EVs will be sustained in Europe—for instance, the creation of additional purchase incentives, the timely creation of EV standard operating procedures, and an infrastructure rollout.

Given the recent loosening of the US federal emissions regulations, how will the trajectory of the US market and the EV strategies of traditional automakers evolve over the coming years?

Russel Hensley (partner, Detroit): Vehicle electrification strategies will remain relatively consistent, despite the uncertainty about current regulations and the ensuing debate between federal and state policy makers. While some automakers may have cut or delayed their EV programs, domestic OEMs must continue their efforts to enhance the average fuel economy of their new fleets, given the large share of light trucks, SUVs, and compact utility vehicles.

Many automakers use plug-in hybrid electric vehicles (PHEVs) as a bridge to a fully electric future. How will this technology develop?

Ruth Heuss (senior partner, Berlin): Over the past few years, sales of plug-in hybrid electric vehicles have been growing more slowly than sales of pure battery electric vehicles (BEVs). PHEVs represented less than a third of the global EV market in 2019. While most automakers offer them, the number of available models will remain less than half of the number of BEV models over the coming years. Although a higher driving range is one of the major advantages of PHEVs, the electric range of BEVs has been constantly increasing: it rose by 55 percent from 2017 to 2020 and is now around 400 km. Given typical driving behavior, PHEVs recently started to face regulatory headwinds as their environmental impact raised concerns. In reaction, some countries have reduced or entirely abolished monetary subsidies for PHEVs, further increasing their already higher price point for consumers. In 2019, among the key EV markets, PHEVs dominated EV sales in only three countries: Finland, Iceland, and Sweden. We therefore currently forecast that PHEVs will represent only 5 to 10 percent of the global market by 2030. That could fall even further as emissions regulations are increasingly based on real consumption.

We hear very little about hydrogen–fuel-cell EVs, except for a few models from Japanese and South Korean manufacturers. Will the technology contribute to green mobility in the future, and if so, will it emerge first in the passenger or light commercial-vehicle segment?

Anna Orthofer (associate partner, Vienna): There is actually quite some noise around hydrogen on the commercial-vehicle front. Most large OEMs have teamed up to work on the technology—for example, Daimler and Volvo, Toyota and Traton, and Honda and Isuzu. New players, such as Nikola and Hyzon, are entering the market, and Chinese companies are moving fast. The big suppliers are following by building a comprehensive system offering in fuel cells.

Overall, we see fewer and fewer OEMs that do not think about hydrogen as a necessary part of their powertrain portfolios. In light of carbon-dioxide regulation for trucks (such as the European Union's "–30 percent by 2030" target), each ton in weight and each kilometer in range will improve total costs of ownership for fuel cells relative to batteries. For long-haul trucks, our models show that fuel-cell electric vehicles can break even with battery electric vehicles within the next five years. They will also achieve lower total costs of ownership than diesel before 2030.

Markets such as China, Sweden, and the United Kingdom have reacted strongly to EV-incentive changes. Yet customer demand—independent of government subsidies—remains a major concern in the industry. Who is currently buying EVs, and what is required to scale up the market?

Timo Möller (partner, Cologne): Early adopters of BEVs appear to constitute a specific segment of consumers, best described as tech-savvy urban people with above-average incomes and a familiarity with online shopping. Beyond first movers, consideration of EVs has significantly increased among consumers over the past few years as they have come to recognize the numerous benefits of EVs. To scale up the market, OEMs should thus systematically try to affirm the consumers' growing positive attitudes about many aspects of EVs, such as the driving experience and subsidies. OEMs should also disprove consumer fears, such as range anxiety, that do not reflect reality and solve pressing pragmatic problems, such as the availability of charging stations.

Shifting portfolios from internal-combustion engines (ICEs) to EVs is a major challenge for traditional automakers, especially considering profitability. What is the current view of profits for EVs sold today? Will falling costs and rising consumer demand overcome the need for government support, and how can OEMs share the pain?

Patrick Hertzke (partner, London): Shifting the vehicle portfolio from ICE to PHEV/BEV—a change driven by regulation and shifting consumer demand—is now a paramount focus for traditional automakers. Many of them are concerned about profitability. The majority of EV models are still unprofitable, but this is changing. At-scale EV producers will have a clear cost advantage in the near term, while other OEMs are more likely to seek partnerships to co-develop EV platforms or even fully merge. EV growth across transport sectors also remains one of the most critical levers in global efforts to reduce carbon-dioxide emissions and improve urban air quality. EV supply chains will get even greener over time with the expansion of renewables and the recycling and reuse of batteries. COVID-19 and the related economic crisis will raise the stakes further as the world seeks cleaner transport solutions but could require governments to continue their subsidies and penalties as well. They may also need to add other measures, such as green early-scrappage programs, which encourage consumers to swap older cars for EVs.

Inspired by the ambitious EV strategies of automakers, battery-cell suppliers are ramping up their capacities. What are the key trends and challenges for the battery supply chain?

Markus Wilthaner (associate partner, Vienna): The uptake of EVs has supercharged industrialization and expansion in the industry. Battery-cell makers have an outsize growth opportunity in front of them. By revenue, they could become some of the largest automotive suppliers globally. This opportunity comes with huge challenges and trade-offs. They need to ramp up production capacities fast, while remaining disciplined about capital expenditures. Battery-cell makers must also stabilize production processes and achieve very high yields, while constantly pursuing product innovations. Every year, they must reduce costs to deliver on long-term contracts and remain competitive, while simultaneously seeking new business models and opportunities for differentiation. Finally these suppliers must solve challenges related to sustainability by turning the whole battery value chain, from mining to recycling, into a sustainable and responsible industry.

Demand for battery cells is expected to increase at least fourfold over the next five years, and cell chemistry is moving to nickel-rich cathodes. What are the developments and challenges on the battery raw-materials side?

Ken Hoffman (expert, New Jersey): There are three main challenges for the battery raw-materials supply stream. First, will the industry produce the quality of the nickel, lithium, and cobalt necessary? Second, will it produce the extremely specific quality needed? Third, can this production meet the ever more stringent environmental, social, and governance requirements imposed by regulators?

What will enable a truly sustainable form of electric mobility in the future? Where does the industry stand on sourcing raw materials sustainably, green electricity, and battery recycling? Is awareness of these challenges increasing?

Hauke Engel (partner, Frankfurt): The journey to truly sustainable electric mobility has only begun. The industry has made great progress increasing the number of available hybrid and fully electric-vehicle models, and costs keep coming down. Now the industry must work hard to drive down the cost of batteries and to achieve end-to-end sustainability—from truly sustainable raw-materials supplies (such as zero-carbon steel) to circular-economy principles in vehicle design. I'm excited to see OEMs increasingly starting to recognize and embrace these challenges. The scale and complexity of the problems may seem daunting, and solving them will require imagination, determination, and new forms of collaboration. Failure is not an option. We must simultaneously solve the climate challenge and secure the prosperity of our automotive industries and the people they employ.

EV market trends vary by region

Key EV markets suggest shifting regional dynamics, with China and the United States losing ground to Europe. EV sales remained constant in China in 2019, at around 1.2 million units sold (a 3 percent increase from the previous year). In the United States, EV sales dropped by 12 percent in 2019, with only 320,000 units sold. Meanwhile, sales in Europe rose by 44 percent, to reach 590,000 units. These trends continued in first-quarter 2020 as EV sales decreased from the previous quarter by 57 percent in China and by 33 percent in the United States. In contrast, Europe's EV market increased by 25 percent.

China

The relatively slow 2019 growth of China's EV market reflects both an overall decline in the light-vehicle market and significant cuts in EV subsidies. The central government, for example, eliminated purchase subsidies for vehicles that achieve electric ranges (e-ranges) of less than 200 kilometers and reduced subsidies by 67 percent for battery electric vehicles (BEVs) with e-ranges above 400 kilometers. These cutbacks reflect the government's strategy of scaling back monetary incentives for new-energy vehicles (NEVs) and transitioning to nonmonetary forms of support. Since 2019, OEMs have received credits for each NEV produced. The credits take into consideration factors such as the type of vehicle, as well as its maximum speed, energy consumption, weight, and range. Regulators base credit targets for each OEM on its total production of passenger cars. If a manufacturer does not reach the target, it must purchase credits from competitors that have a surplus or pay financial penalties.

In first-quarter 2020, China was heavily affected by the COVID-19 pandemic. EV sales dropped by 57 percent from the fourth quarter of 2019 as consumer demand declined sharply. Several EV manufacturers were also forced to halt

Key EV markets suggest shifting regional dynamics, with China and the United States losing ground to Europe.

production. In response, the central government extended through 2022 (though at reduced rates) monetary incentives that were about to expire. The government also prolonged the purchase-tax exemptions of NEVs through 2022. These measures, together with the government's recent decision to invest billions of renminbi in the charging infrastructure as part of an economic-stimulus program, could help EV sales rebound in 2020.

The United States

EV sales rose by 80 percent in the United States in 2018, driven by the market launch of the standard version of the Tesla Model 3. The increase slowed in 2019 because of several developments. With Tesla's overseas deliveries increasing and the gradual phaseout of the federal tax credit in January and July 2019, the brand's US sales for that year declined 7 percent, or 12,400 units. Meanwhile, the Chevrolet Volt was phased out, and its sales fell by 14,000 units. Sales of the Honda Clarity also decreased by 8,000 units.

Some international OEMs did successfully launch new models in the United States in 2019, including Audi (the e-tron) and Hyundai (the Kona). Sales of VW's e-Golf also increased. These three brands accounted for more than 24,500 units of EV sales, but their strong performance could not offset the decline of other models. US sales of EVs decreased further in first-quarter 2020, by 33 percent from the previous quarter.

The federal government's recent moves to loosen regulations could further decelerate the EV market in the United States. In March 2020, for instance, the government revised fuel-economy standards, to a 2026 target of 40 miles per gallon (mpg), from 54 mpg. Today's low oil prices are also contributing to the EV slowdown, since they significantly lower the total cost of ownership for vehicles powered by internal-combustion engines (as compared with EVs). These changes are creating great uncertainty, and the US EV market's development could depend largely on the number of states adopting California's Zero-Emission Vehicle Program and on the vicissitudes of oil prices.

Europe

Unlike other key EV markets, Europe has seen significant EV growth. In 2019, sales increased by 44 percent, the highest rate since 2016. The European Union's new emissions standard—95 grams of carbon dioxide per kilometer for passenger cars—could also boost EV sales because it stipulates that 95 percent of the fleet must meet this standard in 2020 and 100 percent in 2021. BEV sales picked up speed substantially, with a 70 percent growth rate propelled by three models: the Tesla Model 3, Hyundai Kona, and Audi e-tron.

EV sales increased by double-digit percentages in 2019 in almost every European country. Sales in some smaller markets, such as Estonia, Iceland, and Slovakia, declined in absolute terms. EV sales in Germany and the Netherlands contributed nearly half—44 percent—of overall EV-market growth in Europe; in both countries, units sold increased by about 40,000 units. Those numbers translate into a 2018 growth rate of 55 percent for Germany and 144 percent for the Netherlands. In both countries, these strong EV sales resulted from increased demand for new models, the availability of existing models with larger battery sizes, and changed government incentives (for more information on the power of incentives, see sidebar "Purchase subsidies juice EV sales.")

Purchase subsidies juice EV sales

As recent developments in China and Europe show, government subsidies remain a major driver of electric-vehicle (EV) sales. In 2019, several countries changed these incentive schemes in ways that show how sensitive customers are to price adjustments. For instance, the EV market in China declined by 31 percent in the second half of the year after the government cut subsidies. In the United Kingdom, sales of plug-in hybrid electric vehicles (PHEVs) fell by 15 percent after the government stopped subsidies for hybrids. Government subsidies also play an important role in increasing growth. When Germany reduced the company-car tax in January 2019, it promoted a surge in EV sales later that year. Similarly, the strong 2019 showing of the EV market in the Netherlands occurred partly because consumers wanted to purchase vehicles before the benefit-in-kind tax rate increased in 2020.

As first-quarter 2020 figures show, the EV markets in several European countries could accelerate this year because of recently increased incentives:

— France revised its bonus–malus (reward–penalty) scheme, based on carbon-dioxide emissions. Companies must meet new requirements to receive the environmental bonus for low-emitting vehicles and face a drastic increase in the environmental penalty for high-emitting ones.

— Germany extended tax incentives for electric company cars through the end of 2030. It has also increased purchase-price subsidies for EVs and will continue them until the end of 2021.

— Sweden implemented a bonus–malus system in 2018. A January 2020 amendment for test procedures to determine the carbon-dioxide emissions of vehicles will benefit PHEVs.

While government subsidies obviously have a strong influence on the development of the EV market, future growth may depend largely on the extent to which the COVID-19 pandemic hits EV markets in the short term.

In the first quarter of 2020, European EV sales rose as the overall EV penetration rate increased to 7.5 percent. With the exception of Hong Kong, all of the top ten markets for EV penetration were in Europe (Exhibit 2). The strong regulatory tailwinds and high purchase incentives in several European countries could dampen the impact of the COVID-19 pandemic and further boost the EV market. That said, EV sales will probably face tougher impediments in second-quarter 2020, when the pandemic's impact on Europe's countries and economies should peak. So far, no European OEM has changed its plans to roll out EV models, and several countries are discussing additional purchase incentives as part of their economic-stimulus programs.

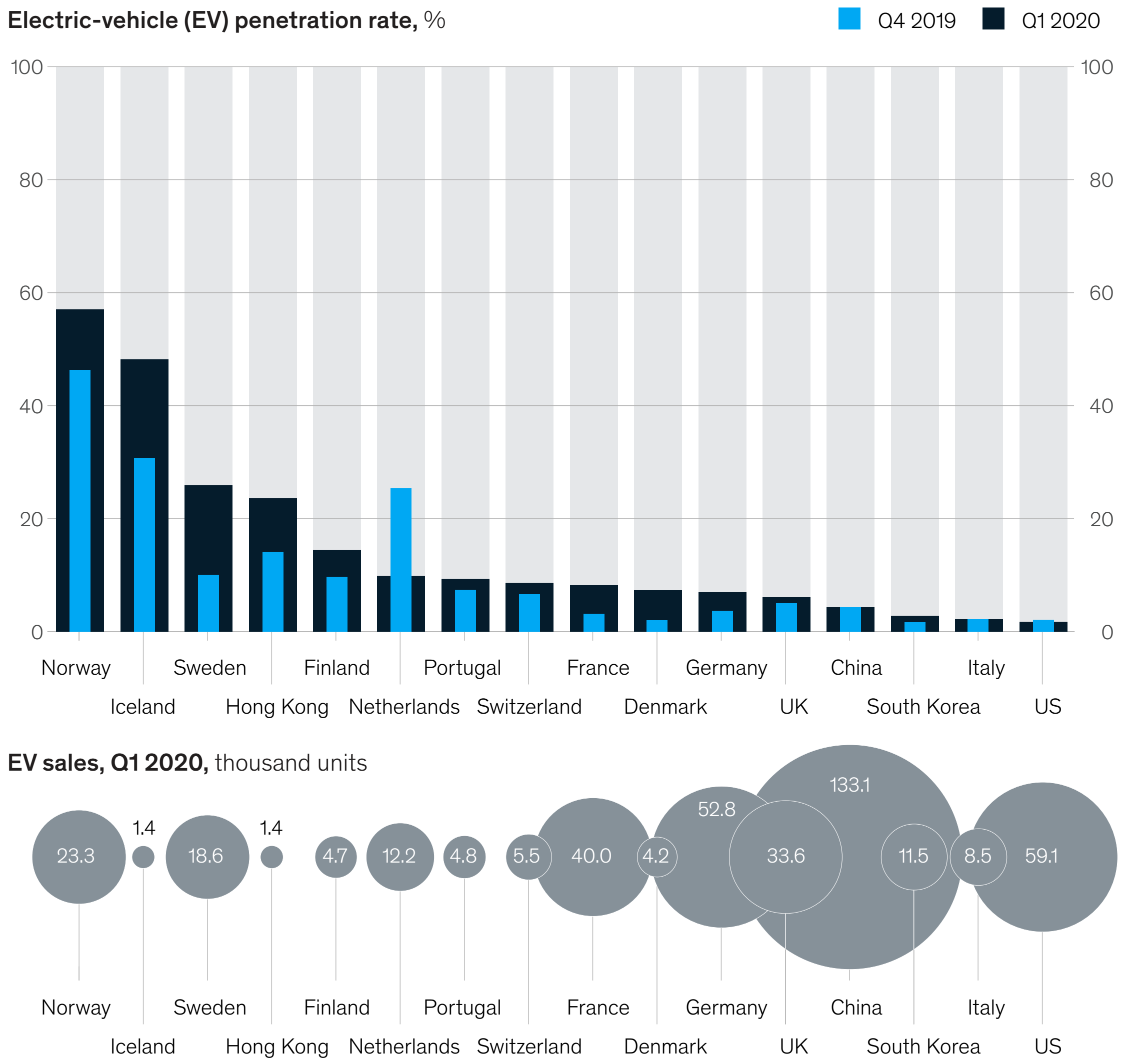
Electric-vehicle makers are debuting new models and boosting sales of existing ones

Automakers launched 143 new electric vehicles—105 BEVs and 38 plug-in hybrid electric vehicles (PHEVs)—in 2019. They plan to introduce around 450 additional models by 2022 (Exhibit 3). Most are midsize or large vehicles. Given the estimated production levels, German manufacturers, with an expected volume of 856,000 EVs, could overtake Chinese players in 2020. That would boost Germany's global production share from 18 percent in 2019 to 27 percent in 2020.

