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The Economic Case for Combating Climate Change

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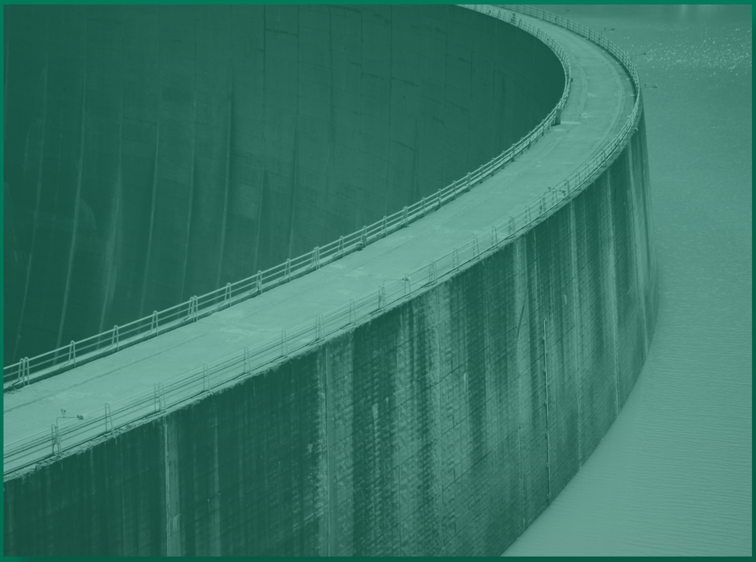

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THE ECONOMIC CASE FOR COMBATING CLIMATE CHANGE

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EXECUTIVE SUMMARY

Contrary to widespread belief, countries that take ambitious action against climate change can benefit macroeconomically—if they prioritize the most economically efficient measures for mitigating emissions. Many businesses strongly endorse such action, but policies must overcome microeconomic hurdles.

How to Decarbonize a Developed Economy: The Example of Germany

In one of the most comprehensive studies of national emissions reduction potentials to date—a study commissioned, supported, and endorsed by German industry—BCG recently showed that Germany can accomplish an 80% reduction from its 1990-level greenhouse gas (GHG) emissions by 2050, using only proven and accepted technologies. Even if Germany moves forward unilaterally, an efficient emissions reduction path would benefit the national economy. With global cooperation, Germany could even achieve 95% reduction without harming growth.

Proven Technologies Can Go a Long Way

BCG applied lessons from this study to six countries that, along with Germany, are collectively responsible for more than 60% of global emissions: the US, China, India, Russia, Brazil, and South Africa. All could close at least 75% of the gap between their current emissions trajectory and their individual 2050 2°C Paris Agreement targets with proven and accepted technologies. For the remaining abatement, solutions also exist today.

The Early-Mover Advantage

Many countries can take significant unilateral action without suffering an early-mover disadvantage. In fact, every analyzed country could benefit economically from moving closer to its 2°C emissions target.

Reaching 2°C—A $75 Trillion Investment Challenge

The last mile to 2°C emissions levels will be much harder to travel. It will require expensive and unpopular measures such as synthetic fuels and carbon capture and storage for some industrial processes (although not for coal power, for which such measures are too expensive). It will also mean a cumulative global investment of about $75 trillion through 2050, or 2% to 6% of countries' annual GDPs.

The Limits of Emissions Trading

Catalyzing this level of investment would require strong government action—and widespread international collaboration on reducing emissions. Global emissions trading, often cited as a measure that could pave the way to 2°C, falls short of being a one-stop solution. All nations need to trigger both cheap and expensive mitigation mechanisms simultaneously, and many countries with lower emissions reduction targets have no incentive to trade. These countries will need low-interest financing support to shoulder their emissions mitigation investments.

Time to Move

Preparing for accelerated emissions reduction can benefit both countries and companies. Given the possible economic gains from such policies, policymakers should focus on developing comprehensive national mitigation agendas that maximize economic advantage and on policies that encourage companies and individuals to act. Businesses should prepare for such a policy push and a faster-than-expected transition from fossil fuels to carbon-neutral technologies. Early movers stand to profit.

THE BIG MYTH

ANY UNILATERAL ACTION HURTS

Consensus thinking holds that the world will have a hard time reaching the headline goal of the Paris Agreement—keeping the increase in global average temperature to less than 2°C above preindustrial levels. Moreover, in the absence of coordinated global action, countries that unilaterally pursue a "2°C path" will face significant first-mover disadvantages.

While the first point is very likely true, the second is not. There are clear paths for most countries to achieve substantial reductions in greenhouse gas (GHG) emissions that can generate near-term macroeconomic payback. Just about all leading emitters could eliminate 75% to 90% of the gap between emissions under current policies and their individual 2050 2°C Paris targets using proven and generally accepted technologies. If they prioritize the most efficient emissions reduction measures, taking the necessary steps will actually accelerate, rather than slow, GDP growth for many countries. All countries can generate economic gain by moving at least part of the way—even if they move unilaterally.

BCG recently completed a study of the economically optimized paths for implementing climate change mitigation efforts in Germany. Using this work as a model, we analyzed six other countries that, together with Germany, collectively account for close to 60% of current global GHG emissions: China, the US, India, Brazil, Russia, and South Africa. For each country, we examined three scenarios: the "current policies path," the "proven technologies path," and the "full 2°C path." (For a full description of our methodology, see Appendix I.)

This report presents the results of our work, including, in Appendix II, summaries of the impact of accelerated climate mitigation actions on each country that we studied. The next few chapters examine our main findings and their implications. Principal among our observations is that there are good economic as well as environmental reasons for many countries to step up their climate change mitigation efforts—starting now.

HOW TO DECARBONIZE A DEVELOPED ECONOMY

IN *KLIMAPFADE FÜR DEUTSCHLAND* (or *Climate Paths for Germany*), one of the most comprehensive studies of national emissions reduction potential to date, BCG, together with the economic research firm Prognos, recently assessed how Germany can meet its stated goal of reducing GHG emissions by 72% to 93% (versus 2015 levels) by 2050. (This is equivalent to the officially quoted 80% to 95% reduction with respect to 1990 levels.[1]) The study presented economically optimized climate-change mitigation paths for reaching these goals, and the findings were surprising.

Under current policies, Germany is already on a path that cuts GHG emissions by more than 45% (60% versus 1990 levels) by 2050. The country can achieve a 77% emissions reduction (80% versus 1990 levels) by pushing further the use of proven technologies—and, if properly orchestrated, such a move would be economically viable even if Germany moves forward unilaterally. With global cooperation, a 93% reduction (95% versus 1990 levels) would not harm economic growth, although it would test the boundaries of foreseeable feasibility and require further maturing of, or overcoming acceptance hurdles against, some technologies.

In an unprecedented position paper, the Bundesverband der Deutschen Industrie (BDI)—the German Industry Association, which commissioned the study—united behind the core findings and demanded more systematic climate action by the German government.[2]

Delivering the German contribution toward a global 2°C scenario requires that emissions decline by 93% from 2015 levels, to 62 million metric tons of carbon dioxide equivalent (Mt CO_2e), by 2050. This is an ambitious goal, to say the least; for most sectors of the German economy, emissions would need to be eliminated entirely.

Germany can achieve >80% emissions reduction with use of proven technologies.

Nevertheless, achieving very substantial reductions is well within reach. Under current regulations and assuming current technology trends, Germany is on a path to reduce GHG emissions from 2015 levels by approximately 45% by 2050. Up to 77% lower emissions can be achieved by expanding further the use of proven technologies. Doing so would require the following changes:

- In the power sector, wind and solar power would need to cover more than 80% of demand, and Germany's coal and lignite generation would need to be phased out in favor of gas to still provide sufficient flexible backup capacity.[3]

- In parallel, all sectors would need to intensify their efficiency efforts—to accommodate new power consumers from the building and transportation sectors, and to avoid overstretching Germany's renewable generation potential.

- Available biomass should be concentrated in the industrial sector, replacing fossil fuels in process heat generation. (See the sidebar "A New Strategy for Biomass.")

- In the building sector, up to 80% of current building stock would need to be renovated by 2050 (an acceleration of today's energetic renovations by nearly 70%). Low-emission district heating could replace individual oil and gas heating in urban areas and heat pumps in less populated ones.

- In transportation, electric mobility would need to take over a large part of road transport— meaning battery power for passenger transport and light commercial vehicles and possibly electric overhead lines for trucks on major highways (a GHG-reduction measure that is already in piloting but remains controversial).

To be sure, the investment required is substantial: a total of $1.6 trillion through 2050 (1.1% of annual GDP).[4] But the annual direct add-on costs (after the substantial savings in operating costs are accounted for) are less than $20 billion. When individual hardships are systematically mitigated, they would barely hurt the German economy as a whole. Moreover, even if Germany moves forward unilaterally, the overall economic impact from a systemically optimized implementation (including "carbon leakage" protection[5]) would be slightly positive, thanks to GDP gains from accelerated investment and a

A NEW STRATEGY FOR BIOMASS

Biomass is a valuable and scarce resource in the battle against climate change. Valuable because it can theoretically replace fossil fuels in all sectors of the economy. Scarce because global supplies are limited and most countries do not have sufficient sustainably available volumes to do so.[1] It pays to think strategically about how this resource is deployed.

Today, most of the biomass used in energy production is consumed in three applications: biofuels to partly replace gasoline and diesel in transportation, scrap wood pellets or regular firewood to heat private households, and residual solid biomass and biogas, which are incinerated in smaller, decentralized units, to produce (baseload) power.

This mix is inefficient, and to accelerate emissions reduction economically, it needs to change. The more ambitious an emissions mitigation target that a country pursues, the more it should avoid using its biomass in applications that suffer further transformation losses (such as third-generation biofuels), that have technology alternatives (such as space heating and water heating), or that use the resource inefficiently (such as in power generation). Biomass should be concentrated primarily in the industrial sector, where it can replace fossil fuels in process heat generation.[2] Beyond using available volumes most efficiently, this application also has a long-term systemic benefit; the emitted nonfossil carbon dioxide can either be recycled to produce synthetic fuels or stored underground to create a "negative emissions" benefit.

NOTES
1. Sustainable volumes do not diminish existing forest or create competition with food production and material use. Algae-based biofuels and similar innovations could become interesting breakthroughs, but they are not yet mature enough to predict large-scale application.
2. Solid biomass can be used to generate low- and medium-temperature heat and steam (<500 °C); biogas can serve in high-temperature heat generation (>500°C).

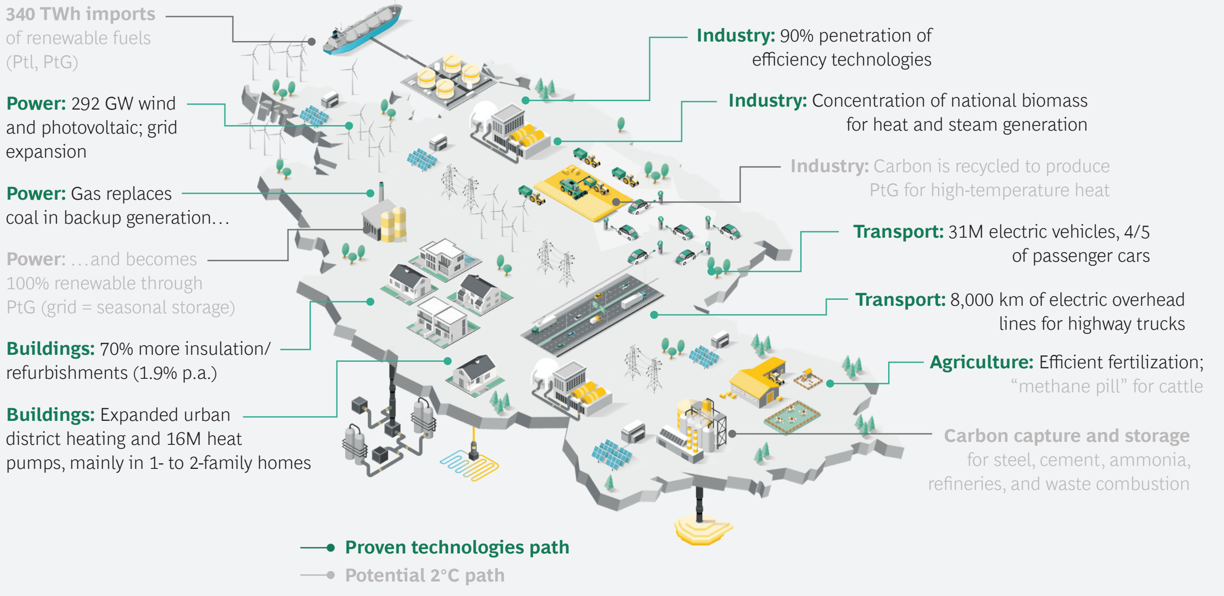
nearly 80% decline in fossil fuel imports, which together would outweigh declining industrial competitiveness.

Achieving the full 2°C target will be much harder. In addition to unpopular carbon capture and storage (CCS) for industrial processes, it will require significant amounts of expensive, imported synthetic fuels to eliminate emissions in power backup and high-temperature industrial heating (power-to-gas) and in shipping, air transportation, and the remaining non-electrified road transport (power-to-liquid). As of today, this will require either solid G20 consensus or alternative—as yet unidentified—technological innovations. (See Exhibit 1.)

NOTES

1. While the COP21 Paris Agreement uses 1990 emissions as a basis, a comparison with 2015 levels is more relevant for an action-oriented analysis. In this chapter on Germany, we indicate emissions reductions through 2050 with reference to both 2015 and 1990. For the rest of the report, we use 2015 as the base year.
2. Bundesverband der Deutschen Industrie (BDI): BDI-Handlungsempfehlungen zur Studie "Klimapfade für Deutschland," 2018.
3. This level of investment will require accelerated grid expansion, more storage capacity (mostly from batteries), and a flexible system integration of, for example, e-cars and heat pumps.
4. This estimate includes investments for current noneconomic measures.
5. That is, preventing industrial processes from simply moving abroad, often increasing global carbon emissions while unilaterally hurting the German economy.

EXHIBIT 1 | Germany Can Achieve 80% Emissions Reduction with Existing Technologies, but a 2°C Path Pushes Boundaries



Source: BCG analysis.
Note: All numbers valid for 2050; PtL = Power-to-liquid; PtG = Power-to-gas.

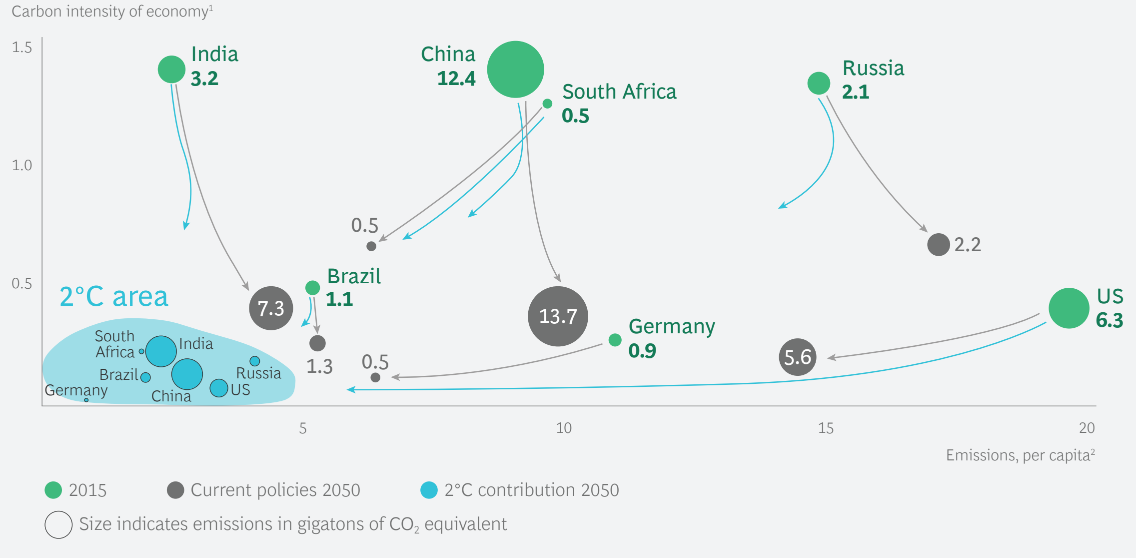
ONE GOAL, DIFFERENT CHALLENGES

THE SEVEN MARKETS THAT we studied reflect the global diversity of economic, demographic, geographic, and technical circumstances affecting climate change mitigation—and reveal many of the challenges that ambitious mitigation paths face. Under current policies, all seven countries will fail to meet their individual 2°C Paris targets; all of them need to invest more in reducing the carbon intensity of their economies. Developed nations must accelerate their decline in per capita emissions. Most developing countries, which continue to employ carbon-intensive technologies in their desire to catch up economically, need to change direction. (See Exhibit 2.)

Europe and the US

Developed economies, such as the US and Germany, have already managed to decouple economic growth from GHG emissions

EXHIBIT 2 | Some Countries Need to Accelerate Mitigation Efforts, Others Must Change Direction



Sources: International Energy Agency, International Monetary Fund, World Bank, World Resource Institute, BCG analysis.
[1]Tons of CO_2 equivalent per dollar of 2015 GDP.
[2]Tons of CO_2 equivalent per person.

growth. At the same time, the mobility and consumption patterns of their prosperous populations result in a high emissions footprint per capita. Under current policies, most developed nations are on a path to lower emissions, thanks to rising efficiency, more electric mobility, and gradual displacement of fossil fuels. The lessons from Germany can largely apply to other European countries because most have comparable economic structures and similar, high levels of fuel importation.

> The lessons from Germany can be applied to the other countries studied.

There are some key differences between European nations and other developed countries, however. For example, while Europe's population (despite continuous immigration) is expected to decline, the US population is expected to increase by one-fifth, or some 67 million people—the equivalent of the population of the UK—by 2050. In the US, with a larger land mass and a strong preference for larger cars, transportation is a much bigger source of emissions. And while Europe needs to import the vast majority of its energy, the US has substantial domestic resources, which reduces the economic benefits of displacing fossil fuels.

These differences have a big bottom-line impact; for example, while Germany will reduce its emissions footprint by 45% under current policies, US emissions are expected to decline by only 11% by 2050.

Reaching their respective 2°C targets would require both countries to substantially accelerate existing efforts. Similar imperatives apply to all highly developed economies around the world.

The World at Large

Many other countries face an even harder challenge. To catch up economically, they continue to employ low-cost and carbon-intensive technologies, increasing their per capita and total emissions footprints. From the perspective of global climate change mitigation, this situation is not sustainable. Most countries need a change in direction.

The difference in starting points and current trajectories is striking:

- China expects economic growth of more than 300% by 2050. Emissions, however, are expected to increase by only about 6 percentage points under current policies, as the population declines, efficiency increases, and the country burns less coal.

- India combines even more ambitious economic growth (more than 700% by 2050) with a strongly expanding population (a 26% increase). The resulting rise in coal combustion, a principal source of energy for power and industrial processes, will lead India's emissions to more than double by 2050, making it the second-largest emitter in the world. Countries in Southeast Asia face similar challenges.

- In Brazil, economic and population growth is expected to bring higher emissions in all sectors. The country faces a particularly thorny challenge in that more than 40% of its greenhouse gas footprint is caused by agriculture, much of which is for export.

- Among larger developing countries, only South Africa is expected to reduce its emissions footprint, despite economic growth and a population increase of more than 40% by 2050. Inefficient coal power generation today makes up more than half of the country's emissions. As old plants are replaced, this footprint will shrink. The African continent overall, however, is heading toward large population and emissions increases.