New emissions regulations in Europe and China, which will come into force between 2020 and

Exhibit 2

Nine of the top ten markets for electric-vehicle penetration rate were European.



Source: Ev-volume.com; Light Vehicle Sales Forecast, May 2020, IHS Markit

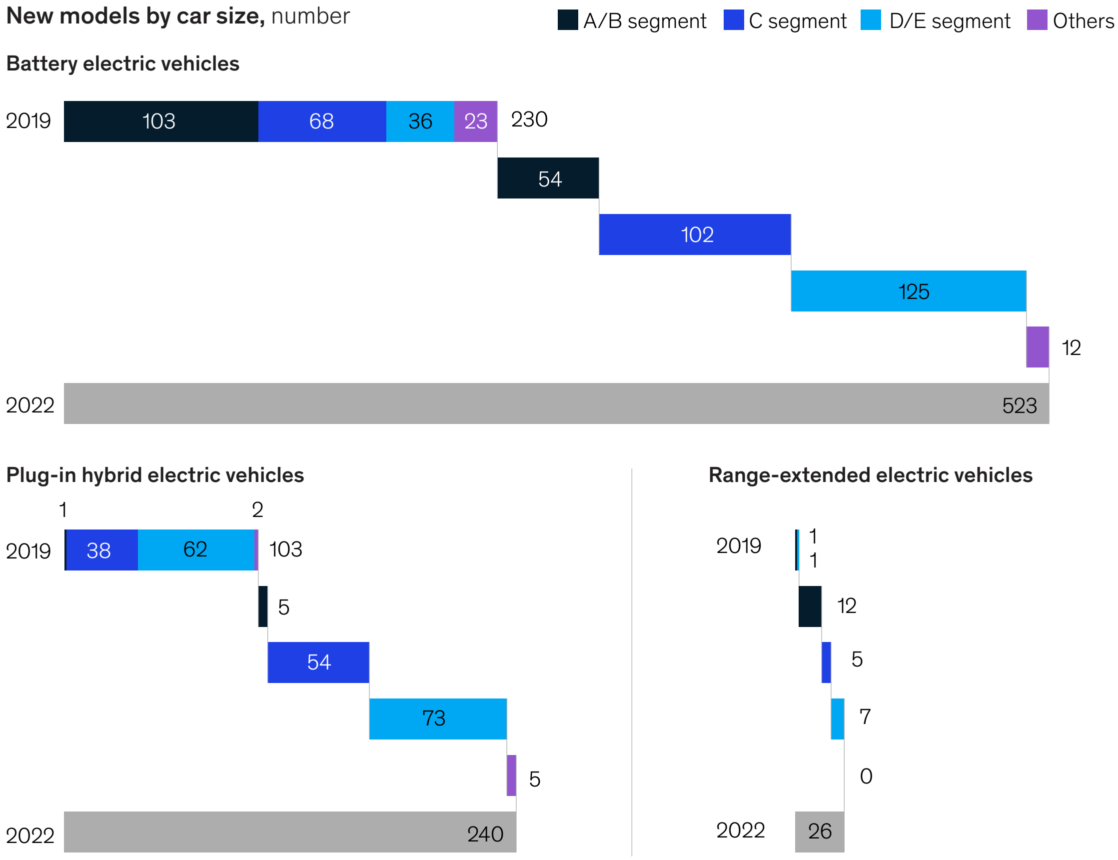
2021, partly explain why EV-model launches have increased significantly. These regulations pose major challenges for automakers, since they will face potential penalties of up to several billion euros unless they increase their EV penetration rates significantly.

Among EV manufacturers, Tesla continued as market leader in 2019, with 370,000 units sold globally, for a market share of about 16 percent, up from 12 percent in 2018 (Exhibit 4). The launch of the Model 3 outside of the United States was the main reason for this surge. With 300,000 units sold worldwide, the Model 3 outpaced sales of the BJEV EU-series threefold and sales of Nissan Leaf fourfold.

At the brand level, most Chinese EV manufacturers faced declining sales, while demand was high for the EV offerings of some international OEMs.

Exhibit 3

About 450 new electric-vehicle models will be launched through 2022.



Source: IHS Light Vehicle Powertrain Forecast, May 2020

The supply chain is localizing

With announced launches of new EV models spiking, both automakers and suppliers are increasing their global footprints in target markets by localizing the production of vehicles and components. For example, Tesla began construction of its Shanghai plant in January 2019 and delivered the first locally produced EV that December. The company plans to build its next production plant in Germany by 2021. Similarly, Volkswagen and Toyota have announced plans to set up EV plants in China.

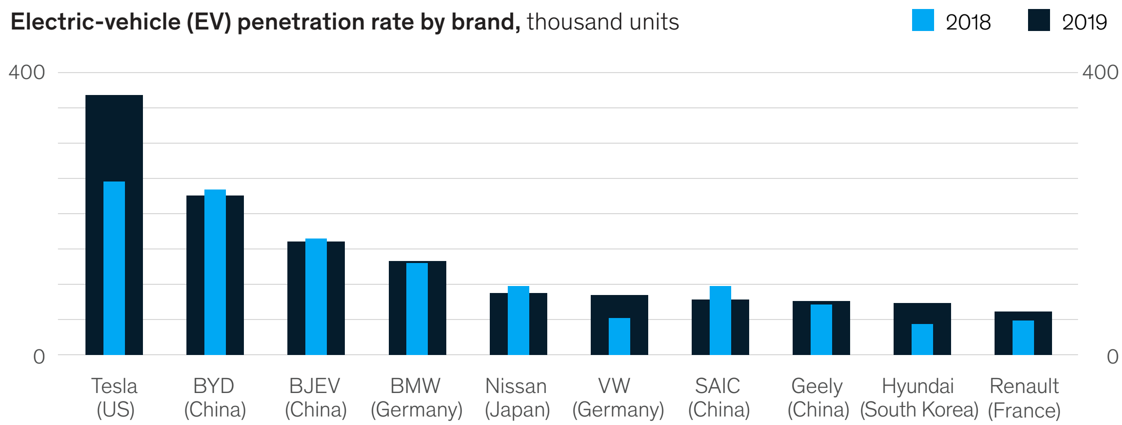
In a similar development, battery-cell manufacturers are increasing their production capacities in target markets. The total lithium-ion–battery market for EV passenger cars grew by 17 percent, to 117 gigawatt-hours in 2019, enough to power 2.4 million standard BEVs. Most of the new capacity will be established in Central Europe, with companies preparing to meet demand throughout the region. Company announcements suggest that the global market should expand to about 1,000 gigawatt-hours by 2025. The Chinese battery maker CATL had the largest market share in 2019, at 28 percent, while its absolute capacity grew by 39 percent. CATL has recently continued its global expansion, signing new contracts with several international OEMs and setting up a factory in Germany.

South Korean manufacturers are trying to catch up with large-scale investments in new overseas production plants. SK Innovation, for example,

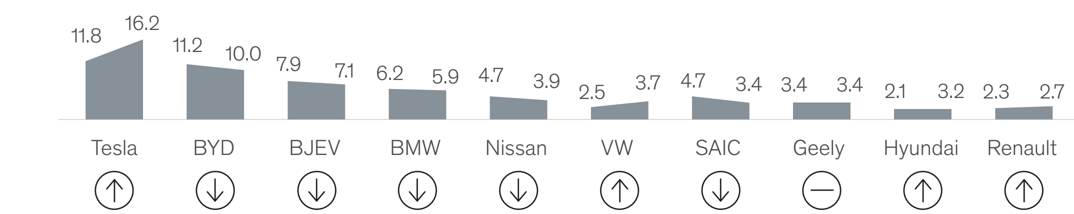
Exhibit 4

Tesla increased its global market share to about 16 percent in 2019, with the Model 3 alone accounting for 13 percent of sales.

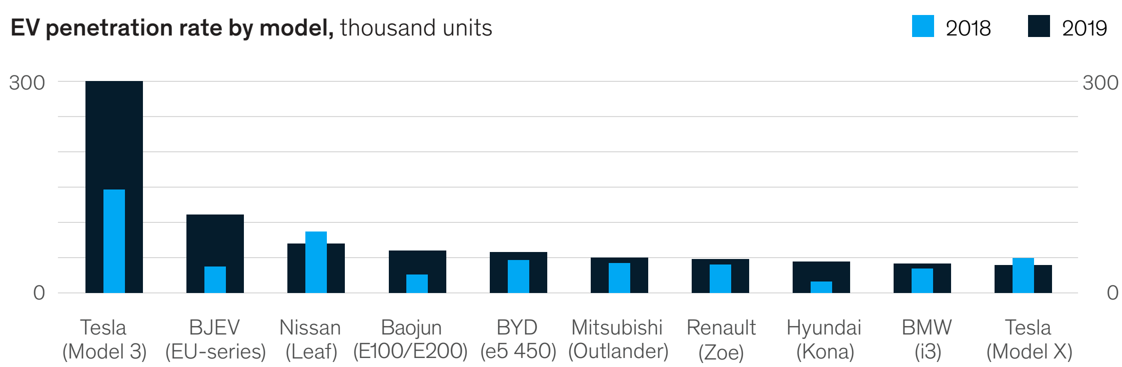
Electric-vehicle (EV) penetration rate by brand, thousand units



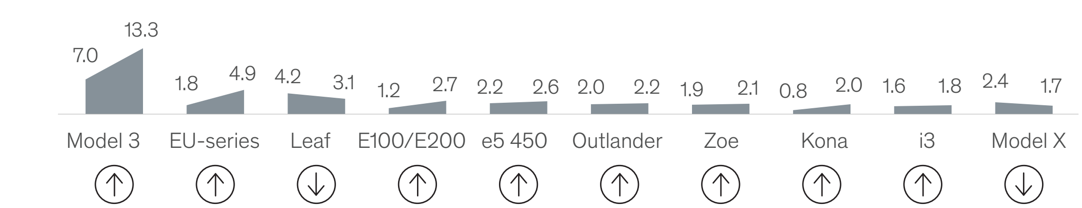
Market share by brand, 2018 and 2019, %



EV penetration rate by model, thousand units



Market share by model, 2018 and 2019, %



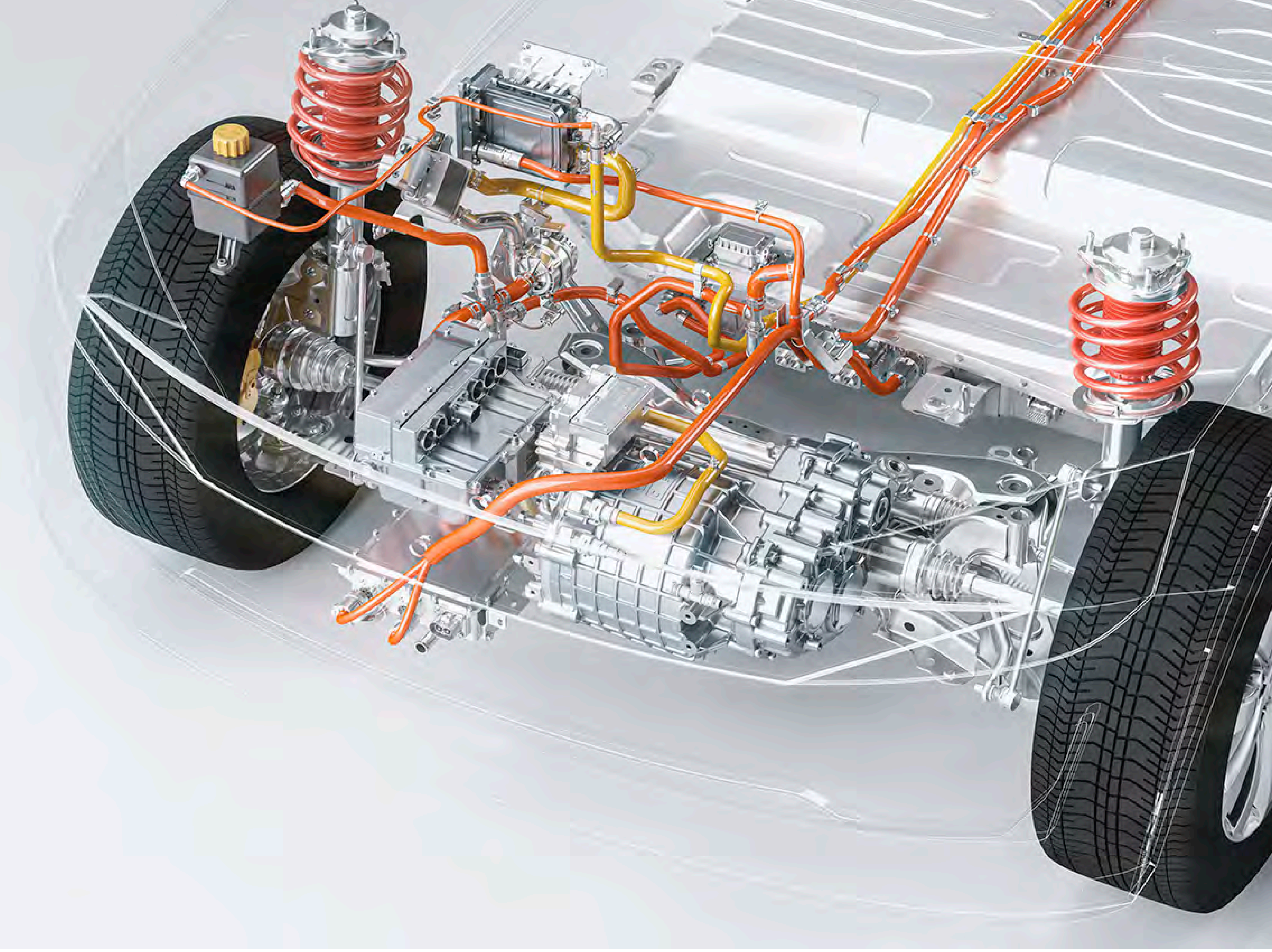
Source: Electronic Vehicle World Sales Database, EV-volumes.com; McKinsey analysis announced it would invest an additional €5 billion in its planned US factory, while LG Chem is investing $2.3 billion in a joint venture (JV) with General Motors in the United States.

Overall, JVs are becoming a popular collaboration model in the battery industry, with an increasing number of partnerships announced in 2019. This trend mainly reflects the fact that JVs enable automakers to lock in enough capacity to reach their ambitious sales and production targets. Automakers also prefer multisourcing strategies involving a number of cell makers. Even Tesla, which used to rely solely on cells from Panasonic, signed new contracts with CATL and LG Chem for the Chinese market in 2019.

The EV market has grown quickly, but the dynamics vary by region. In key markets, the transition from ICEs to electric powertrains reached a tipping point in 2019, fueled by more stringent emissions regulations, access restrictions in cities, advancing EV technologies that lengthen driving ranges and cut prices, and the expansion of the charging network. The same forces will further expand uptake over the coming years, but their evolution will vary by market.

To win, automakers and suppliers must develop a detailed view of what's happening in each market by monitoring the regulatory environment, customer preferences, infrastructure development, and the moves of competitors—especially new entrants, including start-ups from outside the industry. Companies that match customer demand with suitable EV models and catch regulatory tailwinds may secure the most promising pockets of growth going forward.

Thomas Gersdorf is a consultant in McKinsey's Munich office, where **Patrick Schaufuss** is an associate partner and **Stephanie Schenk** is an expert; **Patrick Hertzke** is a partner in the London office.



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How to drive winning battery-electric-vehicle design: Lessons from benchmarking ten Chinese models

Chinese OEMs use existing concepts and manufacturing technologies, as well as off-the-shelf components and a high level of modularization, for battery electric vehicles.

by Mauro Erriquez, Philip Schäfer, Dennis Schwedhelm, and Ting Wu

Many automotive OEMs and suppliers in Europe, the United States, and Japan are starting large-scale launches of battery electric vehicles (BEVs) in their core markets. But in China, a rapidly growing BEV market and ecosystem have already emerged.

To help global automotive OEMs and suppliers truly understand the major challenges and opportunities of the Chinese BEV market, we analyzed ten BEVs that are popular in China in depth. We covered a large portion of the market, looking at vehicles from both incumbent OEMs and new players, including Buick, BYD, GAC, Geely, JAC, NIO, Roewe, SAIC, and Weltmeister. The companies included in our analysis cover 45 percent of the market with their complete BEV and EV portfolio.[1] The benchmarking consisted of a detailed technical analysis, as well as a cost estimate down to the level of individual components.

Our research on the Chinese market and our analysis of the benchmarked BEVs yielded the following insights:

1. The Chinese BEV market—dominated by Chinese OEMs, which had a market share of approximately 85 percent in 2019—is growing not only as a result of subsidies and regulations but also the increasing attractiveness of these products to customers.