- The trajectory of Russia's emissions depends in large part on the global demand for fossil fuels. Assuming current policies continue, emissions will slightly increase despite mitigation measures and a decreasing population. (See the sidebar "The Challenge for Russia.")

THE CHALLENGE FOR RUSSIA

Russia offers extreme examples of the climate change challenges faced by carbon-intensive economies that do not have high per capita incomes.

Russia's GDP is about half that of Germany's, but its fossil fuel-based economy emits nearly 2.4 times as much GHG emissions. As a result, following a 2°C path would require about two and a half times higher investment ($5.5 trillion through 2050). In proportion to its economic capacity, the difference is even greater (6.1% of annual GDP versus 1.4% for Germany—more than four times as high). With the additional factors of high capital costs and cheap domestic fuels, implementation of an aggressive Russian climate change mitigation agenda would need to overcome massive obstacles.

This does not mean it cannot be done. Saudi Arabia, for instance, which has some similar structures, has announced one of the world's most ambitious programs to turn its economy toward solar power.

For more information on individual countries and their climate change mitigation paths, see the country-specific descriptions in Appendix II.

PROVEN TECHNOLOGIES CAN GO A LONG WAY

It's a high bar. To reach the global 2°C goal, all of our analyzed countries must significantly accelerate their emissions reduction efforts. To meet their respective Paris commitments, India and Brazil need to eliminate about half of their 2050 current-policy emissions. The US, China, Russia, and South Africa must eliminate all but one-quarter, and Germany all but one-eighth. (See Exhibit 3.)

Technically, these are achievable goals. All seven countries can close 65% to 90% of the gap between current-policy emissions and their individual 2050 2°C Paris targets with proven and generally accepted technologies. And for the remaining abatement gap, solutions also already exist.

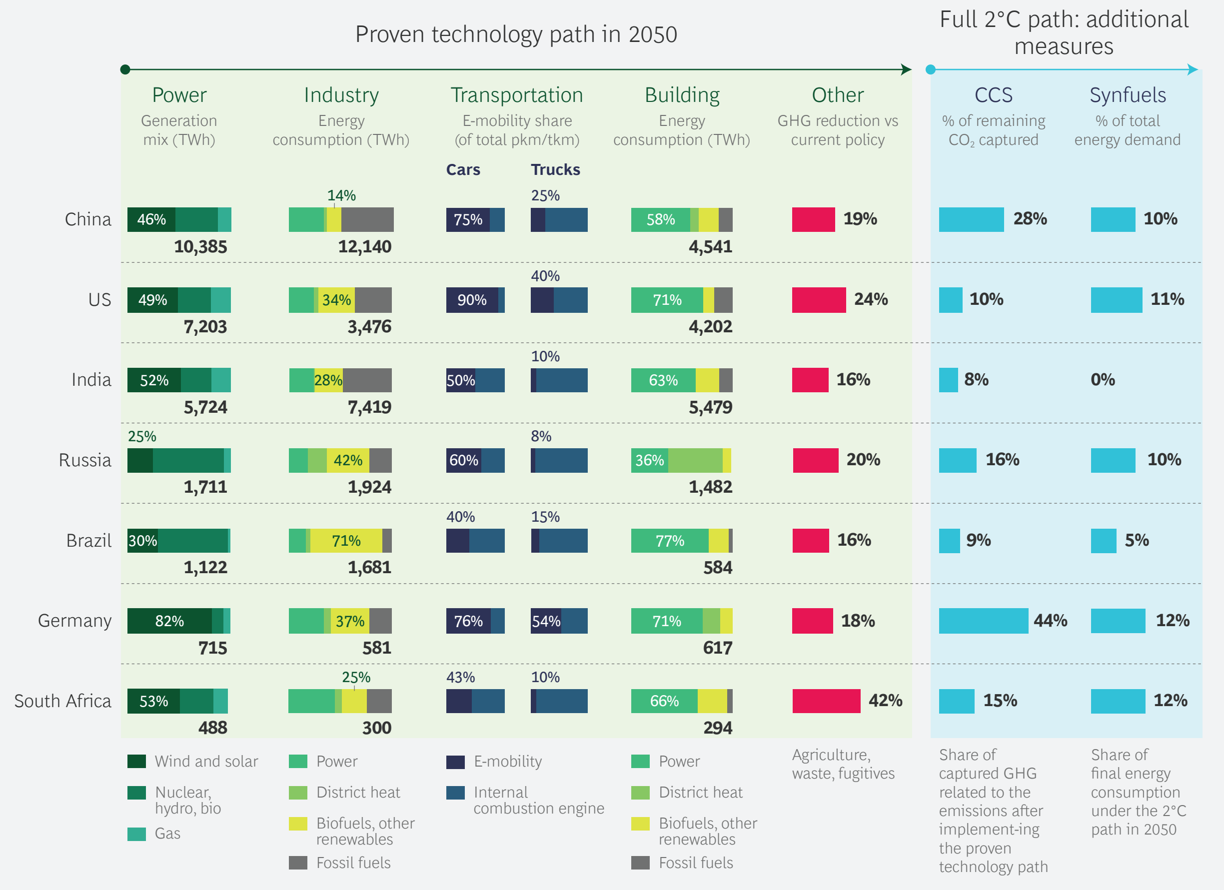
In the following sections we note the changes needed in each of the major carbon-emitting economic sectors. Exhibit 4 illustrates how the most effective technology path differs by country, and why all of the countries analyzed require a national emissions reduction agenda.

Exhibit 3 | All Countries Could Substantially Close the 2°C Gap with Proven Technologies

GHG emissions (Gt CO_2e)		China	US	India	Russia	Brazil	Germany	South Africa
2050 current policies		13.3	5.6	7.3	2.2	1.2	0.5	0.5
Gap to 2°C (100%)	Proven technology path	74%	74%	92%	74%	76%	67%	78%
	Full 2°C path	26%	26%	8%	26%	24%	33%	22%
2050 full 2°C path		3.7	1.3	3.8	0.5	0.5	0.06	0.1
Average annual gross investment (share of GDP)[1]	Proven technologies path	1.0%	1.0%	1.8%	2.2%	1.0%	1.1%	1.9%
	Full 2°C path	1.7%	1.5%	1.9%	6.1%	1.7%	1.5%	3.5%

Sources: International Energy Agency; BCG analysis.
[1]The investments for the full 2°C path include the investments in the proven technology path.

EXHIBIT 4 | Countries' Optimal Technology Paths Require Different Reduction Agendas



Sources: International Energy Agency (2017), World Resource Institute (2017), BCG analysis.
Note: pkm = passenger kilometers; tkm = ton kilometers.

Power Generation

By 2050, all of the countries studied could provide at least 80% of their power with low-carbon technologies such as wind, solar, hydropower, biomass, and nuclear. The exact mix depends on country-specific circumstances. For example, Russia will continue to rely heavily on nuclear power, but Germany decided to phase out this technology, along with fossil fuels. Brazil benefits from extensive hydropower capacity. Other countries will need to rely on a wider technology mix. In most, more wind and solar generation would need to be complemented by additional investment in grid infrastructure and demand flexibility, which, together with backup capacity, help to curb volatile generation profiles. (See the sidebar "The Myth of Excess Power.")

To further reduce emissions, the use of coal in power generation will need to decline over time. In many countries, this will result from both regulatory pressures and economic forces. As the cost of renewable energy sources continues to fall, and as their share of the power production mix rises, coal will gradually be pushed into a backup role. For this role, coal's high fixed costs make it a poor fit, which will trigger a gradual shift to gas-based generation in many countries. More ambitious climate change mitigation efforts will accelerate this transition. Because CCS is economically unviable for plants that are running below full capacity, coal plants no longer have a viable economic path to eliminating emissions. For utilities, this means that any new plant construction carries a growing economic risk. (See the sidebar "No Future for Coal?")

Industry

All countries could significantly reduce their industrial energy demand by expanding use of efficiency technologies, such as efficient

THE MYTH OF EXCESS POWER

Popular belief has it that a strong expansion of volatile wind and solar power generation inadvertently creates prolonged periods of "excess power" that can fuel new conversion solutions for cheaply producing hydrogen and power-to-x fuels. This is likely a myth.

In reality, increasing volatile power generation will trigger a "flexibility merit order," in which loss-prone electricity conversion processes are naturally relegated to last in line. In a first step, expanded power grids (including cross-country interconnections) can increase the amount of generated power that matches demand at any given time. In a second step, new consumers, such as electric vehicles, heat pumps, and power-to-heat processes, can all become more flexible in focusing their demand on periods with sufficient available power. As a result, excess power would either be caused by grid bottlenecks (which will be eliminated, if persistent) or concentrated in very few hours of a year (insufficient to make technologies built around excess power economically viable). In our German scenarios, excess power can be limited to only 1.4% of total 2050 net generation, even when more than 80% of power generation stems from intermittent renewables. Most of the excess occurred in fewer than 100 hours in the year studied.

motors and pumps and state-of-the-art process innovations. They could also replace a significant share of the fossil fuels used for industrial process heat generation by redirecting biomass to this application from other sectors. Depending on the availability of sustainable biomass relative to demand in each nation, this shift could eliminate between 14% (in China) and 70% (in Brazil) of all industrial energy emissions.

Transportation

Cost-effective emissions reduction in the transportation sector requires a widespread shift to electric propulsion.[1] Our research sug-

NO FUTURE FOR COAL?

In a recent publication, we argued that in the years ahead coal demand could remain relatively stable, given no drastic changes in consumption patterns and regulations. (See "Why Coal Will Keep Burning," BCG article, March 2018.) In the longer term, however, such changes, combined with evolving economics, may give us a very different outlook.

Driven by a rapid decline in costs, the share of renewable technologies in the global energy mix is rising significantly. If these costs continue to fall, coal plants could be pushed into a backup role, for which they are not well suited given their high fixed costs. Many plants being planned or built today face the risk of becoming stranded assets—even in countries with rising power demand. More ambitious climate change mitigation efforts would exacerbate this effect because coal plants have no economic path to eliminating emissions if they are running far below full capacity.[1] In all the countries we analyzed, closing down existing coal plants, even prematurely, and replacing them with a mix of intermittent renewables and gas backup would be cheaper than installing CCS capabilities. The risk premium on new plant construction in the coming decades may put the case for coal-based business models in peril.

Note
1. Low-emission coal generation is realistic only with carbon capture and storage (CCS). The further plant utilization declines as a result of intermittent renewables, the further the abatement costs of CCS increase.

gests that about half of all new automotive powertrains will be partly or fully electric by 2030. (See *The Electric Car Tipping Point*, BCG Focus, January 2018.) New passenger cars and light trucks could all be electric by 2050 in the US, China, and Germany. The same is likely true for all of Western and Central Europe. Depending on the dynamics of fleet renewal in each country, this would lead to an overall e-mobility share of 75% to 90% in 2050. Developing countries would follow with a slight delay, although some could struggle to reach similar electrification levels given their infrastructure constraints.

Cost-efficient reduction of emissions from larger trucks is possible with a mix of electric mobility technologies, including batteries, fuel cells, and overhead electric lines on highly frequented roads, complemented by renewable fuels. Germany, which has the highest road-freight transport density of all analyzed countries, could electrify more than half of its heavy transport with overhead lines. Such moves would not be necessary in countries such as Russia, where more than 60% of freight already travels via low-emitting rail.

Buildings

In the building sector, direct emissions can be reduced significantly by improving the efficiency of buildings and appliances and by expanding the use of heat pumps in place of gas and oil heating in suburban and rural areas. For countries that employ district heating systems (such as China, Germany, and Russia) it will be easier to phase out fossil fuels in cities. In warmer countries such as India and Brazil, solar thermal could play a growing role in water heating. In these countries, increased building efficiency will also help slow the power demand increase for air conditioning and cooling.

Other Sectors

In agriculture and waste management, efficient soil nitrification, better utilization of manure (for biogas production, for example), efficient waste utilization, and a ban on landfilling can help bring down emissions. Reduced mining and fossil fuel use would also help curb fugitive emissions. To reduce emissions from deforestation, several countries must employ more sustainable land use policies. (See the sidebar "LULUCF: A Burning Platform.")

NOTE
1. Electric propulsion includes battery-powered (both full-time and hybrid) and fuel cell vehicles. The switch to electric mobility clearly presupposes continuous emissions reductions in the power sector.

LULUCF
A Burning Platform

The worldwide greenhouse gas impact from land use, land-use change, and forestry (LULUCF) is currently 3 Gt CO_2e, or about 6% of total global emissions. These emissions are not subject to international climate commitments under the United Nations Framework on Climate Change. Yet under a global 2°C path, they would need to be cut by half.

Achieving this will require a significant increase in agricultural productivity—enough to stop the conversion of forests into farm land. The (quite literally) burning platform for this change lies in Indonesia, which currently causes more than half of the world's net LULUCF emissions (distantly followed by Zambia and Brazil, with about 10% each).[1] If Indonesia alone managed to reduce deforestation to the level in Brazil, and all other countries stayed at current levels, the global LULUCF 2°C trajectory would be met.

NOTE
1. A major driver of Indonesia's LULUCF contribution is the increasing global demand for palm oil.

THE EARLY-MOVER ADVANTAGE

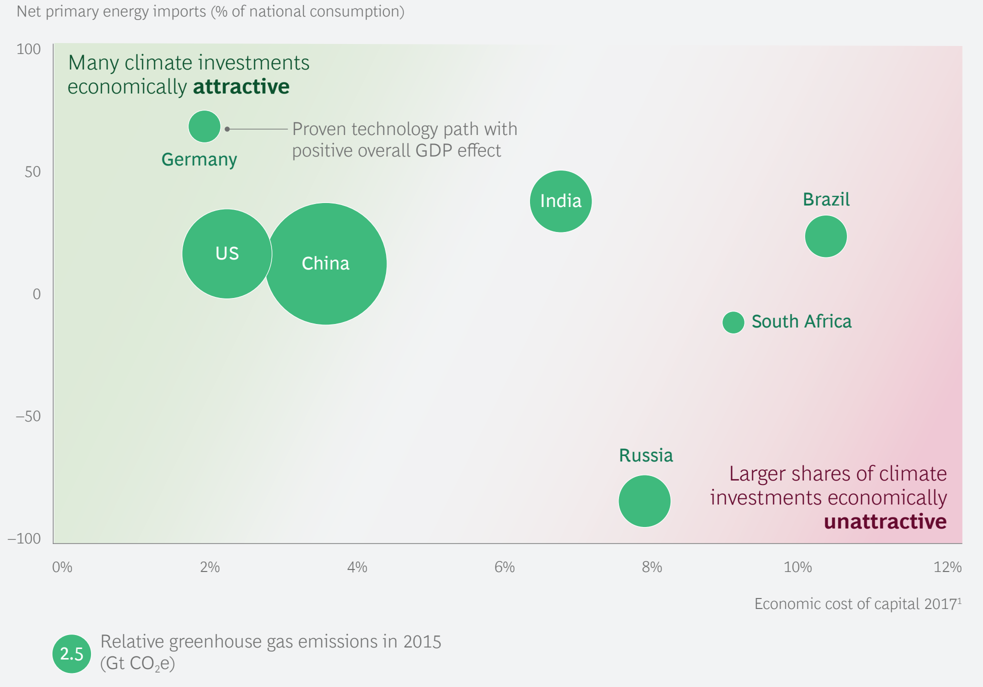
Collectively, the various national paths described in the previous chapter could close about three-quarters of the gap between current-policy and 2°C emissions levels in the seven analyzed countries. The cost is high: some $28 trillion in total investment through 2050. The US, China, Brazil, and Germany (and likely most other OECD countries) would need to invest about 1% of their GDPs in accelerating emission reductions. India, Russia, and South Africa would need to invest nearly twice as much. In the latter countries, two sectors (power and buildings) account for more than 80% of the investment requirement; a more aggressive cost decline in renewables could relieve the financial burden.

All countries could narrow their 2°C emissions gap without suffering economically.

But, contrary to conventional wisdom, countries that move unilaterally to lower emissions need not suffer an early-mover disadvantage. Planned and managed properly, unilateral climate change mitigation can have a positive impact on GDP because the required investments create significant economic stimulus. How much of this stimulus translates into a positive net impact depends on a country's cost of capital and the share of imported fuel in its energy mix. (See Exhibit 5.) For countries with low costs of capital, the investment is relatively affordable. For countries that import a lot of their fossil fuels, energy savings carry higher macroeconomic value.

For Germany, and for many OECD countries with similar circumstances, all or most of the proven technology path creates positive macroeconomic value. In countries with high costs of capital, such as Brazil, India, and South Africa, higher interest payments on investment-heavy emissions reduction measures crowd out the benefits from energy savings. Countries with cheap domestic fossil resources, such as South Africa and Russia, do not save GDP-deflating imports. Russia is in a particularly tough spot regarding climate investments; capital is expensive, and even potentially large energy savings have little economic value while fossil fuels are domestically ubiquitous. Nonetheless, all of the countries we analyzed can create economic growth by moving closer to their 2°C target.

EXHIBIT 5 | The Macroeconomic Attractiveness of Investments Depends on Capital Costs and Energy Imports



Sources: Oxford Economics; International Energy Agency; BCG analysis.
[1]Yield on ten-year government bonds, 2017.

REACHING 2°C

A $75 TRILLION CHALLENGE

Although realizing the proven technology path will be hard, traveling the last mile to 2°C emission levels will be tougher still. To reach its 2°C GHG reduction target of 93% by 2050, Germany, for example, would need to eliminate entirely the emissions from all but two of its economic sectors (process industry and agriculture). It would be forced to employ persistently unpopular CCS to remove process emissions from steel, cement, and ammonia production. It would need to import about 340 terawatt hours (TWh) of expensive renewable synthetic fuels for emission-free flexible power backup, high-temperature industrial heat, and air traffic and shipping, and replace all fossil fuels in road freight transport and passenger cars. Finally, unless meat and cheese consumption patterns change, it would even need to reduce natural emissions from its cattle population, potentially by using methane-suppressing food additives ("methane pills"). (Agriculture would still remain Germany's largest emitter, by a wide margin.)

A challenging problem for all countries is that costs rise in nonlinear fashion as measures become more far-reaching. To close the final quarter of their gaps to a 2°C path, the seven countries we analyzed would collectively need to step up investments by another 60% (to $45 trillion in total through 2050). Globally, this translates into a $75 trillion challenge, or 2% to 6% of countries' annual GDPs.[1]

The additional investment burden would vary among countries. Most would need to spend less than an additional 1% of their GDP, but South Africa (at 1.6% more) and Russia (3.9% more) would be hit particularly hard.

For the final push to 2°C, it is difficult for countries to act without broader international consensus.

For this last mile, it is difficult for countries to act without broader international consensus, at least at the G20 level. With such consensus in place, however, even very ambitious mitigation efforts in many countries would not be detrimental to economic growth. Such efforts might also offer a softer landing for some of the world's fossil fuel-based economies as the world inevitably moves toward renewables. (See the sidebar "The Oil Exporter Paradox.")

Note
1. This estimate includes the cost of synthetic fuels to replace international bunkers.

THE OIL EXPORTER PARADOX

If the results of our study are correct, emission reduction efforts should accelerate on a global scale thanks to environmental and economic incentives. This creates a strategic trilemma for major fossil fuel exporting economies: whether to resist, adapt, or embrace decarbonization.