2. For first-generation BEVs, many Chinese OEMs are focusing on low capital expenditures (capex) and a fast time to market, together with an ecosystem dominated by local suppliers. They use existing concepts and manufacturing technologies, as well as off-the-shelf components and a high level of modularization for pre-assembly. This approach creates a potentially profitable business case for at least some of the benchmarked BEV models.

3. Differences among e-powertrain designs (including e-drive,[2] power electronics, and battery systems), electrical/electronic architectures (E/E), and pricing models of the benchmarked BEVs indicate that there are still significant design- and cost-improvement opportunities.

1. China—the world's largest automotive profit pool—is quickly moving toward e-mobility

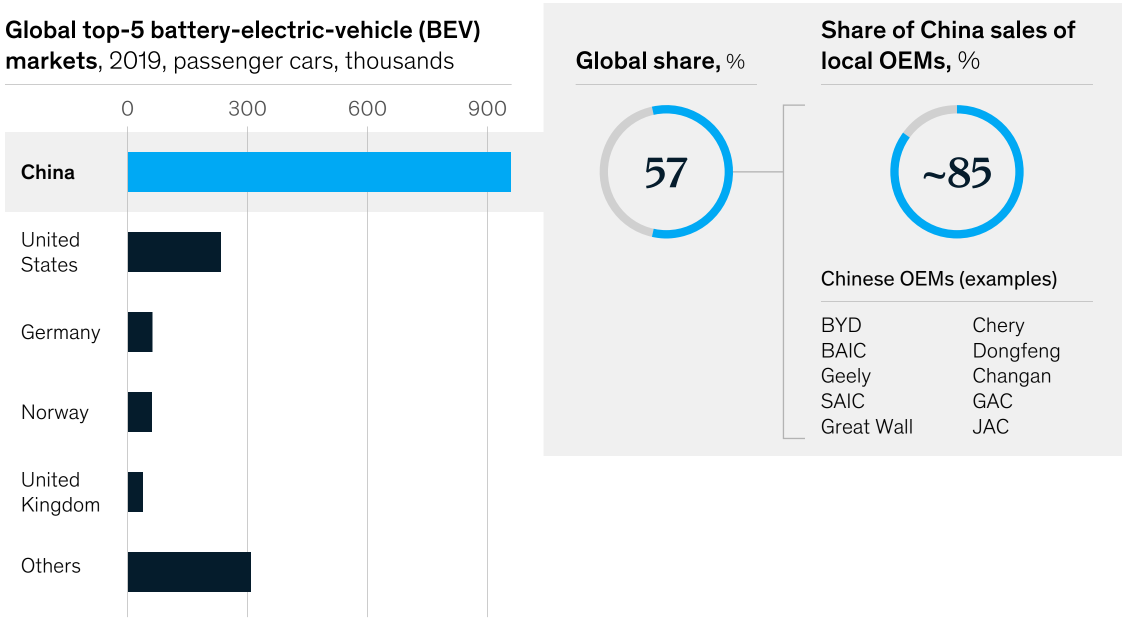
The Chinese automotive market is the world's largest automotive profit pool, accounting for one-third (about $40 billion[3]) of the global total. The market is now shifting toward e-mobility. From 2014 to 2019, BEV unit sales in China increased by 80 percent a year. With more than 900,000 units in 2019, 57 percent of the BEVs sold throughout

[1] Calculation of total battery-electric-vehicle market share in China is based on EV-volumes.com's wholesale unit sales figures for China in 2019.
[2] An e-drive includes the e-motor, transmission, and inverter.
[3] This figure is derived from McKinsey's proprietary automotive-profit-pool model.

In China, a rapidly growing battery-electric-vehicle market and ecosystem have already emerged.

Exhibit 1

The Chinese BEV market, mainly controlled by local OEMs, is the world's largest, with a share of global volumes of more than 50 percent.



Note: Numbers are based on wholesale volume (similar to CAAM), which have generally been higher than the corresponding retail insurance volumes.

Source: EV-volumes.com; McKinsey analysis

the world were sold in China, making it the world's largest BEV market. A look at OEM market shares reveals that Chinese OEMs dominate the market almost completely. International OEMs had a mere 15 percent of annual BEV sales in 2019 (Exhibit 1).

Looking back over the past few years, we see that BEV growth in China was triggered primarily by two factors:

— *Subsidies, quotas, and regulations facilitated production and adoption— and will continue to do so.* Early subsidies, along with the mandate that OEMs increase the share of BEVs in their portfolios, have been a significant driver of the greater availability and adoption of BEVs in China. In 2019, the reduction of subsidies slowed growth in demand, but China's CAFC[4]/ EV credit rules still point to a percentage of EV penetration—mostly of BEVs—in the mid-teens by 2025.[5] Regulations on ride hailing and government fleets, as well as restrictions on traffic in city centers, will also keep up BEV demand.

— *The value proposition of BEVs is increasingly attractive to consumers.* Even though the decrease in BEV sales to individuals in 2019 showed that public policy still drives most of the demand for these vehicles, consumer-

[4] Corporate average fuel consumption.

[5] See Robin Zhu, Luke Hong, Xuan Ji, *China EVs: Unique detail on Chinese EV sales by province and city, and buyer type*, Bernstein, February 13, 2020, bernstein.com.

sentiment analysis shows more promising trends. The general perception of BEVs is exceptionally good regarding safety, performance, connectivity, and brands. Consumers know the financial and environmental advantages, and the driving experience stands out as the largest benefit of BEVs. Still, lingering concerns limit demand. Availability of charging infrastructure, cited by 45 percent of respondents, was the most significant concern.[6]

Many new models designed with Chinese consumers in mind have contributed to the acceptance of BEVs, which had a consideration rate of 80 percent in 2019.[7] Customer-sentiment analysis of the ten benchmarked vehicles shows that with an average approval rating of 85 percent, all OEMs have been able to tailor their products to the needs of customers (Exhibit 2).

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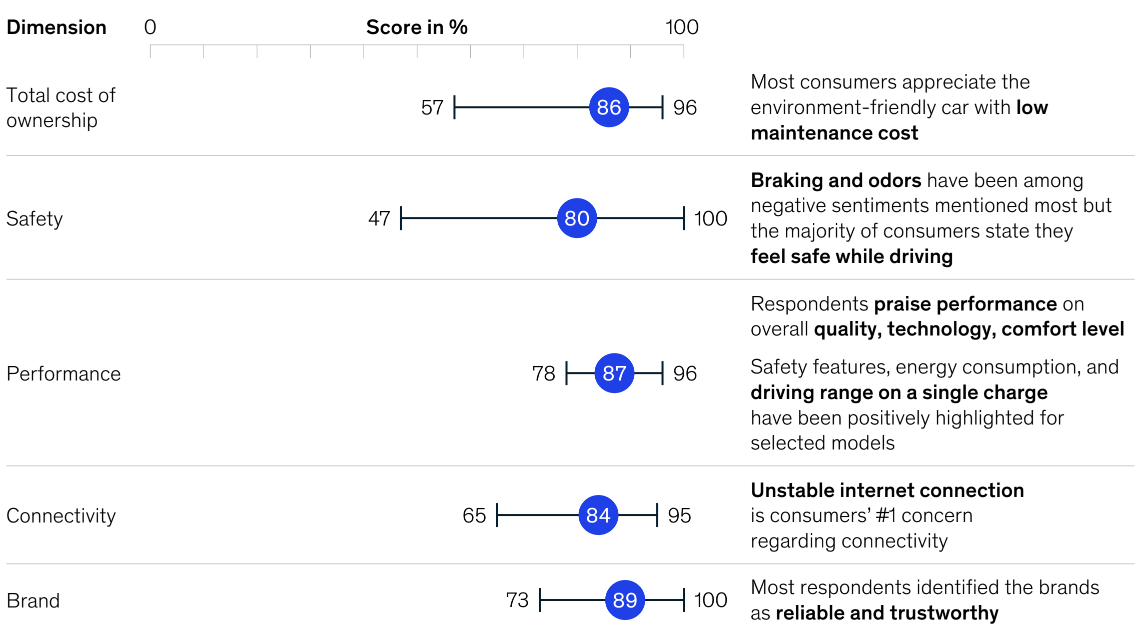
[6] See findings from the McKinsey electric-vehicle consumer survey 2019, published in Thomas Gersdorf, Russell Hensley, Patrick Hertzke, Patrick Schaufuss, and Andreas Tschiesn, *The road ahead for e-mobility*, January 2020, McKinsey.com.
[7] Ibid.

Exhibit 2

Consumers largely acknowledge the performance of the ten benchmarked battery electric vehicles.

Consumer sentiment analysis, % of positive rating

Average rating of responses

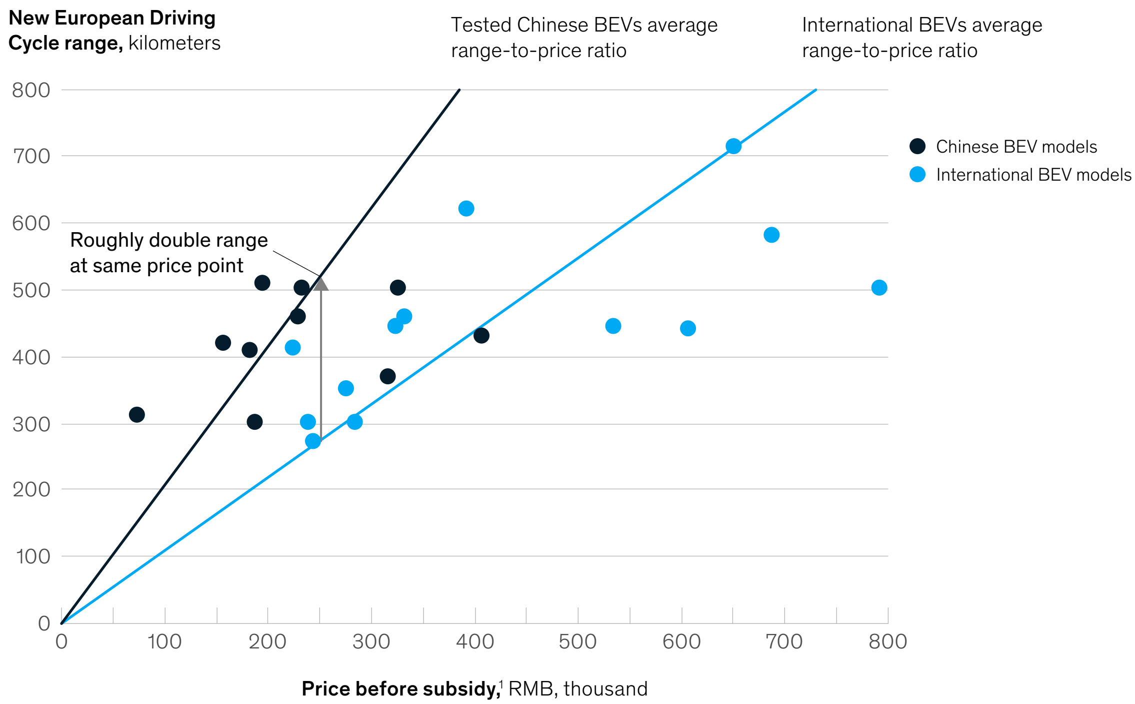


Source: McKinsey analysis

Exhibit 3

Compared with BEVs from established global OEMs, many Chinese models offer better range-to-price ratios.

Comparison between Chinese and international battery electric vehicles (BEVs)



[1] Due to launch timing and availabilities, prices of Chinese models are from official Chinese websites before subsidies whereas prices of international models are based on average Western markets.

Source: OEM website; press research; McKinsey analysis

All benchmarked vehicles perform like comparable European, US, or Japanese BEVs in absolute range or power but outperform them in range-to-price ratios (Exhibit 3). The tested Chinese BEV range is nearly double that of international models at the same price points.

The outlook for the market is promising: BEV penetration in China is expected to grow from 3.9 percent in 2019 to 14 to 20 percent in 2025—a sales volume of roughly 3.8 to 5.0 million vehicles.[8] With the COVID-19 crisis affecting global BEV markets, China's central government decided in March 2020 to extend purchase subsidies by two more years to fuel BEV sales. Therefore, we expect that after stagnation in 2020—compared with the double-digit growth before COVID-19—the BEV market will pick up again, both absolutely and relatively, in 2021.

[8] Figures are derived from McKinsey's proprietary Mobility Market Model and Sustainable Mobilty xEV Model.

2. Chinese BEV producers are on the verge of becoming profitable, given sufficient volumes

Several BEVs have the potential to be profitable, as their product cost structures benefit from several unique characteristics of the Chinese market. The reuse of existing internal-combustion-engine (ICE) platforms decreases time to market, and off-the-shelf components and a high level of modularization keep down capex. These design principles and their effects are supported by an ecosystem of local suppliers with long-established expertise across electronics and batteries.

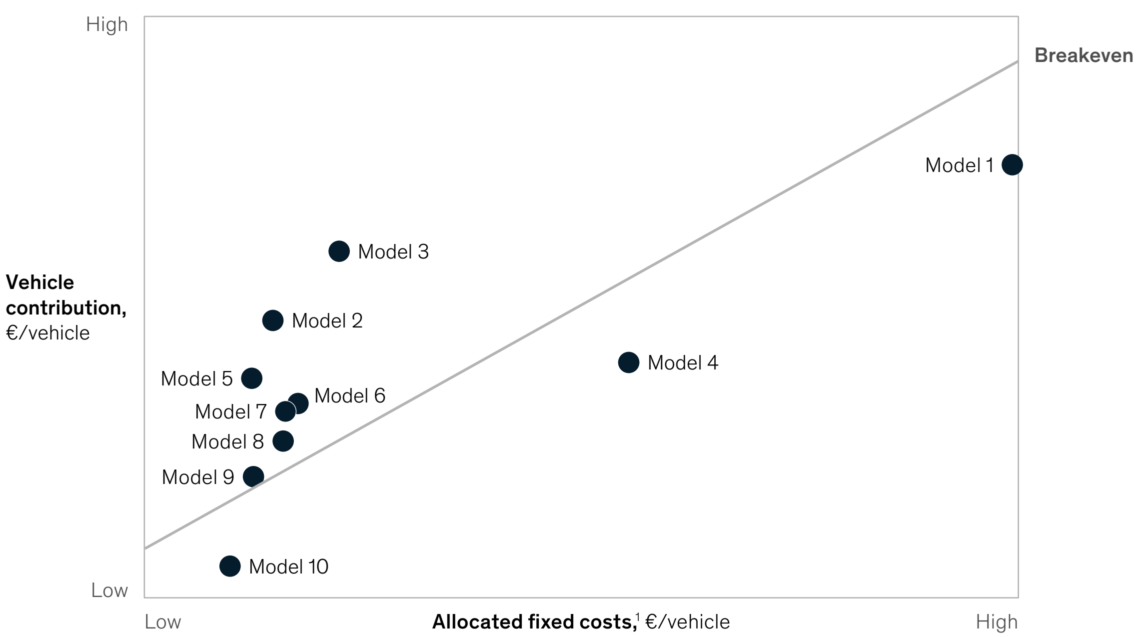
Our bottom-up estimate of materials and production costs, based on more than 250,000 data points, reveals that nine out of ten vehicles may achieve a moderate to solid contribution margin of up to 50 percent. However, we estimate that a lower share may actually achieve a positive operating margin when we take into account warranties; selling, general, and administrative costs; R&D; and capex (Exhibit 4). The high variance in fixed costs can stem from various factors, such as the depth of integration and differences in sourcing strategies or the overall volume of OEMs.

New market entrants in particular need to deal with structural challenges and low overall vehicle volumes. Together with further efforts to excel in R&D, the optimization of capex through flexible manufacturing and strategic value-chain positioning could help more OEMs turn a profit with their BEV models.

Exhibit 4

Battery electric vehicles from our benchmark set may be profitable after they ramp up to full volume.