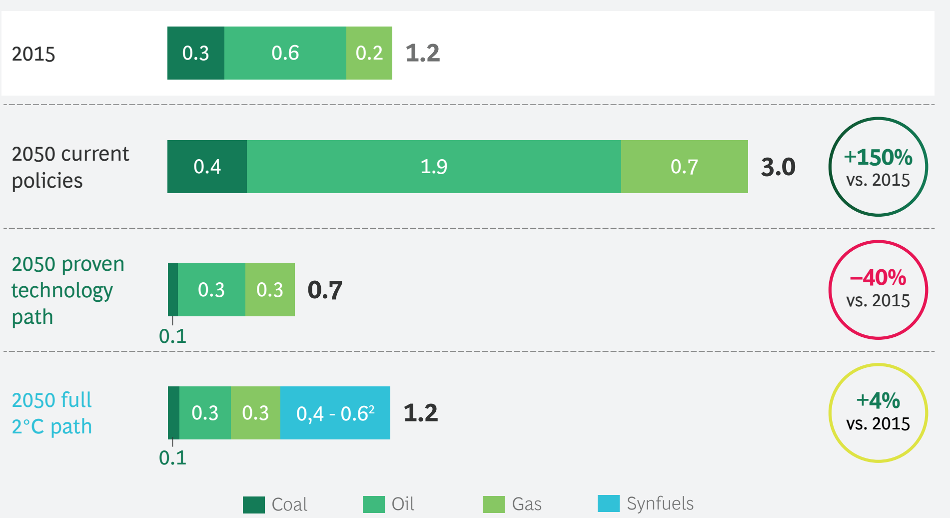
If the world (or—out of self-interest—many of its major emitters) were to adopt an accelerated climate change agenda based on proven technologies, investments in efficiency and renewable technologies would duly displace all types of fossil fuels. Moreover, coal would be replaced by natural gas, liquefied natural gas, and biomass in the power and industrial sectors. Such a path would significantly challenge the business model of all fossil fuel exporting economies as the following dynamics take hold:

- After "peak oil" in 2030, the global oil market declines by half.
- The value of coal use drops by more than $200 billion in just the seven countries analyzed.
- The value of gas use increases only marginally (by about $20 billion, assuming constant prices).

On the other hand, many current hydrocarbon exporters (those that can combine existing infrastructure with strong wind and solar conditions) have a clear advantage for producing synthetic fuels. If global demand for such fuels picks up—which would be necessary to meet the 2°C target—their revenues could partially compensate for the falling sales of fossil fuels. As a result, a globally coordinated and ambitious 2°C effort could actually offer a softer landing for energy-exporting countries and oil and gas majors because it avoids the low-demand, low-price scenario that they might otherwise face. (See the exhibit.)

Synthetic Fuels Could Offer a Softer Landing for Oil and Gas Companies

Total hydrocarbon fuel costs for China, India, US, Russia, Brazil, Germany, and South Africa[1]
($trillions, 2015)



Sources: International Energy Agency, BCG analysis.
Notes: 2015 and 2050 current-policy fuel costs calculated with IEA WOE 2017 "New Policies" fuel prices; 2050 proven technology and 2°C paths calculated with IEA WEO "Sustainable Development" fuel prices; energy content of hydrocarbon fuels used in these countries: 2015 = 222 EJ, 2050 current-policies path = 284 EJ, 2050 proven technology path = 109 EJ, 2050 2°C path = 116 EJ.
[1]Without biomass and other renewables, including industry processes.
[2]At synfuel costs of $140-$180/MWh.

THE LIMITS OF EMISSIONS TRADING

To shoulder the investments needed, some countries will need help. Dedicated, low-interest financing and risk-reduction measures for companies making climate mitigation investments could enable many countries to accelerate their emissions reduction while safeguarding GDP growth. Current financing volumes, however, would need to rise significantly to have an impact.

Global emissions trading would help, but it is not a one-stop solution.

One frequent recommendation—putting a global price on emissions—could convert what are now vague political ambitions into tangible investment incentives (and help alleviate the competitive imbalances that might arise in sectors where some countries move faster than others). Another widely touted instrument, global emissions trading, has some potential to increase economic efficiency by enabling developed countries with high abatement costs to pay for cheaper measures in less developed nations. In our judgment, however, this mechanism has limitations.

First, the notion that cheap mitigation measures should be implemented before expensive ones—the idea that underpins the emissions trading concept—begins to crumble in the face of ambitious reduction targets. If countries need to eliminate most of their emissions, there is greater economic benefit from implementing both cheaper and more costly measures from the start, because many involve durable capital goods with long replacement cycles. For example, if space-heat generation needs to be emission-free by 2050, an oil-fueled boiler with a 25-year lifespan that is replaced in the next decade should be switched to a non-emitting technology, even if cheaper short-term alternatives for emissions reduction exist. Even under a global emissions trading scheme, corresponding national regulation will be required to reach national targets efficiently.

Second, in their early phases, many technologies (electric vehicles, CCS, and synthetic fuels, for example) will be more expensive than mature mitigation alternatives. The cost of such technologies will fall over time, but they need to be deployed early, so that learning and scale can enable cost reductions.

Third, the ability to shift the emissions burden among countries has clear limitations, since many countries with lower reduction targets have no long-run incentive to trade. In principle, developed economies need to invest in more expensive abatement measures sooner, while countries such as China and

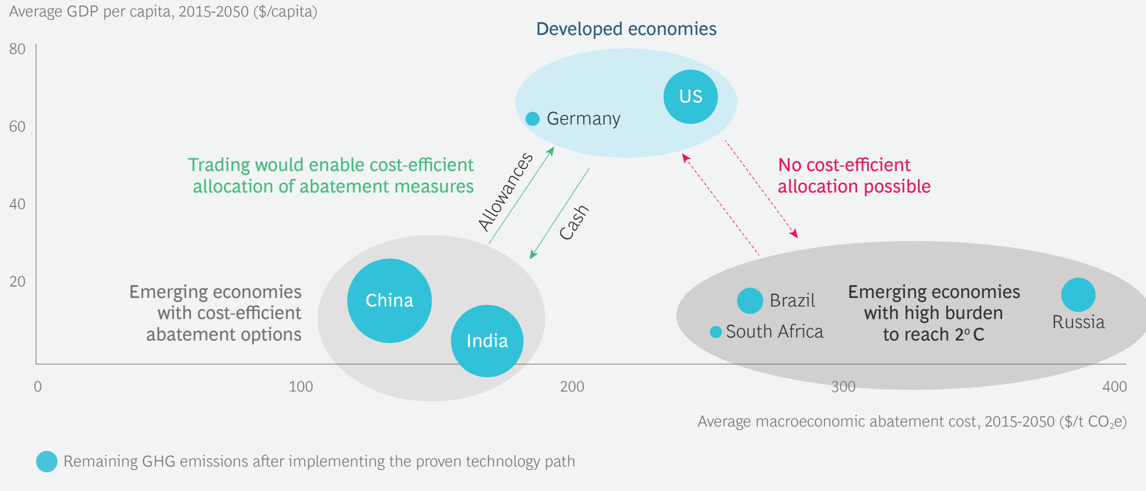
India can continue to implement less expensive measures for a number of years.[1] Efficient emissions trading systems between developed and less developed economies should thus reduce abatement costs for everyone. However, for many countries the same logic does not hold. In reality, the high costs of capital in many countries with lower immediate national reduction ambitions (such as South Africa, Brazil, and Russia, along with others) make abatement costs for these countries as high or higher than those in the developed world. As a result, even advanced countries with only expensive national measures have no incentive to trade with them. (See Exhibit 6.)

Even an effective carbon trading scheme would therefore need to be accompanied by a range of global and national policy instruments, including low-interest financing support, research funding, and market ramp-up support for immature technologies that are required to reach the 2°C path, as well as new regulations (designed to increase energy efficiency and phase out inefficient fuel subsidies) at the sector level.

NOTE

1. Another key concern related to global emissions trading is that regulating authorities in different countries compete, and emissions will always flow to the country with the most loopholes. The entire system would thus only be as strong as its weakest member.

EXHIBIT 6 | Emissions Trading Alone Will Not Help All Countries Reach Their 2°C Targets



Sources: International Monetary Fund, World Bank, BCG analysis.
Note: The costs for emissions abatement reflect the average macroeconomic costs for closing the gap between the proven technology and 2°C paths.

TIME TO MOVE

All in all, countries should—and will—accelerate emissions reduction. In many sectors (power generation and transport, for example), the shift toward climate-friendly technologies is already under way. As these technologies mature, their markets will grow, especially if governments around the world start pursuing more ambitious emissions mitigation agendas. The results of our study suggest that many will.

Policymakers have a clear case for more decisive unilateral action to reduce national emissions. Most countries can make significant progress toward their Paris accord targets without triggering any first-mover disadvantages, and many even stand to benefit economically. Moreover, global leadership in many new technologies is still up for grabs, and early movers can establish footholds in strongly growing markets. Given these benefits, policymakers should develop economically optimized mitigation agendas and implement thoughtful policies that incentivize companies (and individuals) to act and help them overcome the investment hurdle.

For their part, companies need to prepare for a world that moves far beyond current emissions policies and adopt much more ambitious emissions reduction in their strategies and planning. Leaders should start moving their business portfolios toward low-emission solutions and prepare for declining fossil fuel consumption. They should also enter into active dialogue with their respective governments to encourage policies that help address investment hurdles. The transition will likely be faster than expected. Early movers stand to benefit.

Limiting global warming is one of humanity's defining challenges in the 21st century. Although the odds of reaching the 2°C goal remain challenging, comprehensive national action can help achieve a much-needed change in direction—and close a substantial portion of the gap while safeguarding economic growth.