Estimation



[1] Excludes any ramp-up cost.
Source: McKinsey analysis

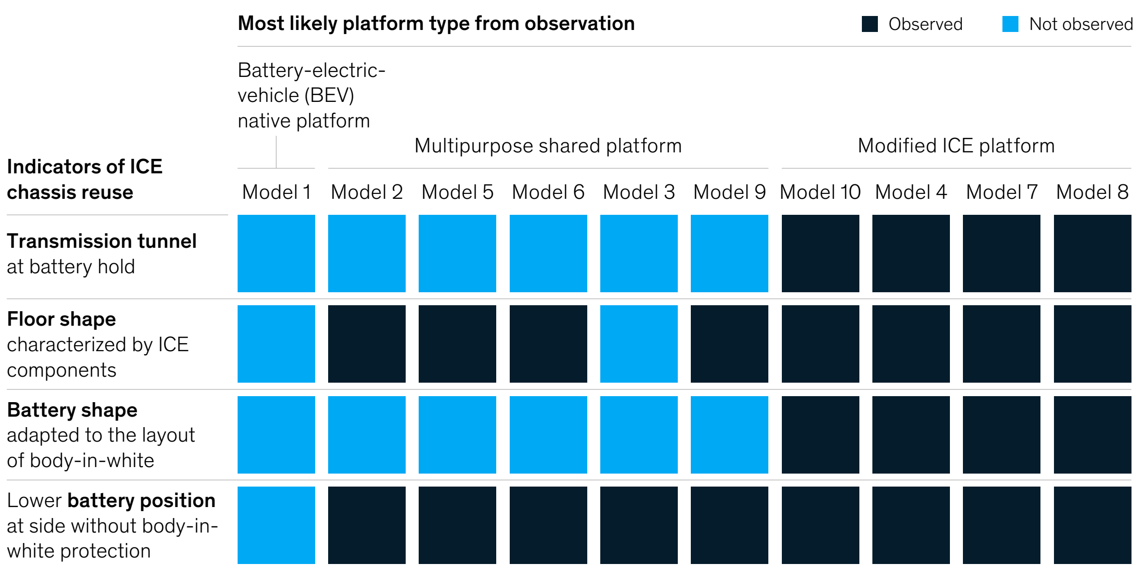
To offer a wide range of BEV products and models quickly, most Chinese BEV OEMs manufacture these cars by modifying their existing ICE platforms or using multipurpose shared platforms. We compared the designs of the vehicles during the physical teardown, leveraging our 3-D digital-twin/virtual-reality software. This work showed that nine of the ten benchmarked BEVs share features such as battery shapes, battery positions, and floor shapes. That indicates the reuse of an ICE chassis and thus a modified or shared ICE platform (Exhibit 5). Likewise, the use of similar designs facilitates industrialization, since existing blueprints for processes and manufacturing technologies can be leveraged. Industrialization takes up a significant share of the product-development process, so this approach is essential for achieving short time to market.

In addition, we observed OEMs implementing a segment-focused design, focusing on existing concepts and manufacturing technologies, and using off-the-shelf components. These allow for reduced capex and rapid industrialization (Exhibit 6).

High modularization and outsourcing promote capex–efficient manufacturing. Once modularized, content can be pushed toward preassemblies and suppliers to increase the level of outsourcing, which permits a less complex mainline assembly process.

Exhibit 5

Body-in-white designs indicate the use of modified internal-combustion-engine (ICE) or shared platforms.



Source: McKinsey analysis

Exhibit 6

Many players use preexisting steel body-in-white, so the share of lightweight components is low.

Type of body-in-white		Descriptions
State-of-the-art aluminum body	Model 1	Full aluminum body with mostly nonthermal joining methods as well as usage of carbon-fiber reinforced polymer parts in trunk of vehicle
Modern steel body	Model 2, 5, 6	Fully automated body-in-white with aluminum share in closures and usage of, eg, high-strength steel for improved crash performance and reduced weight
Steel body optimized	Model 7, 8, 10	Full-steel body with mostly traditional joining methods (weld spots), but usage of optimized material concept (eg, hot-formed steel)
Traditional full steel body	Model 3, 4 9	Simple steel body using manual welding operations (especially in low-capacity lines)

Source: McKinsey analysis

In particular, we observed a high degree of assembly flexibility in three out of ten models: the e-drive and further power electronics (DC/DC-converter and onboard charger (OBC)) are preassembled on a subframe as one module. Moreover, the battery system can be built into the vehicle at any time during assembly, providing for late integration and making assembly more flexible (Exhibit 7). This, in turn, further reduces capex demand.

Regarding fast industrialization, the current supplier ecosystem speeds up time to market. China's long-established expertise in electric machine production, semiconductors, electronics, and, especially, batteries makes it possible for local companies to supply all components of the e-powertrain (Exhibit 8). Depending on the level of vertical integration, OEMs source 45 to 100 percent of e-powertrain components from local suppliers.

However, in the broader context—providing production equipment and setting up manufacturing lines—global players remain involved. The know-how of Western manufacturing-equipment OEMs enables Chinese suppliers to deliver the quality needed for the entire value chain, in paint shops, for example.

3. Substantial variety in design and technology remains—the game is far from decided

Local OEMs have demonstrated a position of strength in the Chinese BEV market, but a deeper look at the technology reveals that substantial differences across OEMs remain. Variations in three aspects of vehicles will influence the development of next-generation BEVs and may provide an opportunity for others to gain a foothold in the market.

E-powertrain. The benchmark revealed a large variety of concepts throughout the e-powertrain, such as the battery layout, the thermal management design and routing, and drivetrain-module integration. Our 3-D models show that half of the benchmarked models use grid and row layouts for the battery pack, increasing the utilization of space and, potentially, lowering module-production

Exhibit 7

The ten benchmarked battery electric vehicles used a variety of assembly-modularization approaches.

Modularized | Partially modularized | Individual component level

<table>
<tr><th>We see different archetypes of assembly modularization</th><th></th><th>E-drive (including axle)</th><th>Power electronics</th><th>Battery</th><th>High-voltage harness and tubing</th></tr>
<tr><td>Type 1
The front-axle integrator
Widely spread modularization across key car components to simplify main-line assembly</td><td>Model 4, 8, 10</td><td colspan="2">Preassembled module (on subframe)</td><td rowspan="2">Fully independent module (flexible integration throughout assembly process/ late integration possible)</td><td>Preassembled to main line with various connectors</td></tr>
<tr><td>Type 2
The electronics integrator
Modularization of different electronics components</td><td>Model 1, 2, 5, 7</td><td rowspan="2">Self-supporting axle with simplified assembly rack; additional components assembled separately</td><td>Integrated module (eg, 1-box design)</td><td>Fully preassembled complete electronic module, 1-connector assembly in main line</td></tr>
<tr><td>Type 3
The component assembler
Low level of modularization; complex assembly resulting in high capital and operating expenditures</td><td>Model 3, 6, 9</td><td>Single-component assembly</td><td>Early integration in assembly main line required</td><td>Individually assembled on main line</td></tr>
</table>

Source: McKinsey analysis

costs thanks to a lower level of packing variety than multiple-sized battery modules would require (Exhibit 9).

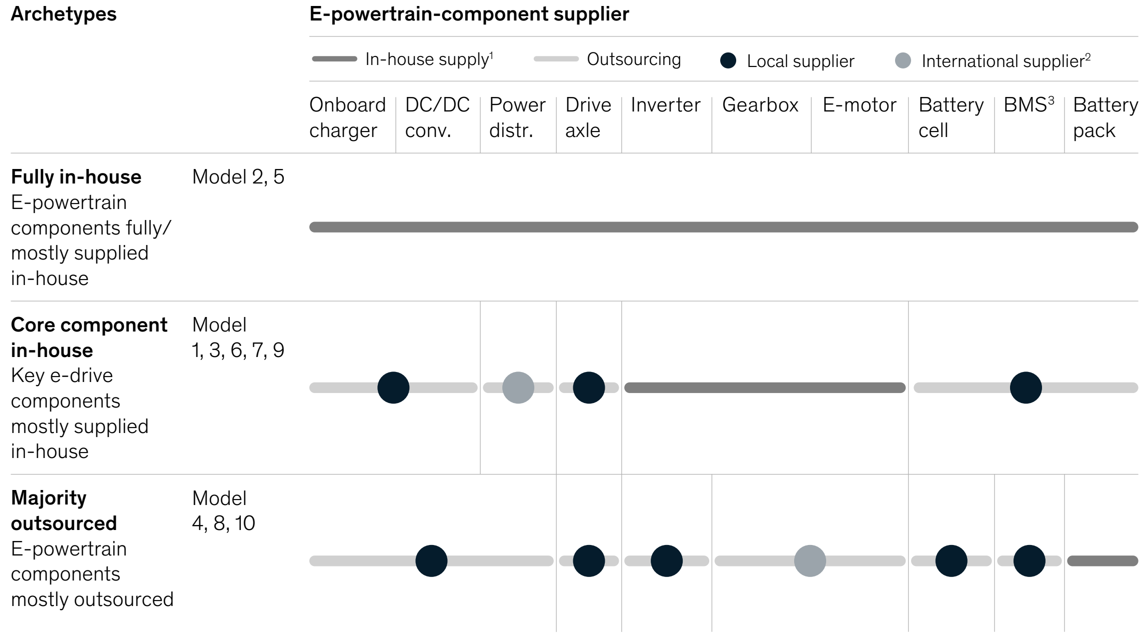
In addition, the degree of physical integration varies. Only three models show a high level of it: electric components and the e-drive are physically integrated, and the thermal management spans all components. Two models show the same level of physical integration, but the thermal management is separate for the e-drive and for the battery. The remaining models use less integrated components: separate electric modules and separate thermal management. Of these, three models use passive air cooling, which limits the charging speed when compared with the other models, which use liquid cooling of the battery (Exhibit 10).

E/E architecture. The benchmark shows that the weight of low-voltage wiring and harnesses differs among models with similar functionalities. That suggests significant design and cost-improvement opportunities in the E/E architecture. Similarly, OEMs of the benchmarked BEVs chose different ADAS[9] functionalities, use different designs for the electronic control unit (ECU) integration, and differ in the number of ECUs used. The bench-marked BEVs have six to 19 decentralized ECUs (Exhibit 11). One potential direction would be to inte-grate all functions in one vehicle controller, as a BEV player in the United States does. That might increase performance at a relatively low cost but calls for substantial R&D investments and advanced internal software-development capabilities.

[9] Advanced driver-assistance system.

Exhibit 8

Chinese OEMs rely heavily on local suppliers, with three archetypes of module integration.

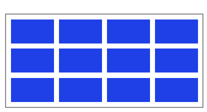
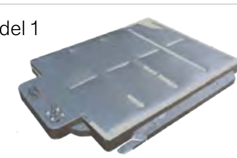
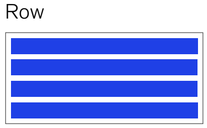
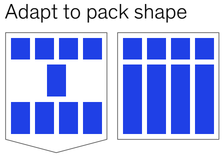


[1] By OEM internally or by JV/subsidiaries supplier of OEM.
[2] Including joint ventures with international suppliers.
[3] Battery-management system.

Source: McKinsey analysis

Exhibit 9

There are three designs for battery-pack module layouts, with implications for pack-space utilization and module packaging.

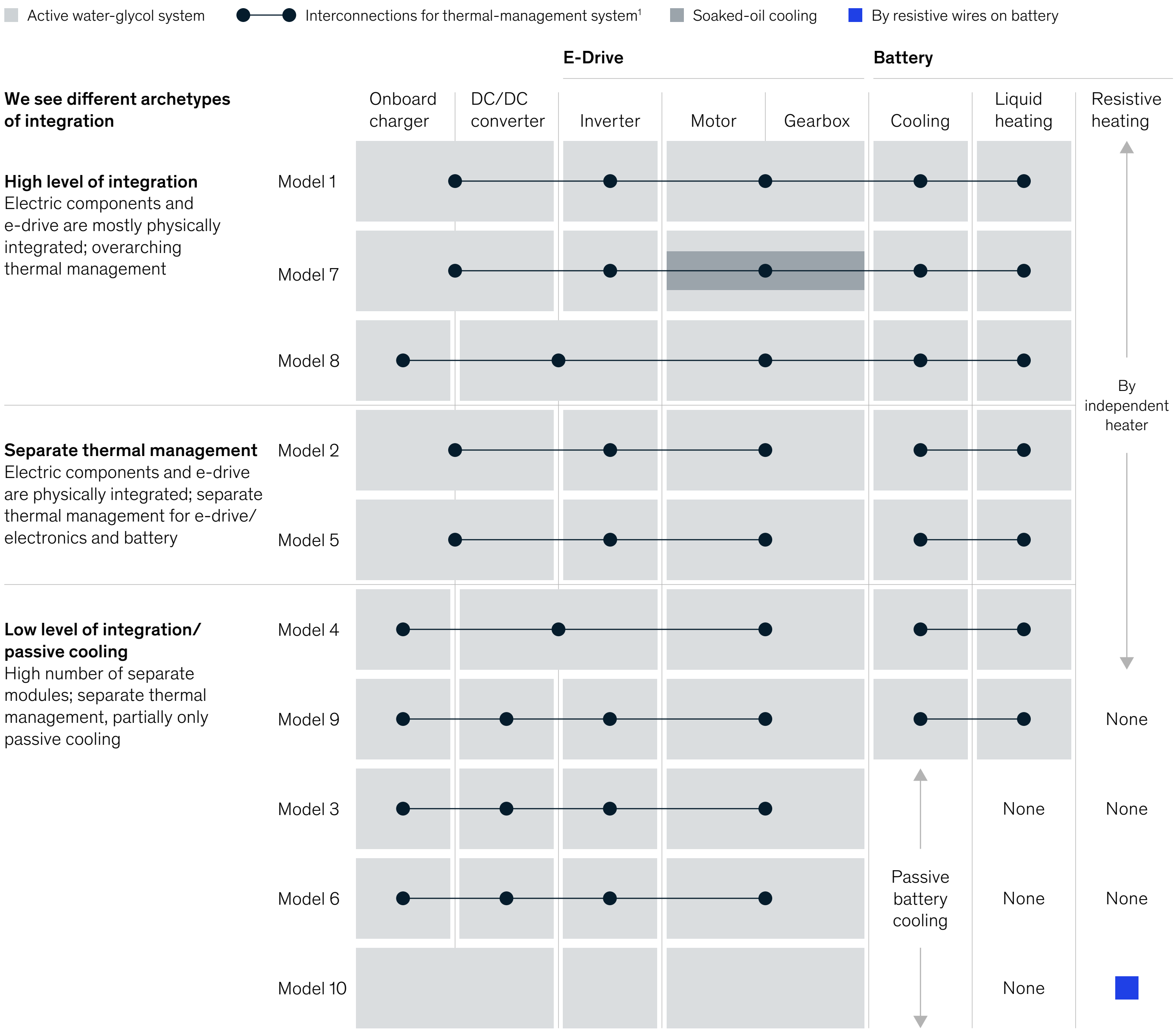
Module layout	Description	Test vehicles	Examples
Grid 	Identical sized and shaped module Layout in equally spaced grids	Model 1, 3, 9	Model 1 
Row 	Mostly identically sized and shaped modules Layout in equally spaced row	Model 2, 5	Model 5 
Adapt to pack shape 	Mostly multiple-sized and -shaped modules Arranged according to pack shape/varied module distance	Model 4, 6, 7, 8, 10	Model 7 

Source: McKinsey analysis

Exhibit 10

As with Western battery electric vehicles, there is no convergent powertrain design among Chinese BEVs—yet.

Comparison of powertrain and thermal management design



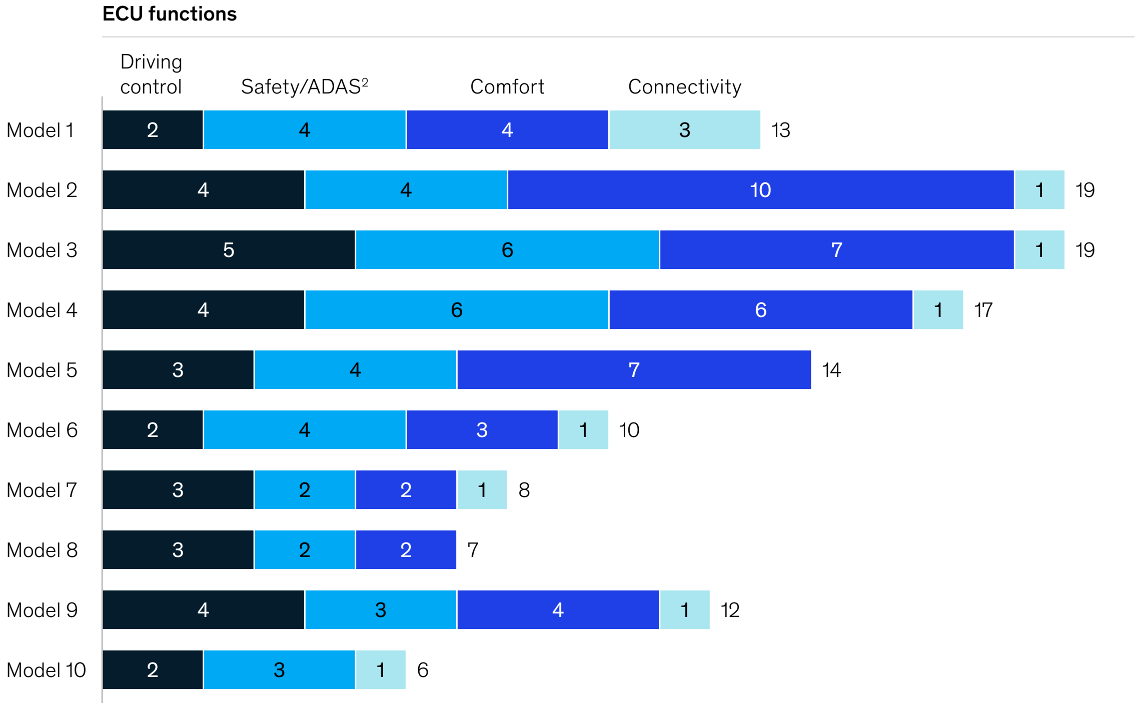
[1] Direct cooling jacket/pipeline/evaporator/heat exchanger connection.

Source: McKinsey analysis

Exhibit 11

Electronic-control-unit (ECU) usage is roughly correlated with design features, and some OEMs integrate ECUs in more sophisticated ways.

Low-voltage (LV) ECU function distribution, number of ECUs[1]



[1] ECUs of high-voltage system and chassis excluded.
[2] Advanced driver-assistance systems.

Source: McKinsey analysis

Trim packages. Chinese BEVs offer two to four trim packages on top of the base model. That reduces complexity and costs compared with the larger portfolio of options common among Western OEMs. Seven out of ten benchmarked models therefore have a price spread of less than 50 percent between the base models and the fully loaded ones (Exhibit 12). Five out of ten offer battery or motor upgrades independent of the trim package, and three offer priced exterior options, such as color and wheels. Consequently, there might be untapped revenue potential in pricing strategies or non-hardware revenues, such as over-the-air software updates. Overall, global automotive OEMs may use our findings as a signal to simplify their portfolios or as a point of differentiation, especially when they think about entering the Chinese market.

4. Several strategies can help companies be successful in the market

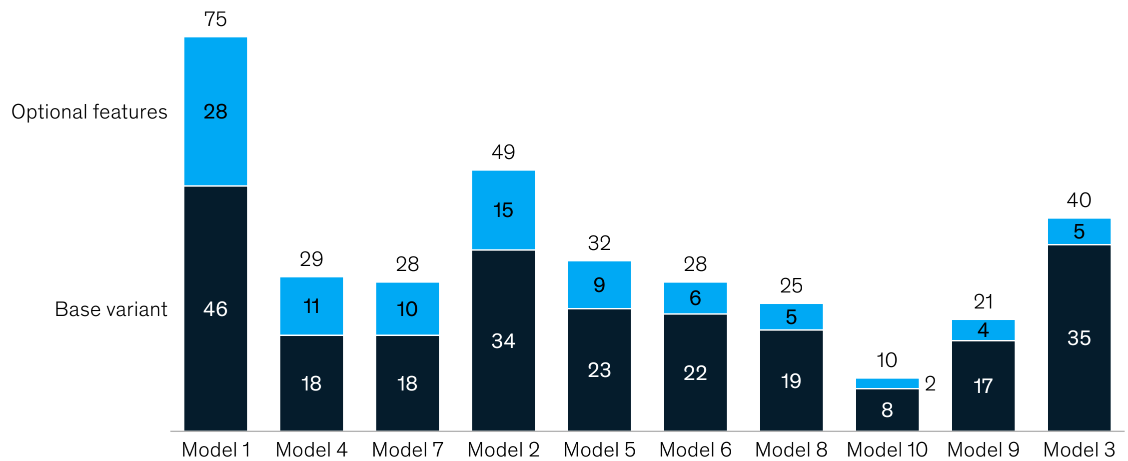
Given the dynamic environment, succeeding in the Chinese BEV market presents significant uncertainties. Yet international OEMs and suppliers cannot afford to miss out on the Chinese BEV market in the long term, considering its sheer size and opportunities. In contrast, Chinese players will need to secure their dominant position and continue to focus on profitability.

The insights gained through the benchmark indicate several trends in the Chinese BEV market, each pointing to an associated strategic action or opportunity.

Exhibit 12

Battery electric vehicles have a low price spread between the base and the fully loaded model.

Price of vehicle base variant and optional add-up, € thousand



Additional price for fully loaded model compared with base variant	61%	61%	53%	44%	38%	30%	27%	27%	23%	15%

Source: McKinsey analysis

Development cycles are accelerating. To increase profitability and achieve a competitive advantage, OEMs are speeding up the development cycles of their BEVs. For current (and mostly first-generation) models, OEMs have cut time to market by reusing or modifying existing ICE platforms and relying on off-the-shelf components. But it is expected that for the next generation of BEVs, time to market will continue to fall as more OEMs develop dedicated BEV platforms and produce higher volumes. In addition to reducing time to market, the higher volumes will convey cost and design advantages.

The market composition will probably change. There are now around 80 BEV brands in China owned by about 50 companies. Of these, twelve are start-ups, with a market share of approximately 7 percent in 2019.[10] However, start-ups—especially if they haven't started production yet—will find that market conditions become increasingly unfavorable to them as a result of their cost structures. In particular, high fixed costs at low volumes burden these companies, so any start-up that cannot scale up quickly will disappear. By contrast, international OEMs will aim to capture additional market share, since they must extend their penetration of the BEV market to adhere to regulations, such as dual-credit policies.

E-powertrain technology will standardize. The observed technological variance in batteries, power electronics, E/E, and e-drives is expected to decline. The market will converge on just a few standardized designs, as happened with ICE powertrain designs. This presents a significant opportunity for suppliers that can deliver integrated platform solutions for the powertrain, especially if they have a competitive capex base through synergies and economies of scale.

[10] Number of start-ups and their market share were derived from calculations using production data for electric vehicles from IHS Markit, Light Vehicle Powertrain Production Forecast, April 2020. Please note that while the production data are from IHS Markit, the classification into start-up and incumbent, as well as the calculation of the start-ups' market share, were developed by McKinsey and are neither associated with nor endorsed by IHS Markit.

Native BEV platforms will gain higher shares. The benchmark shows that Chinese OEMs have realized short time to market by using shared or modified ICE platforms. However, as noted earlier, we expect more OEMs to develop dedicated BEV platforms to satisfy demand—a trend that will reduce time to market while also conveying design and cost advantages. Moreover, it is expected that BEVs will increasingly be produced on dedicated production lines instead of (at present) flexible, shared ICE/BEV production lines.

Non-Chinese OEMs will need to leverage their assets, such as an exciting brand image, superior engineering expertise, and state-of-the-art production facilities, to differentiate themselves from their Chinese competitors. Simultaneously, they must simplify their portfolios to offer fewer but highly targeted and locally adapted options, supported by additional revenue streams through software and other technologies. In contrast, Chinese OEMs should continue to increase their profitability by focusing on cost savings while increasing their revenues through more differentiated offerings. Sophisticated pricing strategies and new revenue streams will be important.

For suppliers, partnerships will be crucial. Non-Chinese suppliers could leverage their engineering maturity to become leaders in innovation. Chinese suppliers might broaden their customer base by helping non-Chinese OEMs to gain a foothold in the market (Exhibit 13).

Exhibit 13

Our insights give an idea about potential actions for players to drive winning battery-electric-vehicle design in China.

	International	Local
OEMs	Adapt a **customer-centric-design** philosophy and prioritize features and functions valued most by customers	Intensify **design-to-cost practices** to unlock potential cost savings
	Leverage assets—eg, brands, state-of-the-art production, and superior engineering; innovate using **design-to-cost** concept rigorously	Leverage **knowledge of consumer preferences** to differentiate offerings and to expand into **new revenue models**
	Reduce portfolio and adopt agile product development to **shorten time-to-market**	Solidify **brand image** to differentiate products from existing and new competition
	Expand into **new revenue models**—eg, software updates and maintenance	Further enhance **customer experience**
Suppliers	**Partner** with Chinese OEMs to advance engineering maturity and to help maximize cost savings	Select **long-term strategy** and develop **integrated solutions** for key modules
	Strive for **innovation leadership** in highly valued fields, potentially through strategic partnerships	**Broaden OEM customer** base and experiment with innovative business models

Source: McKinsey analysis

Mauro Erriquez is a senior partner in McKinsey's Frankfurt office, **Philip Schäfer** is a partner in the Dusseldorf office, **Dennis Schwedhelm** is a senior knowledge expert in the Munich office, and **Ting Wu** is a partner in the Shenzhen office.

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Leaving the niche: Seven steps for a successful go-to-market model for electric vehicles

To regain momentum after the COVID-19 pandemic ends, the players in this market must reconsider their strategies.

by Sebastian Kempf, Philipp Lühr, Patrick Schaufuss, Anna Strigel, and Andreas Tschiesner

To date, electric vehicles (EVs) have been niche products, so many OEMs have focused their go-to-market (GTM) strategies on a small, tech-savvy segment of automobile customers. Then, just as electric mobility was about to take off and sales were accelerating in several markets around the world, COVID-19 struck.

There are many questions about how the coronavirus could affect the global EV market. The answer will vary by region. Regulation and consumer incentives drive China's EV market, and the central government extended purchase subsidies by two years in March 2020. In Europe, regulators and industry stakeholders lean toward incentives that would favor clean powertrains. EU member states are also expected to maintain the 95-gram CO_2 fleet-emission target from 2020 through 2021, though it will affect the number of vehicles sold. The US automotive market—probably the hardest hit—will require some time to recover: EV sales may stagnate for one or two years before consumer confidence recovers and people are willing to pay for EVs. One big factor in the delay is record-low oil prices, which have widely eliminated the advantage EVs had for total costs of ownership.

Now more than ever, a radically new GTM approach is required to win consumer support for EVs, since COVID-19 could fundamentally influence the attitudes of consumers toward mobility. If they have recently experienced clean air in cities, will that make them lean toward EVs? What's more, a majority of the population is now getting used to online shopping. Will that make consumers more likely to consider buying cars online? And since people now have to avoid crowded spaces, will individual mobility increase after the pandemic ends? Finally, some consumers are avoiding gas stations. Will the ability to charge at home become a purchase consideration for EVs?

Although such questions are difficult to answer, consumers may be more reluctant than ever before to make big purchases, such as cars. Yet the increased public focus on climate change, shifting environmental regulations, and technological advances are making the case for a green-mobility transition and thus for EVs. First, however, the current GTM approach must change, and that will require both OEMs and their partners in the EV ecosystem to change as well.

The challenges ahead

Many challenges for the growth of the EV market lie ahead, but some stand out. In particular, a scalable GTM model for EVs must address new regulations that may influence competition, the customer base, infrastructure, and the business case for and profitability of these vehicles (Exhibit 1).

The regulatory environment

In reaction to increasingly tight CO_2 regulations and the anticipated sizable penalties for noncompliance, most automotive players have ambitious EV-growth plans: OEMs have announced the launch of more than 600 new EV models by 2025,[1] and competition will probably grow as many new players enter the market. Increasing sales of new EVs will be a complex challenge, and OEMs may find it more difficult to make profits if governments reduce subsidies as EV technology advances.

Customers

Our 2019 EV Consumer Survey shows persistent hesitation among consumers in the largest automotive markets—China, Germany, and the United States. While many people consider purchasing EVs (36 to 80 percent of car buyers, depending on the market), few actually do (2 to 5 percent). This hesitation is also reflected in the OEMs' low levels of "EV sales readiness,"

[1] IHS Markit (alternative propulsion forecast as of November 30, 2019).

Exhibit 1

Original equipment manufacturers face four main challenges in the electric-vehicle market.

Electric-vehicle (EV) go-to-market model

Regulatory environment

- Time to market is critical since OEMs will face severe regulatory penalties in many markets for failing to meet CO_2 emissions requirements from 2020 onward
- Gradual decline in government subsidies expected as technology advances

Customers

- Customers not yet requesting EVs; consideration is up 50% or more but purchase conversion still low
- Top concerns and purchase barriers involve batteries, driving range, and charging
- EV buyers have different preferences than internal combustion engine buyers, such as a preference for digital channels, app interaction, pay-as-you-go options, and personalization; they rely heavily on sales staff for advice

EV infrastructure

- Charging network rollout has been accelerated, but availability is still limited, especially for fast-charging stations
- Seamless and compelling charging experience is not yet widely available due to high market fragmentation
- Critical enablers still absent for scaling up EV aftersales and parts operations, such as battery recycling and re-usage capabilities

EV business case and profitability

- EV business case at risk, since consumers are not yet willing to pay extra cost of EV powertrain
- EVs have up to 60% lower aftersales revenues compared to vehicles with internal combustion engines

documented in McKinsey's 2019 EV Mystery Shopping survey, which revealed the core challenges facing OEMs that sell EVs: their in-store presentation, the accessibility of test drives, and the EV knowledge and processes of sales associates. Sales staff must, for example, understand how to discuss total costs of ownership, batteries, and charging. If OEMs do not address these issues proactively, the growing supply of EVs might outpace demand. OEMs would then be stuck between high penalty payments and rising incentive-spending levels.

The EV infrastructure

On the charging side, the EV infrastructure is insufficient. The network of charging stations, particularly fast-charging ones, is sparse. Battery quality, the time needed to charge, and limited access to chargers are the biggest concerns for potential EV buyers, accounting for 38 percent of all concerns raised.[2] The rollout of charging infrastructure is accelerating, but no integrated, seamless, and compelling solution is available, because the market is very fragmented. OEMs should take the lead in this area.

On the EV-parts side, challenges arise from long delivery times—especially for EV batteries—and the failure to prepare adequately for EV after-sales services.

The EV business case and profitability

EVs will become more crucial to the OEMs' overall success as they begin to represent a growing share

[2] Thomas Gersdorf, Russell Hensley, Patrick Hertzke, Patrick Schaufuss, and Andreas Tschiesner, "The road ahead for e-mobility," January 2020, McKinsey.com.

of the portfolio. Profitability of the EV business case is at risk for many OEMs for several reasons, including the high investment required, initially low sales volumes, the high cost share of the battery, and lower aftersales revenues. This gap could present challenges for both OEMs and their dealers. As we mentioned earlier, other issues—including falling government subsidies, increasing competition, and persistent customer concerns—also limit EV sales and put additional pressure on profitability. Without proactive countermeasures, it could fall enough to endanger the current business models of leading OEMs and dealers.

Seven innovations for GTM success

As we explained in our recent article on EV profitability, OEMs have previously attempted to tackle the businesses challenges primarily by making changes on the production and technology sides (for instance, improvements to battery sourcing, platform strategies, and alliances and ecosystems). Now, however, OEMs must also develop innovative GTM models to sell the required number of EVs and to find a sustainable business model. Our research and discussions with leading practitioners in the field have led us to believe that seven radical innovations in four areas—offerings, sales, after-sales services, and business models—will shape the OEMs' EV future (Exhibit 2).

1. Reinvent brand positioning

OEMs ought to create a compelling value proposition for their EVs, focusing on differentiating themes. The value proposition should align with the overall brand but also be specific to EVs. An OEM might, for instance, emphasize that it has a large charging network. Volkswagen, which emphasizes "E-mobility for all," provides a good example of effective positioning.

OEMs should also develop attractive new offerings: integrated EV-mobility bundles that include products and services, with a focus on the overall experience. In addition to the vehicle itself, for example, a successful bundle might include charging, on-demand features and services, revenues from data, financing options (such as battery leasing), mobility services, and after-sales packages (for instance, Care by Volvo). Combined, these elements could create a compelling offer that enhances the customer experience and may resolve concerns that could hinder the adoption of EVs.

Communication will be the key: OEMs should use innovative and personalized approaches, such as digital campaigns, to reach and educate prospective EV customers. Focusing on areas and customer segments that are actively considering EVs will be critical to reach scale quickly and to create a network of EV advocates for each OEM brand.

Exhibit 2

Seven innovations will shape the electric-vehicle go-to-market model.

Innovations for 2020

Create your offering			Master sales		Optimize aftersales services	Disrupt business model
1	2	3	4	5	6	7
Reinvent brand positioning	Shape the charging ecosystem	Monetize the life cycle	Perfect omni-channel approach	Massively reskill and refocus sales force	Upgrade aftersales customer-centricity and readiness	Transform business model to achieve profitability at scale

2. Shape the charging ecosystem

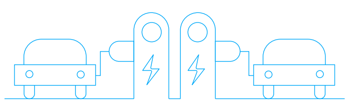
Be early to provide a seamless charging experience. OEMs ought to develop and manage networks of leading ecosystem players to create end-to-end charging systems with single access points as quickly as possible—and at a reasonable cost to the consumer (Exhibit 3). To create such an infrastructure at scale, the OEMs should also integrate the different charging options (home, public, and dealer) into the existing system and app landscape, working closely with leading ecosystem partners.

First, OEMs should help enable home charging by bundling a cobranded wallbox with the EV, including a dealer margin to boost sales. In partnership with Centrica, for example, Ford offers home-charging installations and electrified-vehicle tariffs from British Gas. To address one of the most prevalent customer concerns, OEMs could also establish international partnerships to create a public charging solution with a sufficient network of both standard and fast chargers. These partnerships, including mobility service providers (MSPs) and governments, would enable retailers, offices, and residential buildings to install charging stations. A variety of payment models (for example, pay-as-you go or subscription) would have to be developed. Another possibility would be to accelerate the adoption of EVs, and to provide additional customer benefits that would increase loyalty, by using dealer networks to

Exhibit 3

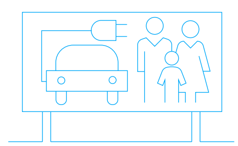
Original equipment manufacturers should provide convenient solutions for public and private charging.