APPENDIX I
METHODOLOGY

For any country, designing the economically optimized path toward its 2050 2°C Paris target requires a depth of analysis similar to that in our study of Germany—as well as a similar level of stakeholder involvement and validation. For this report, we used a simplified approach to show what cost-efficient climate change mitigation paths might look like for China, the US, India, Russia, Brazil, and South Africa and what their economic costs would be. This appendix gives a broad overview of our modeling approach.

CONTENT	MODELING APPROACH
Baselining (current-policies emissions)	For the **current-policy** scenario, we assumed that the analyzed countries will fulfill their existing Paris pledges (NDC), all of which fall far short of their 2°C goals. For **energy-using sectors and process industries**, the emissions trajectories correspond with the "New Policies Scenario" (NPS) of the IEA WEO 2017 through 2040.[1] For the decade to 2050 we extrapolated the emission trends with slightly higher negative CAGRs to reflect faster emissions reductions in later years. We correlated **fugitive emissions** with domestic consumption of fossil fuels in the respective countries within the IEA WEO NPS 2017. For Russia (a net energy exporter), we correlated fugitive emissions with global fossil fuel consumption. We modeled the emissions from the **waste and agriculture sectors** using historical trends, available forecasts (sources: World Resource Institute, Food and Agricultural Organization of the United Nations), and macroeconomic indicators, and we calibrated the results with the median "pledges scenario" time series of the Climate Action Tracker (CAT), an independent scientific analysis that tracks progress toward the 2°C Paris goal.

CONTENT	MODELING APPROACH
2°C emissions targets	The total emissions budget for each country for the target year 2050 corresponds with relative burden sharing per the IEA "Energy Technology Perspectives (ETP) 2°C scenario." We did not consider emissions trends beyond 2050. For the **energy-using sectors and process industries**, we used the emissions trajectories of the IEA "Energy Technology Perspectives (ETP) 2°C scenario." We correlated **fugitive emissions**, as described above, on the basis of the IEA ETP 2°C fossil fuel consumption data. For **waste and agriculture**, we assumed that in China, the US, India, Russia, Brazil, and South Africa the target emissions intensity of these sectors would correspond to that of Germany in 2015. For the US, we set the emissions intensities in these sectors the same as for Germany in 2050 in the proven technology scenario. We calibrated the results with the median values of the "2°C consistent" global time series of CAT. The difference between current-policies emissions and the 2°C emissions targets represents the **emissions gap** that the countries need to close by deploying climate-friendly technologies.
Timeframe in scope	The scope of our analysis covers the **period until 2050**, but in some decisions we considered longer-term cost impacts, such as in our decision to favor combined-cycle gas turbine (CCGT) over coal with CCS. (CCGT is synfuels-ready for post-2050. CCS is a sunk cost.)
General modeling logic	For the backcasting of measures to reduce energy consumption and GHG emissions to close the gap, our analysis employed the following logic: • We **adapted the IEA Energy Technology Perspectives 2017 2°C scenario** according to the findings of the ***Climate Paths for Germany*** study. Additional data sources for the modeling work included Proceedings of the National Academy of Sciences of the United States and the International Institute for Systems Analysis for heating and cooling in buildings; Shell Global Energy Resources Database for the assessment of nationally available biomass potentials; FAO for abatement measures assessment in agriculture; Economist Intelligence Unit for trends in the transportation sector; and the International Monetary Fund and the World Bank for macroeconomic data. • We used the ***Climate Paths for Germany*** study for all **technology-specific data** (for example, efficiencies and learning curves) in all sectors, including waste and agriculture. • We modeled measures and deviations from the IEA 2°C path with the goal of **minimizing weighted average macroeconomic costs for emissions abatement** for the years 2015-2050 for the individual countries. • In addition to, or instead of, backcasting analysis, we forecast several variables or sectors bottom-up in parallel, leaning on the lessons from the German climate paths study. For instance, fuel consumption in the transportation sector is forecast assuming transportation activity as per IEA ETP and a learning curve for internal combustion engine fuel efficiency. We modeled **two cost-efficient technology paths** for each country: a "proven technology path" (which only partially closes the emissions gap) and a "full 2°C path."

CONTENT	MODELING APPROACH
Proven technology path	On the basis of the Germany study, we adapted the IEA ETP 2°C scenario to model the proven technology path. For the **power sector**, we adapted the generation mix to the new demand resulting from the different penetration of e-mobility, heat pumps, and efficiency technologies in buildings and industry. For both the proven technology path and the full 2°C path, we modeled a coal exit by 2050 in all countries. For **buildings**, the German experience shows that overly aggressive new building efficiency standards and refurbishment ambitions for existing buildings lead to very high "last mile" mitigation costs that exceed the costs of technology alternatives. For heating and cooling demand we use the weighted average between retrofit and advanced retrofit scenarios of the International Institute for Applied Systems Analysis (IIASA). Given India's large challenges with infrastructure, we used the retrofit scenario. Our analysis also justified higher penetration of heat pumps and district heating in Chinese and Russian cities. For **transportation**, we increased the penetration of electric mobility. For cars in developed countries we modeled a trajectory toward 100% electric vehicle car sales. For developing countries we assumed a delay based on infrastructure constraints and macroeconomic development. We also increased the e-mobility share in freight road transport; the trajectory in each country depends on transportation density, infrastructure constraints, and the importance of rail. For the **industry** sectors, we prioritized the use of nationally available **biomass** for process heat generation.
Deep dive biomass	From a total system perspective, the use of **biomass for industrial process heat** generation represents the **most efficient** use for this finite (and precious) resource. Other sectors have other cost-efficient technologies for emissions abatement: • The current use of biomass in **power generation** is, from a total system perspective, less beneficial than in the industry sector. Bioenergy plants fired with solid biomass are less efficient and less flexible than other power technology options (such as CCGT and gas motors). Biogas power plants are also less efficient than their larger gas generation counterparts. Their gas motors enable flexible generation, but biomethane can be stored in the fermenters only for a very limited amount of time. • In **buildings** there are other cost-efficient and cleaner technology options to supply space heat and warm water. • The least efficient utilization option for woody biomass would be in the **transportation** sector in the form of second-generation biofuels, where the total conversion efficiency to useful energy (wood to biofuel and biofuel to kinetic energy) is well below 20%, the lowest across all sectors. After supplying the suitable processes in industry, we prioritized the remaining biomass to the power, buildings, and transportation sectors, in that order. We did not reduce the currently used first-generation biofuels in the transportation sector. Approaching the full biomass potential of large countries would mean higher marginal logistic costs, the use of biomass fractions that require expensive conversion technologies, and, finally, the risk of trading off energy emissions reductions with additional LULUCF emissions. While the IEA ETP 2°C scenario assumes close to 100% utilization of the biomass potentials in the US, China, and India, in our modeling we used 90% for the US and 80% for China, India, and South Africa. This means more moderate growth compared with today's utilization. For Russia and Brazil, we adopted the IEA assumption of approximately 40% to 50% of potential utilization.

CONTENT	MODELING APPROACH
Full 2°C Path	For our full 2°C path, we adapted from the IEA ETP 2°C scenario as follows: • For **CCS** in the industry sector (including emissions unrelated to energy), we adopted the IEA scenario. We did not apply CCS in the power sector, since a combination of wind, solar, and gas with synfuels is more cost-efficient. • We closed the remaining gap to the country-specific 2°C path contributions with **synthetic gaseous and liquid fuels** from renewable power and non-fossil carbon. For neither path did we consider a significant change in consumer behavior (for example, giving up meat or air travel).
Investment and macroeconomic costs	We applied the following main principles in our economic analysis: • From the ***Climate Paths for Germany*** study, we translated the costs of individual abatement measures for each country on the basis of the **countries' comparative technological maturity, climate, and demographic variables**. • We used a separate cost of capital for each country, corresponding to ten-year government bond yield. • Investment costs were discounted over the economic lifetime of the corresponding investment, such as 13 years for vehicles, 20 years for energy efficiency in industry, heating systems, and CCS, 30 years for building refurbishments and distribution power grids, and 40 years for transmission power grids. • Energy carrier prices and power generation costs were applied per the IEA NPS 2017 scenario.

[1]IEA Word Energy Outlook 2017.

APPENDIX II
COUNTRY SUMMARIES

CHINA

Current Status: Since 2005, China has been the largest emitter in the world. GHG emissions have grown by 7.4% per year since 2001, compared with a 2.4% global average. Today, GHG emissions of 12.5 Gt account for 26% of the global total. The electricity and industrial sectors are each responsible for one-third of China's emissions.