Public charging infrastructure



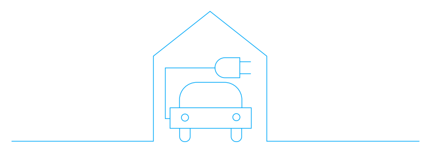
- Offer dense charging network directly or via mobility- or charging-service providers
- Engage in local partnerships with municipalities and infrastructure provider
- Help retailers, offices, and landlords install charging stations easily at low investment

Proactively advertise new charging lifestyle



Team up with businesses or tourist stops on typical travel routes to make charging breaks appealing; in such locations, the 30-minute charging window could become an opportunity to enjoy the surroundings

Provide easy plug-and-play solutions for charging at home



- Provide intuitive Wallbox installation service
- Educate electricians in charging-system installation and customer support
- Demonstrate charging systems live in-store and online
- Provide smart charging solutions through collaborations with utility companies
- Provide a seamless charging experience, regardless of location

43%
of battery-electric vehicles (BEVs) are charged on public charging stations

40%
of public charging locations worldwide are in 25 cities

64%
of BEV owners would like to or already participate in smart charging services

raise the number of charging points, especially in underdeveloped rural areas.

Finally, OEMs should secure access to the acquired data from charging and use them to generate income in the future and to develop smart charging solutions, such as those provided by Renault's Z.E. Smart Charge app. These solutions base charging recommendations on the available level of energy in the grid.

3. Generate income from the life cycle
Don't just sell cars; be there the whole way. In the OEMs' current EV GTM approach, they gain about €100 a year in profit (around 1 cent per kilometer driven) over a car's life cycle after selling a new vehicle.[3] (This profit does not include aftersales revenue.) Despite efforts to reduce the cost of producing EVs, this profit will increase only slightly in the next five to ten years. OEMs and dealers must therefore pursue other revenue opportunities throughout the product life cycle to achieve sustainable margins.

After the purchase, OEMs can, for example, offer on-demand services and features to consumers, as Tesla does through its AutoPilot. Such features might include performance- and battery-boosting software, advanced driver-assistance systems, and services like BMW ConnectedDrive, which includes remote services, concierge service, and on-street parking information, among other benefits. BMW, for example, offers ConnectedDrive in four packages that cost from €69 to €279 a year.[4] Given the attractive profit margins on those services, BMW is able to bolster the overall profitability of its EVs.

Either alone or with the support of third-party data aggregators, OEMs also have an opportunity to generate revenues from the data of customers and vehicles. These data could be used to address a number of use cases involving connected vehicles, to offer personalized services, or to provide third-party marketing. Our research indicates that revenues from data could generate approximately €50 a year per vehicle.

4. Massively reskill and refocus the sales force
Convert your dealers into true EV advocates. Only half of the sales reps in our mystery-shopping efforts at selected dealerships in China, Germany, and the United States conducted balanced discussions about the merits of EV and ICE vehicles when advising test customers who were generally open to both. From our perspective, there were several reasons for the problem: a lack of knowledge among salespeople about some of the potential benefits of EV, the human tendency to avoid criticism, and lower EV dealer margins and after-sales revenues. To change all this, OEMs must not only support their dealers as they build the required infrastructure and capabilities but also, at the same time, provide incentives that make EV sales more economically attractive over the long term. Without such efforts, dealers may wonder if it is worthwhile to sell EVs.

OEMs should monitor performance—both their own and that of third-party dealers—to ensure the consistent delivery of an optimal EV sales pitch. They should also invest in digitally savvy product "geniuses" to serve as trusted advisers for customers. To build the deep EV expertise that makes it possible to address all relevant customer concerns, OEMs should train the geniuses through online and in-person classes that explain integrated EV-mobility bundles.

OEMs should also give dealers incentives to increase the number of test drives, which would expose more customers to the new technology.

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[3] Assuming €1,000 margin on 100,000 km driven in a ten-year life cycle.
[4] Reference price in Germany as of May 2020.

OEMs could, for instance, encourage dealers to reach out to target groups, such as taxi companies and mobility providers, to get additional prospective customers behind the EV wheel. Finally, OEMs should ensure that all showrooms prominently display the entire EV portfolio (including wallbox and charging solutions) and that customers can explore them with digital tools.

5. Perfect the omnichannel approach
Make your online channel an information "El Dorado" for EV prospects, who want to know about these vehicles and are upward of 50 percent more interested in purchasing cars online than traditional buyers are. OEMs should therefore invest significantly in their digital presence to provide easy access to information about important customer concerns; for example, OEMs could feature discussions about customers' key EV pain points on their websites. They could also reduce the complexity and uncertainty of a purchase by providing simple, care-free configuration and ownership options, such as subscription models that permit further personalization through on-demand features.

Ensuring seamless online–offline integration between digital touchpoints and dealers is important too. First, it helps dealers identify likely customers for EVs. Given the central role of online channels during the information phase, they will also have a growing importance in generating leads. Several OEMs have proved that innovative online–offline integration (for example, Polestar) and hyperlocal marketing can significantly increase walk-in rates. NIO has gone a step further and established a second floor in its flagship stores that is dedicated to its customers and their friends, with the goal of improving brand loyalty. The company also has an application that allows users to book services at one-click, share content with other NIO customers, and earn rewards by actively participating in the community.

Since more than 50 percent of prospective EV customers would be willing to purchase a car online, OEMs should also begin to pilot online sales approaches, as Tesla does, to provide a lean, cost-effective retail channel with direct access to customers.

6. Upgrade after-sales customer-centricity and readiness
Learn how to make your after-sales operations leap into the new age. EVs require less after-sales service than ICE vehicles do and have significantly different maintenance needs. They also require highly skilled technicians who understand battery and high-voltage technology. OEMs should therefore develop EV-specific training programs—in battery diagnostics, for example—to train the technicians in their dealer networks. It will also be important to ensure that EV-related parts and tools, such as battery-leak detectors, are easily available. Volkswagen, for instance, is planning to establish a new battery warehouse to pool its stock and provide fast deliveries to its dealers. While demand is still low, several dealerships could share these facilities.

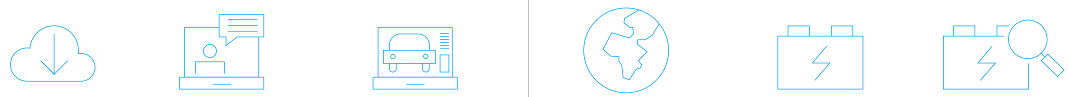
OEMs and dealers should also create EV-specific service offerings and maintenance plans. EVs will have complex proprietary software. For after-sales service, many consumers will rely on the dealer networks affiliated with their cars, and that could partially compensate for lower profits in the overall EV after-sales and parts market (Exhibit 4). OEMs could also create EV-specific offerings to reassure customers by providing additional battery-related support (such as recharging services) via service partners. Such offerings might include long-distance replacement cars or distinctive warranty

Exhibit 4

Original equipment manufacturers can win customers over with superior services online and offline.

Remote online service

Worldwide low-effort service model



Over-the-air software updates

Online service management[1]

Remote repair service for software-related issues

Provide worldwide service warranty to customers

Low-battery emergency services

Offer "battery-care" packages as additional warranty service

70%
of customers disagree with companies claiming to be customer-centric

71%
of electric-vehicle owners use it as their primary vehicle

40%
plan to change the car brand for better connectivity

[1]For example, upcoming checks, usage statistics, and other information are accessible online.

offers—for example, a battery-care package (similar to AppleCare), which Volkswagen already intends to offer.[5]

Finally, OEMs could provide state-of-the-art after-sales services (such as parts-exchange reminders and software updates) that are always available and can be sent, in part, remotely over the air. Such services could significantly improve the customer experience. Tesla, for example, already offers them.

Battery-reusage concepts are becoming more important as a result of increasing regulation in markets such as China and the European Union. OEMs and their ecosystem partners should start to develop their own ideas now, before a standard solution is established. Their efforts could lay the foundation for a possible future revenue stream and mitigate future risks from battery-handling and -recycling regulations.[6]

7. Transform the business model to achieve profitability at scale

Make the unprofitable profitable. For the foreseeable future, though, EVs will probably remain significantly less profitable than traditional cars as a result of higher production costs, lower after-sales revenues, continuing uncertainty about battery reusage and remarketing, and the significant investment required for the charging infrastructure. Additional revenue streams from on-demand services and features, and from sources such as data and charging, probably won't offset these cost pressures, so the current GTM model

[5]Volkswagen plans to guarantee more than 70 percent battery capacity after eight years.
[6]For a deeper perspective on this topic, see Hauke Engel, Patrick Hertzke, and Giulia Siccardo, "Second-life EV batteries: The newest value pool in energy storage," April 2019, McKinsey.com.

must further evolve. A new one will require greater online–offline integration, which will reduce costs across the physical retail network, since consumers will increasingly research and buy cars online. Such a model will also help OEMs shift toward more direct asset-light electric-mobility offerings.

In the short term, OEMs should focus on optimizing their existing dealer networks by easing standards, such as stock requirements. They should also continue to consolidate the number of dealers to achieve synergies through joint back-office operations and larger economies of scale. If necessary, OEMs could restructure their networks to rebalance profits across all stakeholders—for example, by reducing the number of outlets and moving to direct sales. An ICDP study expects that the number of outlets in dealer networks across Europe must fall substantially if they wish to remain viable.[7] Newer players, such as Byton, Polestar, and Tesla, already use that model by building their sales operations around a common digital backbone that seamlessly connects online sales.

In addition to supporting full-service dealers, OEMs should adopt leaner, more customer-centric retail formats, such as urban flagship stores and experience centers, depending on the needs of specific geographies. They can ensure quality of service by offering new after-sales concepts; for instance, Audi's digital service stations, providing automated check-in and check-out, are open 24 hours a day. To pool demand across dealerships, OEMs could also create large service centers in the outskirts of cities.

OEMs should partially transform their sales model from wholesale to retail by increasing their ability and efforts to generate high-quality leads. They should also partially shift to direct-to-consumer sales models (such as subscriptions) for selected geographies or offerings. A direct model implies reduced margins for dealers and more direct access to customers for OEMs.

Before scaling up any changes, OEMs should start pilots to explore and assess a variety of business models. Several OEMs (for example, Mercedes in Sweden and Toyota in New Zealand) have already conducted such experiments. The knowledge gained from them will help the entire industry to mitigate implementation problems, such as insufficient pricing, failed stock management, and unclear marketing responsibilities.

New mobility concepts can also be part of that business-model innovation. OEMs, for example, may gain new revenue streams by creating regional shared-EV pools for major European cities or EV fleets for urban taxi providers. If such mobility services use a subscription-based pricing model, they can help hedge against falling EV prices. The same holds true for other offerings (such as battery-leasing services) related to new mobility concepts.

[7] *ICDP European Car Distribution Handbook 2019.*

The time has come to revise the GTM model for EVs. OEMs can start by taking the following steps:

First, they should use EVs as an accelerator to modernize the GTM. By piloting and quickly scaling up the required short-term measures for online channels, the offline experience, after-sales services, network restructuring, and the like, OEMs can ensure a high level of readiness when new EVs are ready to launch.

Second, OEMs should prepare for novel sources of revenue. They ought to launch and support their markets while dealers tap into new revenue streams, such as charging, bundles for EV mobility, on-demand features, and data from vehicles.

Finally, to stay ahead of the curve, OEMs should be ready to leap by exploring new business models, including alternative sales models, mobility solutions, and battery-reusage concepts.

Sebastian Kempf is a partner in McKinsey's Düsseldorf office; **Philipp Lühr** is an associate partner and **Patrick Schaufuss** is an associate expert partner in the Munich office, where **Andreas Tschiesner** is a senior partner; and **Anna Strigel** is an associate partner in the Berlin office.

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The zero-carbon car: Abating material emissions is next on the agenda

The automotive industry could abate 66 percent of emissions from their material production at no extra cost by 2030—if industry participants work together and start now.

by Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel

The automotive sector is critical to achieving net-zero global emissions by 2050, the foundation of the road map toward limiting global warming to 1.5 degrees Celsius above preindustrial levels. Many original-equipment manufacturers (OEMs) are accordingly setting aggressive decarbonization targets to meet this challenge.[1]

Since 65 to 80 percent of emissions an automobile generates are from tailpipe emissions,[2] and corresponding indirect emissions come from fuel supply, the industry has understandably focused on electrifying powertrains. However, to reach the full potential of automotive decarbonization—and achieve the zero-carbon car—industry players now must turn their attention to material emissions as well (Exhibit 1).

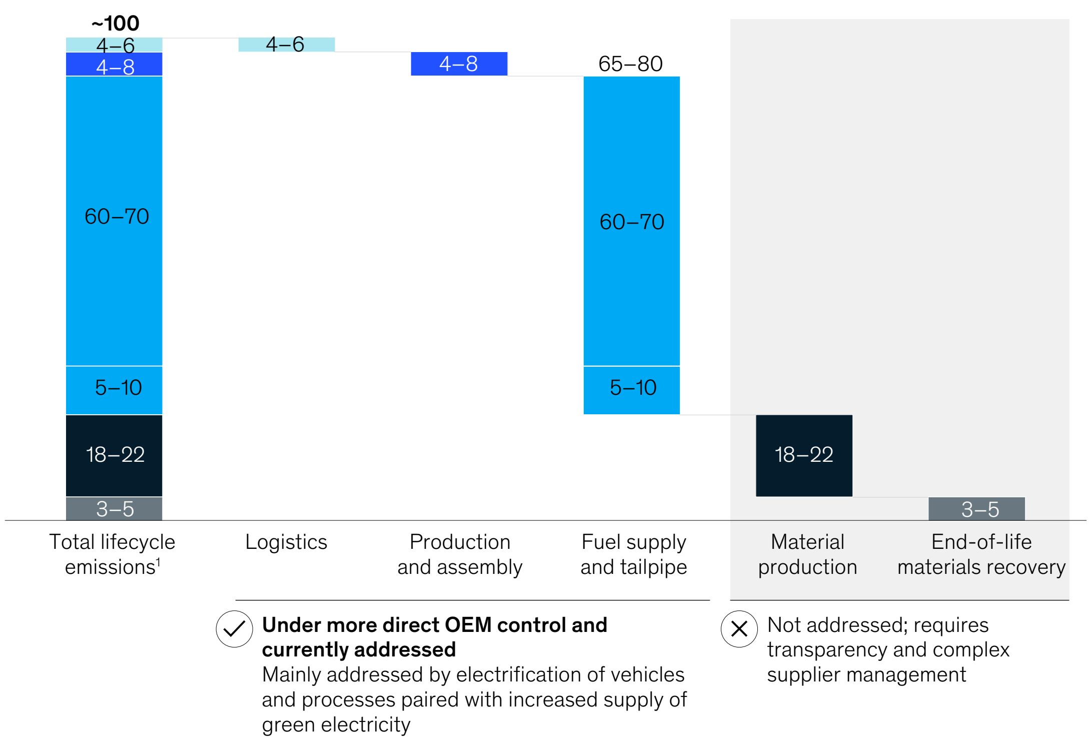
As tailpipe emissions decrease, emissions from vehicles' will increase both absolutely and relatively and soon become a larger share of life-cycle emissions. We estimate that the growing market share of battery electric vehicles that have higher baseline material emissions—and the changing energy mix required to power them—will boost material emissions from 18 percent of vehicles' life-cycle emissions today to more than 60 percent by 2040 (Exhibit 2). This jump presents both a

[1] For the purposes of our discussion, we will focus on internal combustion engine vehicles.
[2] Based on industry analysis and interviews with subject-matter experts.

Exhibit 1

The automotive industry has largely focused on the reduction of tailpipe emissions, but reducing material production emissions is also a priority.

% of total current life-cycle emissions of internal combustion engine vehicles

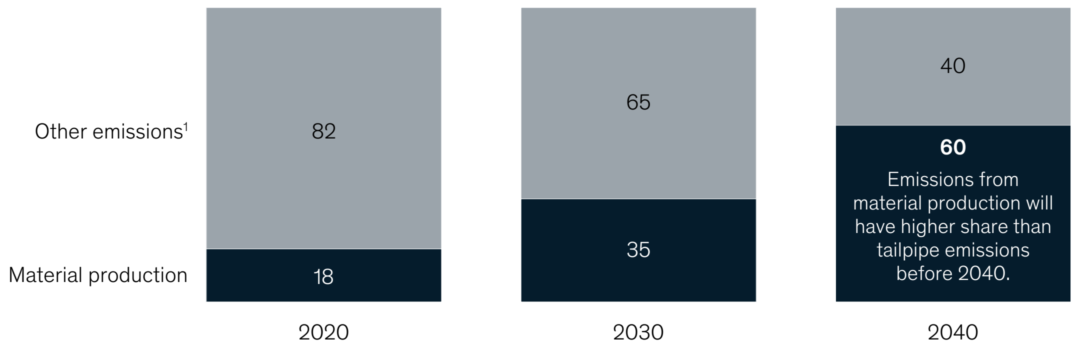


[1]For C-segment vehicle.
Source: Natural and bio Gas Vehicle Association; expert interviews; McKinsey analysis

Exhibit 2

Emissions from material production may reach 60 percent of life-cycle emissions by 2040.

% of life-cycle emissions, (based on required sales data)



[1]Assumed constant range of 150,000 km/vehicle as baseline – End-of-life emissions not considered here.
[2]2018 average ~120gCO2/km, target today 95 gCO2/km. Future assumptions: 2030 75 gCO2/km; 2040 50 gCO2/km.
Source: High level estimation of Circular Cars Initiative (2020) for ambitious EV adoption scenario

challenge and an opportunity on the path to the zero-carbon car.

Developing strategies to address these material emissions today is key because achieving large-scale decarbonization will be a long-term endeavor. This effort requires industry participants to adopt and scale the use of new technologies and their associated processes while managing changing flows of materials. What's more, availability for some low-carbon technologies, such as electric arc furnaces, may be limited in the short term, so early adopters stand to gain outsize benefits. Industry participants should begin to outline the transition now.

To lay the foundation for this transition, we have investigated both the carbon abatement potential as well as the cost implications of a comprehensive set of technical levers for a near-to-full range of automotive materials. This analysis helps to detail the automotive manufacturing ecosystem's path toward the zero-carbon car.

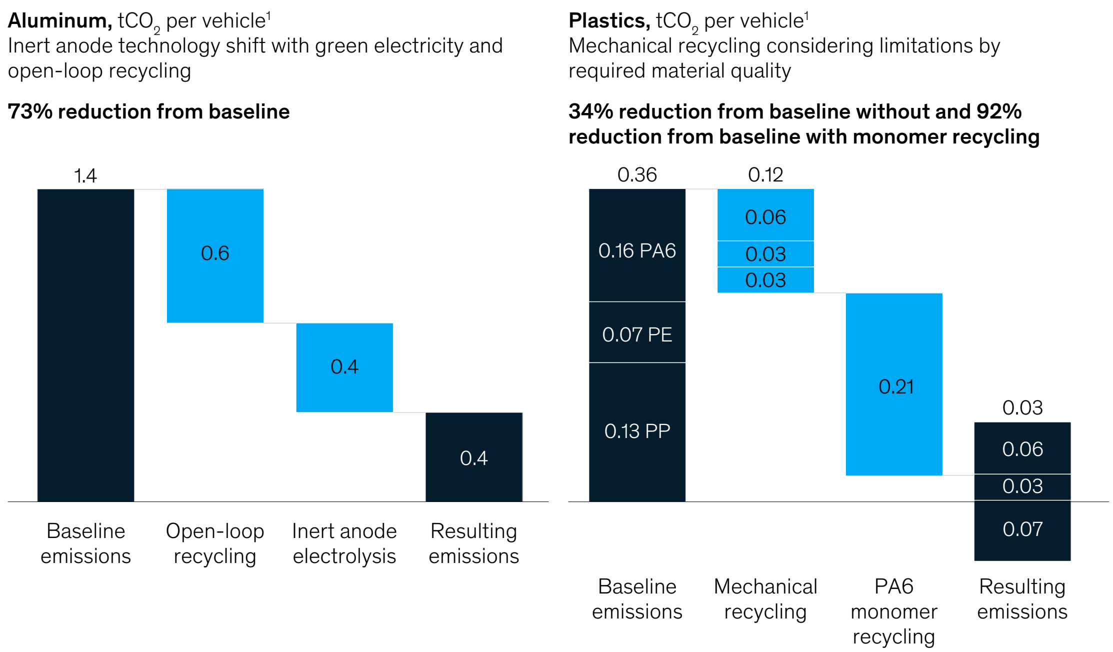
Our analysis shows that for an internal combustion engine vehicle (ICEV), 29 percent of material emissions could be abated in a cost-positive way by 2030. The industry—indeed, automotive manufacturing ecosystems—should prioritize the methods that can help achieve such savings. Most of these savings involve electrifying existing processes, using low-carbon energy sources, adopting and scaling new technologies that reduce process emissions, and both allowing for increased use of recycled materials and actually recycling a greater share of materials.

About 60 percent of these cost-positive decarbonization approaches involve aluminum and plastics. More expansive use of recycled aluminum, new smelting technologies, and green electricity can reduce emissions from aluminum production by about 73 percent from their current levels while also reducing production costs. Similarly, recycled materials such as polypropylene or polyethylene, especially for plastics in parts of vehicles that are not generally visible, can produce savings and cut emissions from plastic production by 34 percent. Scaling nylon recycling technologies could further decrease total plastics emissions by up to 92 percent (Exhibit 3).[3]

[3] The 92 percent decrease in emissions includes carbon credits earned from averted oil extraction.

Exhibit 3

The automotive industry can decrease aluminum and plastics' material emissions significantly while decreasing production costs.



Note: Figures may not sum, because of rounding.

[1] Tons of CO_2; in this analysis we are considering a premium SUV model with 1.95 tons vehicle weight: 1.04 tons steel; 0.29 tons aluminum, 0.10 tons rubber, 0.07 tons PP, 0.03 tons PE, 0.05 tons glass, 92 kilowatt-hour battery.

Source: McKinsey Abatement Model Analysis

Further emissions abatement would add costs, but the associated technologies—such as electric arc furnaces and direct reduced iron for steel production—could scale in the long term. Hydrogen-based steelmaking in particular is already technically feasible. However, widespread adoption is dependent on costs, the necessary supply chain, and the regulatory changes that support this transition.[4]

Automobile manufacturing could further reduce its current emissions if manufacturers increase production of relatively carbon-intensive components such as battery cells in regions with low-carbon power grids; indeed, such activity is already occurring in some areas. If the industry were to implement the measures that have potential for cost savings, those savings could then be applied to an additional 37 percent of abatement measures to offset the measures' costs. The net result would abate 66 percent of emissions while keeping vehicle costs the same.

Despite the environmental and economic promise of decarbonizing materials in the automotive value chain, the specific path forward is challenging because a coordination problem lies at its heart. The carbon-abatement methods we describe require the work of multiple parts of the value chain. In fact, most of the material emissions we've identified are outside OEMs' direct control. For example, our analysis indicates that 79 percent

[4] For more on decarbonizing steelmaking, see Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization challenge for steel," June 3, 2020, McKinsey.com.

of emissions from aluminum production occurs during the smelting process. What's more, many of the technologies required are not yet available at scale and would require significant up-front investments, and the flow of materials is complex and difficult to track. This opacity makes it challenging to prioritize decarbonization efforts based on the size of different materials' and processes' carbon footprints.

And while there are multiple viable ways to fully decarbonize the majority of automotive materials, many of these paths are mutually exclusive. Different players along the automotive supply chain might pursue divergent approaches and set disparate standards, which can create inefficiencies and lead to higher material costs and delay and limit emissions abatement. Indeed, none of the decarbonization approaches we describe can be implemented by a single organization—or an isolated segment of the value chain. An OEM-led, coordinated, collaborative approach across the automotive value chain is critical to optimize impact and costs.

As a first step, OEMs have to understand the decarbonization potential and the cost implications of the materials they use. They can use this information and their own aspirations to evaluate their progress toward their individual decarbonization goals, identify technologies they'll need to adopt, and work with other participants in the value chain to realize their vision (Exhibit 4).

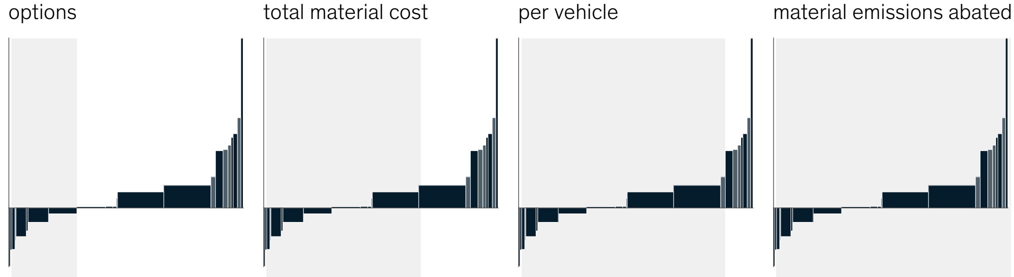
As they explore and articulate their role, OEMs should identify the areas in which they most want to exert influence and where they can create the most competitive advantage.

Exhibit 4

OEMs' approach to decarbonizing materials depends on their ambitions and their customers' willingness to pay.

Illustrative pathways Pathway

	Cost-positive Limit actions to cost-positive decarbonization options	**Net-zero cost** Limit actions to achieve a net-zero impact on total material cost	**"Sustainability premium"** Allow for €200+[1] additional material cost per vehicle	**Zero-emission** Full zero-carbon vehicle pathway with >95% material emissions abated



Example actions	• Mechanical recycling • Open-loop recycling	• Steel: increased scrap and share in electric arc furnace (EAF) route • Plastics: pyrolysis	• Biogas-based direct reduced iron (DRI) for EAF • Increased natural rubber share	• Plastics: power-to-chemicals (PE)

Ambition

Low High

[1]Example additional material cost, reasonable range to be determined.

To make emissions abatement cost effective, OEMs must also collaborate with other ecosystem players. This effort requires an intensive assessment of their suppliers and occasionally a willingness to work with other OEMs to capture the abatement potential at reasonable costs. For example, a coalition of OEMs could harvest high-grade aluminum from end-of-life vehicles.

OEMs should also stay updated on practices and technologies in other industries that could contribute to their decarbonization efforts once these other industries' efforts reach maturity. For instance, many industries chemically recycle plastics, a technology that OEMs could also adopt if it proves to be both carbon saving and cost positive.

After electrifying powertrains, reducing material emissions is the next big opportunity for the automotive industry to define its role in global decarbonization efforts. There are a number of cost-effective ways forward and long-term strategies to act on—but automotive OEMs must take the first step toward replacing the vehicles on today's streets with the zero-carbon car of tomorrow. As leaders of the value chain, they can rally the industry and surrounding players and maintain their place in the driver's seat throughout this transition.

Eric Hannon is a partner in McKinsey's Frankfurt office; **Tomas Nauclér** is a senior partner in the Stockholm office, where **Anders Suneson** is an associate partner; **Fehmi Yüksel** is a consultant in the Cologne office.

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Decarbonization challenge for steel

Hydrogen as a solution in Europe

by Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer

Steel is one of the core pillars of today's society and, as one of the most important engineering and construction materials, it is present in many aspects of our lives. However, the industry now needs to cope with pressure to reduce its carbon footprint from both environmental and economic perspectives. Currently the steel industry is among the three biggest producers of carbon dioxide, with emissions being produced by a limited number of locations; steel plants are therefore a good candidate for decarbonization. While the industry must adapt to these new circumstances, it can also use them as a chance to safeguard its license to continue operating in the long term.

In 2015, the global response to the threat of climate change took a step forward when 190 nations adopted the Paris Agreement. In 2019, the United Nations announced that over 60 countries – including the United Kingdom and the European Union (with the exception of Poland) – had committed to carbon neutrality by 2050, although the three principal emitters China, India, and the United States were not among that number.[1] Moreover, some nations have pledged to work toward earlier dates. Together, these agreements have led to growing pressure to pursue decarbonization across all industrial sectors.

Every ton of steel produced in 2018 emitted on average 1.85 tons of carbon dioxide, equating to about 8 percent of global carbon dioxide emissions.[2] Consequently, steel players across the globe, and especially in Europe, are increasingly facing a decarbonization challenge. This challenge is driven by three key developments that go beyond the Paris Agreement:

1. **Changing customer requirements and growing demand for carbon-friendly steel products.** A trend that has already been observed in various industries, including the auto industry where manufacturers such as Volkswagen or Toyota have the ambitious aim of eliminating carbon emissions completely from their entire value chains (including their suppliers) and taking on a full life cycle perspective.

2. **Further tightening of carbon emission regulations.** This is manifested in carbon dioxide reduction targets, as well as rising carbon dioxide emission prices as outlined in the European Green Deal.

3. **Growing investor and public interest in sustainability.** For example, the Institutional Investors Group on Climate Change, a global network with 250-plus investors and over USD 30 trillion in assets under management, has raised expectations for the steel industry to safeguard its future in the face of climate change. At the same time, global investment firm BlackRock has confirmed its commitment to environmentally responsible business development and sustainable investing.

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[1] Climate Action Summit 2019, *Report of the Secretary-General on the 2019 Climate Action Summit and the Way Forward in 2020*, UN.org.
[2] World Steel Association.

Recent studies estimate that the global steel industry may find approximately 14 percent of steel companies' potential value is at risk if they are unable to decrease their environmental impact.[3] Consequently, decarbonization should be a top priority for remaining economically competitive and retaining the industry's license to operate. Moreover, long investment cycles of 10 to 15 years, multibillion financing needs, and limited supplier capacities make this issue even more relevant and lock in significant lead times for addressing the decarbonization challenge.

In response, decarbonization measures such as establishing or switching to hydrogen-based (H_2) steel production can be implemented either in forthcoming (greenfield) sites or existing (brownfield) facilities.[4] The latter opportunity requires existing equipment to either be retrofitted or for the facility to possibly be completely rebuilt in order to implement a decarbonized production process. The optimal steps to decarbonization will differ by location and site, depending on the likes of technical feasibility, existing infrastructure, market demands, operating costs (i.e., the price of renewable electricity, the price of scrap), and the regulatory environment.

14%

of steel companies' potential value is at risk if they are unable to decrease their environmental impact

[3] Study of 20 global steelmakers. The weighted average value at risk for the sample is 14 percent of net present value under a 2°C scenario, where global carbon prices rise to USD 100 per ton of carbon dioxide. Results range from 2 percent to 30 percent for individual companies.
[4] For example: retrofitting existing EAF plants for hydrogen-based steel production.

The technology landscape for decarbonization in steel production

Going forward, steel producers need to assess, evaluate, and decide on a technologically and economically viable way to decrease their carbon footprint.

Steel can be produced via two main processes: either using an integrated blast furnace (BF)/basic oxygen furnace (BOF) or an electric arc furnace (EAF). While integrated players produce steel from iron ore and need coal as a reductant, EAF producers use steel scrap or direct reduced iron (DRI) as their main raw material. As the predominant production method in Europe is the conventional, coal-dependent BF/BOF process, the need to assess alternative breakthrough technologies to reduce carbon dioxide emissions is high. Indeed, almost all European steel producers are currently developing decarbonization strategies and running pilot plants to assess different production technologies (Exhibit 1). These include:

BF/BOF efficiency programs. Such programs improve efficiency and/or decrease production losses in different ways, for example: 1) optimizing the BF burden mix by maximizing the iron content in raw materials to decrease the usage of coal as a reductant, 2) increasing the use of fuel injection through, for example, pulverized coal injection (PCI), natural gas, plastics, biomass, or hydrogen (as an additional reagent on top), or 3) using coke oven gas in the BF as an energy source, just to name some of the options. These processes may have the potential to decrease carbon dioxide emissions without eliminating them, but do not offer fully carbon-neutral steel production.

Biomass reductants. This process uses biomass, such as heated and dried sugar, energy cane, or pyrolyzed eucalyptus, as an alternative reductant or fuel. As such it is regionally dependent and mainly important in areas where the biomass supply is guaranteed, like in South America or Russia. In Europe, the availability of biomass is likely not enough to reduce carbon emissions on a large scale.

Carbon capture and usage.[5] This uses emissions to create new products for the chemical industry, such as ammoniac or bioethanol. At present, carbon capture and usage remains technologically premature and yet to be proven economically.

Increase share of scrap-based EAFs. This process maximizes secondary flows and recycling by melting more scrap in EAFs. EAF producers are more environmentally friendly and flexible to the ups and downs of demand. However, shifting to EAF-based steel production requires the future supply of renewable electricity to be commercially available, as well as a sufficient supply of high-quality steel scrap. High quality scrap is necessary for the production of high-quality products, which are nowadays mainly produced through the integrated route. If high-quality scrap is not available, lower-quality scrap can be mixed with DRI to ensure a high quality EAF input.[6] Increasing the share of EAF-based steel production will play a key

[5] Carbon capture and storage not further detailed as political/regulatory approval is uncertain across different regions due to potential insecurities during storage.
[6] The exact scrap/DRI ratio depends on the scrap quality and end product.

role in decarbonizing the steel industry. However, this role will be dependent on the regional availability of high-quality scrap and could therefore be limited in regions with an inadequate supply of high-quality scrap, making other technologies a must. Increasing demand for high-quality scrap will also lead to extra cost for the EAF-based steel production.

Optimize DRI and EAF. This requires boosting usage of DRI in combination with EAF. DRI-based reduction emits less carbon dioxide than the integrated method and enables the production of high-quality products in the EAF. High-quality products require the highest quality of steel scrap; if scrap is limited, the use of DRI is necessary to guarantee specific qualities. DRI production requires cheap and readily available natural gas. Thus, regions with low natural gas prices – the Middle East or North America – are big DRI producers whereas the process is less common in Europe. Selected European steel players import Hot Briquetted Iron (HBI, a less reactive and therefore transportable form of DRI) to use either in the BF to optimize the burden mix or in the EAF where they mix it with scrap in order to increase quality.