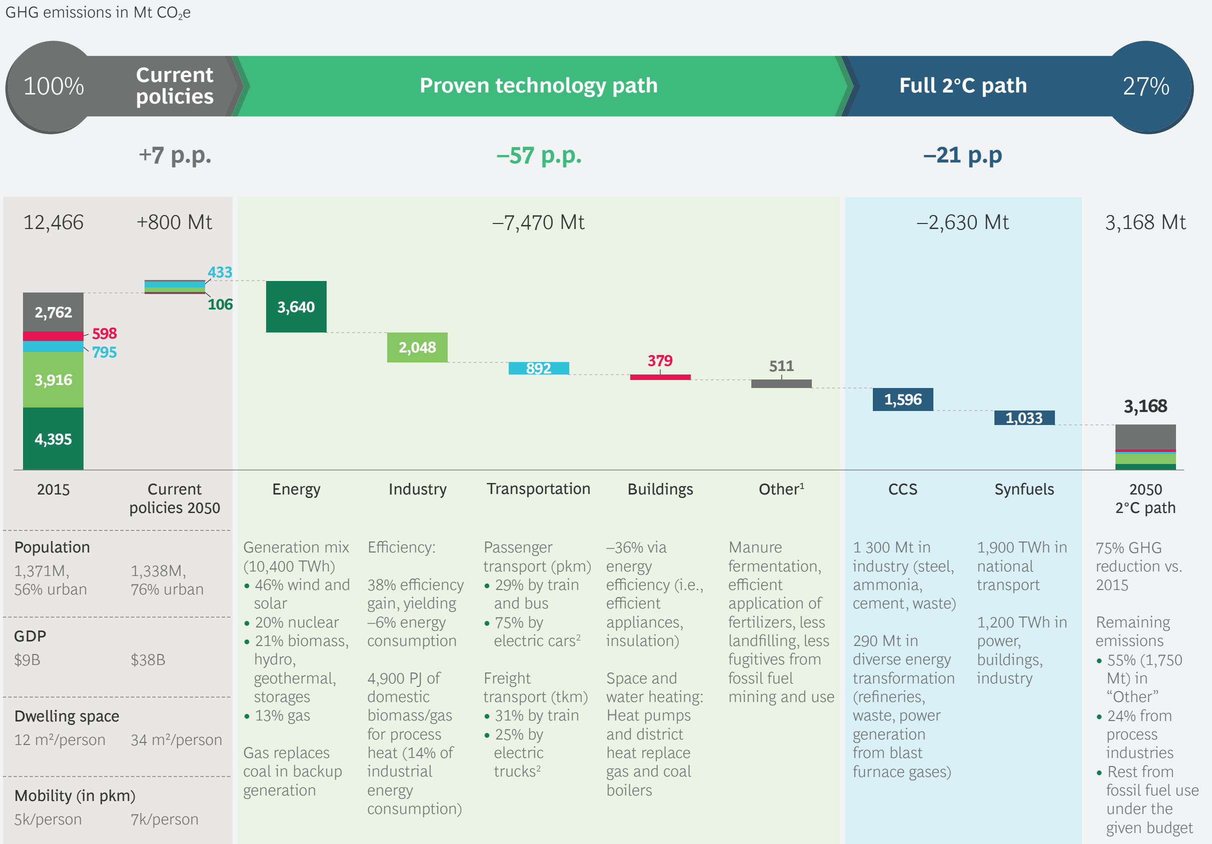
Trajectory: China is making significant efforts to disconnect emissions from economic growth. Under current policies, emissions would grow by 7% through 2050, with the transportation sector being the main contributor.

2°C Gap: In order for China to meet its 2°C contribution, GHG emissions need to decrease by 72% (from 2015 levels) through 2050. This leaves a gap of 10.1 Gt CO_2e between the current policy and the 2°C paths. (See the exhibit.)

Proven Technologies. Using proven technologies could cut 7.5 Gt CO_2e (73% of the gap).

- Transformation of the **power sector** in China is already well on the way with serious efforts in wind and solar technologies. Decarbonization, however, will be an enormous challenge: power consumption will almost double, from 5.9 PWh to 10.4 PWh, by 2050, and sunk costs in coal-fired capacity could slow progress. By 2050, 46% of electricity could come from wind and solar power, 20% from nuclear, and 18% from hydropower. The remaining 17% would be primarily from natural gas. Some 2,500 GW of wind and solar power would thus be needed—12 times the production today. Nuclear power would need to increase by a factor of ten, reaching 280 GW, and hydropower capacity must double to 530 GW.
- In the **industrial** sector, best-in-class efficiency technologies that are available today could curb energy demand by 38% compared with the current policy path. The largest potential is in the iron and steel and petrochemical sectors. Additionally, 11% of energy demand could be covered by substitution of solid biomass for fossil fuels in process heat generation below 500°C. This would require dedication of 82% of China's sustainably available biomass resources.
- In the **transportation sector**, railways could cover 30% of passenger and freight transport by 2050. China is already showing a commitment to scaling up electric mobility, which could reach a 75% market share in passenger transport and 25% in freight transport. In 2050, the

China's 2°C Path Requires 73% GHG Emissions Reduction Between 2015 and 2050



Source: BCG analysis.
Note: PJ = petajoule; pkm = person kilometers; tkm = ton kilometers.
¹Waste, agriculture, fugitives.
²Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

remaining road traffic and aviation will still rely on hydrocarbon fuels, which would make up close to 55% of energy demand for transportation under the proven technology path.

- The **buildings sector** in China is challenged by rapidly increasing living standards, which are seen in a projected increase in the average dwelling space from 12 m² per person to 34 m² by 2050 and growth in residential consumption of cooling and electric appliances. More energy-efficient electric consumers and low-energy new buildings could reduce total energy consumption by 36% (including a reduction in heating and cooling demand of 45%) in 2050 compared with the current-policies path. For space heat and water heating, heat pumps could supply about 35% of the demand and displace coal and oil boilers, especially in rural and suburban areas. Expanded district heating could cover 14% of demand, leaving 15% to natural gas. While practically all new urban areas in northeastern China will be served by district heat, natural gas will remain important in older cities with shorter heating periods. The share of biomass will remain at today's 30%, but there would be a significant shift from open fire to efficient boilers.

- In **other sectors**, conventional GHG abatement measures in fertilizer use, rice cultivation, and manure management will reduce agricultural emissions by 27%. Other measures include efficient waste management and a reduction in fugitive emissions.

The Full 2°C Path. Closing the last 27% of the gap to 2°C (2,600 Mt CO_2e) requires synfuels and CCS.

- After exploiting the feasible potential of proven technologies, the deployment of **CCS technologies** could avoid 1,600 Mt CO_2, which corresponds to 28% of the remaining emissions.

- Fully closing the gap to the 2°C path would require the use of **3,100 TWh synfuels**, of which about 60% would be used in the transportation sector to replace oil in cars, trucks, and airplanes. The remaining 40% would be used to replace all the remaining natural gas for power generation and to substitute for fossil fuels in industry.

- In 2050, about 40% of **the remaining 3.2 Gt CO_2e under the 2°C path** would be emitted in agriculture and waste, and another quarter in the industry sector, mainly from uncaptured CO_2. The remaining emissions would stem from fossil fuel use in other sectors, allowable under the emissions budget. Eventually, after 2051, these fuels would need to be replaced.

The Price Tag. Some $8.1 trillion in investment is required for the proven technology path through 2050, and an additional $5.5 trillion is needed for the full 2°C path.

- **Investments:** Proven technology investments correspond to an average of **1.0% of GDP per year**. Fully closing the gap to 2°C requires an additional 0.7% of GDP per year. These figures are comparable to those for Germany and the US.

- **Cost:** For the proven technology path, China's relatively low costs of capital and high fossil fuel costs result in the lowest macroeconomic costs in relation to the country's economic capacity among all analyzed countries: a cumulative **$2.7 trillion** (**0.3% of GDP per year**). Fully meeting the 2°C path, particularly the high need for CCS in industrial processes, requires an **additional $7.5 trillion** (**0.9% of GDP per year**).

UNITED STATES

Current Status: Emissions in the US decreased by 7% between 2000 and 2015. This is largely a result of the decline in coal power generation in favor of gas. With 6.3 Gt CO_2e, the US was the second highest global GHG emitter in 2015.

Trajectory: In the US, the decoupling of population and economic growth from the development of GHG emissions is under way. Assuming the continuation of current policies and technology trends, we expect a decline in GHG emissions (compared with 2015) of **11% (0.7 Gt CO_2e)** by 2050. The main drivers are the continued displacement of coal by gas in flexible power production, efficiency increases, a moderate substitution of fossil fuels in heat pumps in buildings, and more efficient and increasingly electric cars in the transportation sector.

2°C Gap: In order to meet the US 2°C contribution, GHG emissions would need to decrease 79% (from 2015 levels) by 2050. This leaves a gap of **4.3 Gt CO_2e** between the current-policy and 2°C paths. (See the exhibit.)

Proven Technologies. Three-quarters of the gap (3.2 Gt CO_2e) could be reduced by deploying proven technologies.

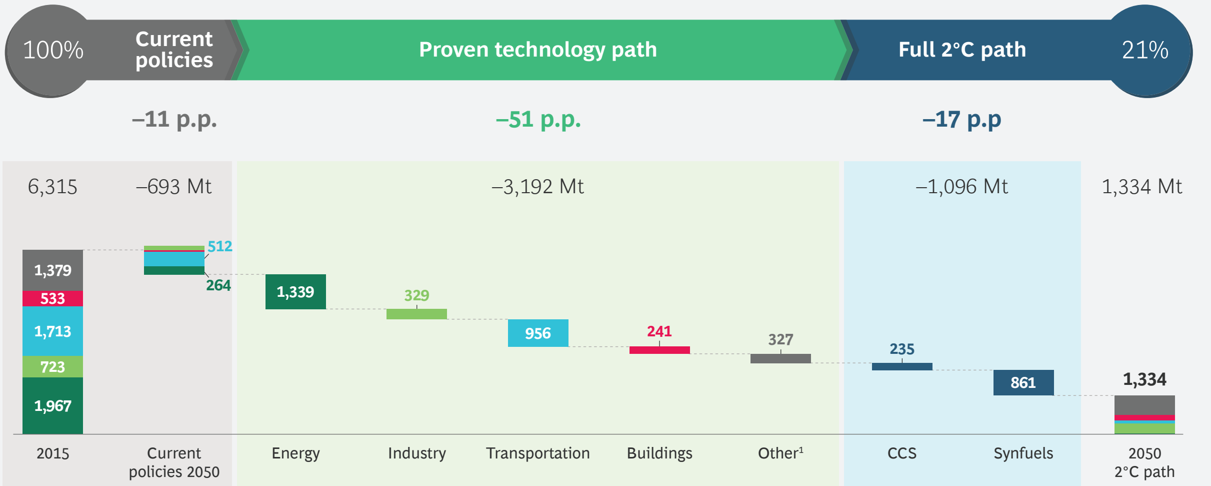
- In the **power sector**, the US has good conditions for the deployment of wind and solar power, which could supply more than 50% of total generation by 2050. This would require a total installed generation capacity of 1,600 GW. For the provision of flexible generation capacity, coal would need to be replaced by a mix of gas (for medium and peak loads) and nuclear and hydro (for base load generation). The total installed capacity from these sources would still amount to 770 GW—about 70% of today's value. As in other countries, stopping construction of new coal-fired plants, accelerated mortality of existing coal plants, and the replacement of coal with a cost-optimized mix of flexible generation technologies represent a lower-cost abatement option than the combination of coal and CCS.