DRI and EAF using hydrogen. This uses green hydrogen-based DRI and scrap in combination with EAFs. The process replaces fossil fuels in the DRI production stage with hydrogen produced with renewable energy. It represents a technically proven production method that enables nearly emission-free steel production. All major European steel players are currently building or already testing hydrogen-based steel production processes, either using hydrogen as a PCI replacement or using hydrogen-based direct reduction. At this point it is important to note that EAF-based steel production will not require a completely green hydrogen-based DRI supply to be able to fulfill current customer requirements and achieve carbon neutrality.

As BF/BOF efficiency programs only result in a reduction in carbon dioxide emissions, without eliminating them entirely, they cannot be a long-term solution. Biomass reductants and carbon capture and usage are either only feasible in certain regions or still in the early stages of development. The share of EAFs producing high-quality steel will increase but requires the availability of scrap and DRI. Hence, adopting an approach combining scrap, DRI, and EAF using hydrogen is currently considered the most viable option and the long-term solution to achieving carbon-neutral steel production, especially in Europe.

Exhibit 1

Steel producers are evaluating decarbonization strategies.

Focus of this document

	CO_2 reduction			Full decarbonization possible		
	Blast furnace efficiency (BOF)	**Biomass reductants**	**Carbon capture and usage**	**Electric arc furnace (EAF)**	**DRI plus EAF using natural gas**	**DRI plus EAF using H_2**
Strategy	Make efficiency improvements to optimize BF/BOF operations	Use biomass as an alternative reductant or fuel	Capture fossil fuels and emissions and create new products	Maximize secondary flows and recycling by melting more scrap in EAF	Increase usage of DRI in the EAF	Replace fossil fuels in DRI process with renewable energy or H_2
Examples	Optimized BOF inputs (DRI, scrap), increased fuel injection in BF (e.g., hydrogen, PCI)	Tecnored process	Bioethanol production from CO_2 emissions	EAF – usage to melt scrap	Current DRI plus EAF plants using natural gas (NG)	MIDREX DRI process running on H_2 HYL DRI process running on H_2
Current outlook	Technology readily available at competitive cost	Process possible in South America and Russia, due to biomass availability	Not available on an industrial scale	Technology readily available at competitive cost	Technology readily available	Technology available at high cost

SOURCE: McKinsey analysis

Green hydrogen-based steel production as a silver bullet?

Although hydrogen is one of the most abundant elements on earth, in its pure form it is rare. Extracting hydrogen from its compounds requires a lot of energy. Although these energy sources can be diverse, the most popular hydrogen production method is carbon dioxide intensive. Most of the world's hydrogen production consists of "grey hydrogen," produced via steam methane reforming (SMR), which forms both hydrogen and carbon dioxide. In contrast, the term "blue hydrogen" is reserved for hydrogen production that involves carbon capture and usage or the storage of emitted carbon dioxide. Additionally, the electricity-intensive electrolysis of water is yet another process for producing hydrogen and is the only carbon-neutral technique (provided that renewable energy sources can be used); this is known as "green hydrogen."[7]

There are generally two ways to use (green) hydrogen in steel production. First, it can be used as an alternative injection material to PCI, to improve the performance of conventional blast furnaces. Although the use of PCI is common, the first pilot plants using hydrogen injection have recently been set up to assess decarbonization potential. However, while the injection of (green) hydrogen into blast furnaces can reduce carbon emissions by up to 20 percent, this does not offer carbon-neutral steel production because regular coking coal is still a necessary reductant agent in the blast furnace.

Second, hydrogen can be used as an alternative reductant to produce DRI that can be further processed into steel using an EAF. This DRI/EAF route is a proven production process that is currently applied using natural gas as a reductant, for example by players in the Middle East with access to a cheap natural gas supply. However, the direct reduction process can also be performed with hydrogen. Based on the use of green hydrogen as well as renewable electricity from wind, solar, or water, a DRI/EAF setup enables nearly carbon-neutral steel production.

In more detail, a large-scale, green hydrogen-based DRI/EAF steel production process involves the following core process steps:

1. **Green hydrogen production.** Green hydrogen is produced by electrolyzing water in a process that requires significant amounts of electricity. Obtaining sufficient electricity from renewable energy sources will be the key challenge for green hydrogen production in Europe.

2. **DRI production.** In the DRI plant, iron ore in the form of DR pellets[8] is reduced with hydrogen in order to form DRI.[9] Using hydrogen as the reductant releases only water (i.e., it does not produce carbon emissions).

3. **Raw steel production using an EAF.** In the EAF, the DRI is heated and liquified together with steel scrap

[7] Hydrogen Europe, US Office of Energy Efficiency and Renewable Energy.
[8] Production of DR pellets is not entirely carbon neutral due to natural gas or oil residues used in baking.
[9] Hydrogen 5.0 with a purity of > 99.999 percent needed as a reduction agent in the DRI.

to produce raw steel. The use of electricity in this process (assuming it is from renewable sources) does not lead to any carbon emissions.

The key cost drivers for the pure hydrogen-based production process, i.e., maximum use of green hydrogen-based DRI, are similar to those of the EAF process, and include raw materials and electricity as well as processing and labor costs. The biggest cost differences and uncertainties are the generation of hydrogen (mainly determined by the electricity costs for water electrolysis) and running the EAF and caster on renewable energy.

Green hydrogen prices today are high, but these are expected to decrease rapidly over time (Exhibit 2).

Historically, gas used for grey hydrogen production was cheaper than renewable electricity for green hydrogen production, such that electrolysis has been rarely used in the past. Today, grey hydrogen is less than half the price of green hydrogen; however, prices are expected to turn around by 2030. This decline in price for green hydrogen is driven by: a) lower renewable electricity costs driven by lower prices for solar and wind energy, and b) falling costs for electrolyzers. The falling costs for electrolyzers are based on scaled up production, learning rate, and an increase in system size from 2 to 90 MW as well as efficiency improvements. As a result, green hydrogen is predicted to become significantly cheaper. Grey hydrogen prices will suffer as a result of increasing penalties for carbon dioxide emissions. The price outlook for blue hydrogen is relatively stable.

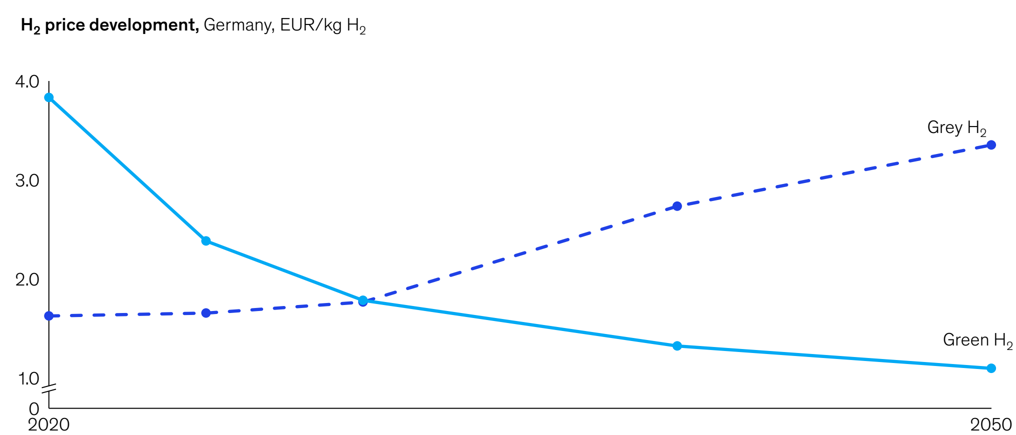
To assess the holistic economic competitiveness of pure green hydrogen-based steel production compared to conventional blast furnace production, one also needs to consider the cost of carbon dioxide.

In Europe, the EU emissions trading system (EU ETS) pursues a cap-and-trade strategy. The total amount of greenhouse gases that companies within the EU ETS can emit is limited by an industry-specific "cap" on the number of emission allowances. Over time, the cap is reduced, and total emission allowances fall. Within the cap, companies can receive or buy allowances. Every year, companies must relinquish all their allowances to cover their emissions, otherwise heavy penalties are imposed. Carbon dioxide prices are expected to significantly increase until 2050 and will be highly dependent on political regulations in every EU country. At the end of 2019, the average price of carbon dioxide in Europe was EUR 25/ton. Germany has already announced prices in the range of EUR 55 to 65/ton after 2026[10] and, by 2050, carbon dioxide prices in the range of EUR 100 to 150/ton could be a reality in Europe.

[10] For the transport and buildings sector.

Exhibit 2

Green hydrogen prices are expected to halve over the next ten years.



SOURCE: Hydrogen Council

Further, the cost competitiveness assessment of hydrogen-based steel is only viable if the capex implications (depreciation) are excluded, as conventional steel production assets are largely written off. However, capex requirements for the setup of pure hydrogen-based steel production (DRI plus EAF) in combination with the required hydrogen transport and storage will be significant. Surging carbon dioxide prices and decreasing hydrogen prices are crucial to ensuring the economic viability (according to cash cost) of pure hydrogen-based steel production. For this, renewable electricity prices need to fall below a threshold of approximately EUR 0.027/kWh to ensure cost-effective production of green hydrogen (Exhibit 3).

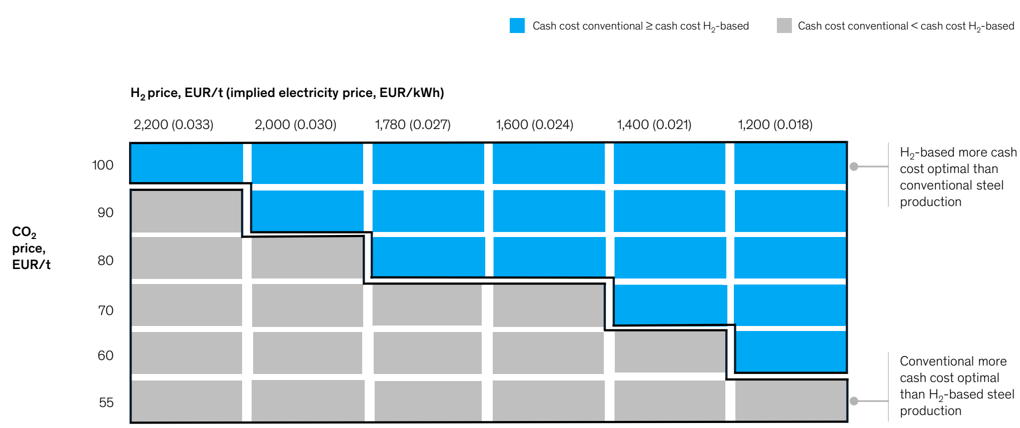
With expected carbon dioxide prices of around EUR 55/ton and hydrogen prices of some EUR 1,780/ton (implied electricity price at EUR 0.027/kwh) in 2030, conventional steel production still retains a cash cost advantage. However, this scenario changes as soon as hydrogen prices drop (driven by the cost of electricity) or carbon dioxide prices increase. Following this logic, pure hydrogen-based steel production is expected to be cash cost competitive between 2030 and 2040 in Europe.[11] As a consequence – and leaving aside environmental issues and any potential public concerns and investor fallout from not meeting carbon dioxide emission targets – the industry is likely to see the first large-scale replacements of integrated production facilities with DRI and EAF setups in Europe.

In this context it is important to note that a complete transition to a pure hydrogen-based steel production will not be needed to achieve the goal of a carbon-neutral steel industry. Instead, hydrogen-based steelmaking will represent one key production technology to replace the current integrated BOF route (likely with a focus on the share of high-quality products produced using the integrated BOF route) together with other production technologies such as the extended use of scrap-based EAFs. This mix will result in lower operating costs (as highlighted above for the pure hydrogen-based steel production), reduced investment needs, and will enable carbon-neutral steel production.

[11] Cost competitiveness assessment of hydrogen-based steel is only viable if capex implications, i.e., depreciation, are excluded, as conventional steel production assets are largely written off.

Exhibit 3

Cost competitiveness of pure hydrogen-based steel production based on hydrogen cost decline and carbon dioxide price rise.



SOURCE: McKinsey hydrogen-based steel model

Potential path forward for steel players in Europe

Today, hydrogen-based steel production using an EAF is technically feasible and already considered to be part of a potential long-term solution for decarbonizing the steel industry on a large scale. The question is not whether but when and to what extent this transformation will happen. However, there are a variety of interdependent factors that will determine when the decarbonization tipping points will occur in the steel industry. We have identified six external factors that will shape the future development and time to adoption of green hydrogen-based steel:

1. **Power supply.** Green hydrogen-based steel creates a need for a significant capacity increase in electricity derived from renewables. To put this into perspective, the total energy required to produce two million tons of hydrogen-based steel is about 8.8 TWh, which equates to the output from 300 to 1,100 wind turbines (depending on the output capacity of current and future turbines).[12] Hence, availability, steady supply, and competitive renewable energy costs are key decisive factors for the technology shift.

2. **Hydrogen-supply security.** The future shift to hydrogen-based steel relies heavily on the broad availability of green hydrogen on an industrial scale. Producing two million tons of hydrogen-based steel requires a green hydrogen amount of 144,000 tons. A capacity of 900 MW, or nine of the world's largest planned electrolysis plants producing 100 MW (for example those in Hamburg), are needed to produce this amount of green hydrogen. Hence, providing the required production capacity and infrastructure for hydrogen-based steel production on a large scale has a significant impact on the timeline for the commercial availability of hydrogen-based steel. Furthermore, green hydrogen prices, largely driven by renewable electricity, must decrease simultaneously to make the economics work, linking hydrogen supply security to the importance of renewable power supply. Finally, other industries and applications will compete for green hydrogen as it is likely going to be a scarce resource. To produce steel in Europe it will, however, be important to clarify that hydrogen needs to be leveraged to stay a player in the arena.

3. **Raw material.** To switch production from BF/BOF to DRI/EAF using hydrogen, raw material changes are necessary and will especially increase demand for DR pellets. The security of DR supply in the case of a massive switch to hydrogen-based steel production is uncertain and could result in rising price premiums, negatively affecting the economics of the new production method. Moreover, to guarantee carbon neutrality throughout the whole value chain, tight cooperation with steel suppliers, such as the iron ore industry, is essential.

4. **Production technology.** The basic production method for DRI/EAF powered with natural gas is already established and working on a large scale in certain markets that benefit from an abundant supply of cheap natural gas. Moving forward, switching the process to an entirely hydrogen-powered process is technically feasible, although the overall cost is still high, and the technology has yet to be proven on a large scale. On the upside, however, it is considered relatively easy to switch a DRI/EAF production method powered by natural gas over to hydrogen. Also, flat steel producers in North America have shown that even high-quality products can be produced via the DRI/EAF method.

[12] Assuming approximately 3.5 and 13.0 MW installed capacity per wind turbine, respectively. Assumed utilization 25 percent.

5. **Willingness to pay.** Considering steel's vital role in the global economy, customer support, acceptance, and eventually demand are required for the success of green hydrogen-based steel. Only if customers value carbon-reduced/neutral products, and are willing to pay for decarbonization, can this shift in production technologies happen. End user industries show a growing interest in carbon-reduced/neutral steel products to decarbonize their own value chain, in combination with a willingness to pay a price premium, also driven by recent discussions on Ecolabel approaches by the European Commission. Alternative to this would be a legislative intervention that takes the balance of benefits and extra cost into account. Given the nature of emissions it is clear that this regulatory initiative requires focus on regional production as well as on imports.

6. **Regulation.** The economics of increasing the share of hydrogen-based steel are dependent on continuing political momentum for decarbonization via measures such as carbon dioxide pricing and carbon border tax to avoid carbon leakage. Equally important is the provision of start-up capital and subsidies for initial investments to compensate for the capex requirements of the technological shift. Depending on scale, a plant based around DRI and EAF using hydrogen would have significant capex requirements. Therefore, this technological shift is dependent on a collaborative effort between regulators, governments, and industry stakeholders to facilitate access to required capital and to eliminate potential red tape.

Taking stock, the shift toward hydrogen-based steel cannot happen overnight and is only one key production technology that can be leveraged to achieve a carbon-neutral steel industry. Future availability of cheap energy from renewables and regulation will be the two key drivers for the adoption of hydrogen-based steel. Despite the goal of becoming carbon neutral (in Europe) still being 30 years in the future, it is crucial to act now: industrial sites have lifetimes exceeding 50 years and investment planning horizons of 10 to 15 years. Asset and footprint decisions need to be made today and must follow a clear decarbonization road map. The road map itself must combine long-term goals with actionable quick wins to allow for a gradual shift toward decarbonization that keeps all stakeholders on board. In Europe, green hydrogen-based steel production is likely to become one key technology that shapes the route to decreasing emissions – this could entail first optimizing BF/BOF processes, then switching to EAF using scrap and DRI powered with natural gas or imported HBI – and ultimately adopting carbon-neutral EAF production using a mix of scrap and hydrogen-based DRI. The mix of scrap versus DRI-based production using EAFs will depend on future product portfolios. The DRI method using hydrogen will be key to enabling the production of high purity steel grades in the future without the emission of carbon dioxide. As such, hydrogen-based steel is an opportunity to secure the future production of steel in Europe.

Christian Hoffmann is an associate partner in McKinsey's Düsseldorf office, where **Benedikt Zeumer** is a partner. **Michel Van Hoey** is a senior partner in the Luxembourg office.

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