- In the **industrial** sector, best-in-class efficiency technologies that are already available could curb energy demand by 23%, compared with the current-policy path. Additionally, 27% of the resulting energy demand could be covered by substitution of solid biomass for fossil fuels in process heat generation below 500°C.

- In the **transportation** sector, the US has favorable infrastructure conditions to scale up electric mobility to 90% of road passenger transport (cars). Road freight transport could also be electrified in urban areas and on the most frequented highway

The US 2°C Path Requires 79% GHG Emissions Reduction Between 2015 and 2050

GHG emissions in Mt CO_2e



	2015	Current policies 2050
Population	321M, 82% urban	388M, thereof 76% urban
GDP	$17B	$33B
Dwelling space	51 m²/person	68 m²/person
Mobility (in pkm)	15k/person	13k/person

Energy	Industry	Transportation	Buildings	Other[1]	CCS	Synfuels	2050 2°C path
Generation mix (7,200 TWh) • 49% wind and solar • 18% nuclear • 14% biomass, hydro, storages • 19% gas Gas replaces coal in backup generation	Efficiency: 23% efficiency gain, yielding –16% energy consumption 4,300 PJ of domestic biomass/gas for process heat (34% of industrial energy consumption)	Passenger transport (pkm) • 18% by train and bus • 90% by electric cars[2] Freight transport (tkm) • 29% by train • 40% by electric trucks[2]	–28% via energy efficiency (i.e., efficient appliances, insulation) Space and water heating: Heat pumps and solar thermal replace oil and gas boilers (gas boilers remain in dense urban areas)	Manure fermentation, efficient application of fertilizers, less landfilling, less fugitives from fossil fuel generation and use	195 Mt in industry (steel, ammonia, cement, waste) 40 Mt in diverse energy transformation (refineries, waste, power generation from blast furnace gases)	1,300 TWh in national transport 1,000 TWh in power, buildings, industry	79% GHG reduction vs. 2015 Remaining emissions • 50% (45 Mt) in "Other" • 25% from process industries • Rest from fossil fuel use under the given budget

Source: BCG analysis.
Note: PJ = petajoule; pkm = person kilometers; tkm = ton kilometers.
[1]Waste, agriculture, fugitives.
[2]Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

routes. In 2050, the remaining road traffic and aviation will still rely on hydrocarbon fuels, which will make up close to 60% of energy demand for transportation.

- In **buildings**, there is substantial potential for increased efficiency. We estimate that increased penetration of energy-efficient electric appliances, low-energy new buildings, and building refurbishments could reduce specific energy consumption (per square meter building area) by two-thirds by 2050. For space heat and water heating, heat pumps could supply about 35% of the demand and displace gas boilers, especially in rural and suburban areas. However, the absence of district heating grids in many cities means that gas boilers will remain an important heating solution in areas with high heat demand, particularly in the Northeast and Midwest. Considering the realistic reinvestment cycles in buildings and the very high investment and technical hurdles in setting up a completely new district heating infrastructure in all major US inner cities, we expect that, in 2050, gas boilers will still serve about 40% of space heat and warm water demand.

- In **other sectors**, conventional GHG abatement measures in fertilizer use and manure management will reduce agricultural emissions by 39%. Other measures include efficient waste management and a reduction in fugitive emissions.

The Full 2°C Path. Covering the remaining 1.1 Gt CO_2e (26%) of the gap to the 2°C path will require CCS and synfuels.

- After exploiting the feasible potential of proven technologies, the deployment of **CCS technologies** could avoid 235 Mt CO_2e (10% of the remaining emissions).

- Fully closing the gap to the 2°C path would require the use of **2,300 TWh synfuels**, of which about 60% would be used in the transportation sector to replace oil in cars, trucks, and airplanes. The remaining 40% would be used to replace all remaining natural gas for power generation and to supplant fossil fuels in buildings. This synfuel demand could be significantly **reduced** only in the event of a visible **behavior shift in private consumption**, such as moves toward smaller cars and less housing space per capita.

- In 2050, about half of **the remaining 1.3 Gt CO_2e under the 2°C path** would be emitted in agriculture and waste, and another quarter in industry, mainly from uncaptured CO_2. The remaining emissions would stem from fossil fuel use in the other sectors, allowable under the given emissions budget. Eventually, these fuels would need to be replaced.

The Price Tag. The US requires $8.7 trillion in investment for the proven technology path through 2050 and an additional $5.4 trillion for the full 2°C path.

- **Investment:** These figures correspond to average investments of **1.0% of GDP per year** under the proven technology path and an additional **0.6% of GDP per year** to fully close the gap to the 2°C path.

- **Cost:** Because of the availability of domestic low-cost fossil fuels, the energy cost savings generated by climate investments are comparatively small. The resulting cumulated macroeconomic costs would amount to **$8.7 trillion** (**0.9% of GDP per year**) under the proven technology path and additionally **$4.9 trillion** (**0.6% of GDP per year**) to fully close the gap to 2°C.

INDIA

Current Status: The emissions growth rate in India has picked up since 2003 and is now 5.1% per year. Annual population growth of 1.4% and accelerating industrialization have resulted in an emissions-intensive power sector and one of the largest shares of emissions from agriculture (20%).

Trajectory: Continued industrialization and population growth, coupled with modest climate policies, will result in more than a doubling of GHG emissions by 2050 under current policies. The electricity and industrial sectors will be responsible for 68% of the growth.

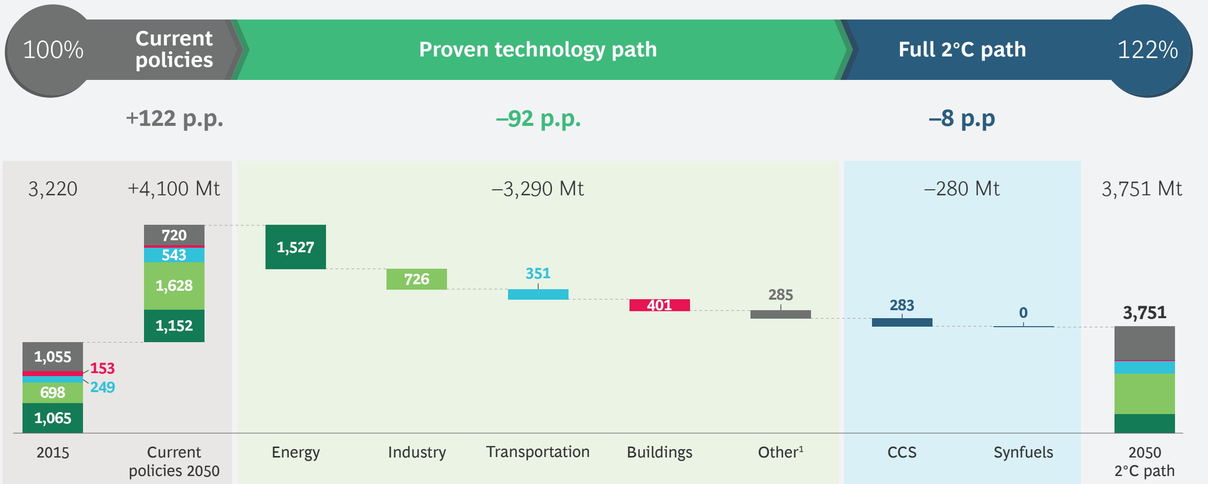
2°C Gap: Given India's extraordinary growth, its 2°C contribution in absolute terms is modest: GHG emissions may increase 22% (from 2015 levels) by 2050. However, this leaves a gap of **3.6 Gt CO_2e** between the current-policy and 2°C paths. (See the exhibit.)

Proven Technologies. 3.3 Gt CO_2e (92% of the gap) could be reduced by deploying proven technologies.

- The **power** sector in India is simultaneously the biggest lever and the greatest challenge: the low-cost abatement potential is huge, but renewable electricity is needed to cover rapid demand growth. Electricity demand is expected to grow by 400%, to 5700 TWh, by 2050. More than half of the power supply could be covered by 1,500 GW of solar and wind power, 16% by 120 GW nuclear, and 10% by 190 GW hydropower. The remaining 22% would be covered primarily by 210 GW of natural gas. Just as in most other rapidly growing economies, phasing out coal can prove challenging yet necessary for decarbonizing the power sector. Rapid development of network infrastructure will be necessary for such a transformation.

- In the **industrial** sector, best-in-class efficiency technologies that are already available could curb energy demand by 16% compared with the current-policy path. Practically no retrofitting is required; industrial activity and energy demand is on a strong growth trajectory, and high-efficiency technologies are to a large extent already adopted in current policies. With current policies, energy demand would be 3.3 times that of today. The largest potential is in the iron and steel and nonmetallic minerals sectors. Additionally, 26% of the resulting energy demand could be covered by solid biomass, which would substitute for fossil fuels in process heat applications below 500°C. This would require commitment of 82% of sustainably available biomass resources.

India's 2°C Path Allows 22% GHG Emissions Increase Between 2015 and 2050



	2015	Current policies 2050
Population	1,309M, 33% urban	1,659M, 50% urban
GDP	$2B	$19B
Dwelling space	19 m²/person	32 m²/person
Mobility (in pkm)	2k/person	6k/person

Energy	Industry	Transportation	Buildings	Other[1]	CCS	Synfuels	2050 2°C path
Generation mix (5,700 TWh) • 52% wind and solar • 16% nuclear • 14% biomass, hydro, storages • 19% gas Gas replaces coal in backup generation	Efficiency: 16% efficiency gain, yielding +171% energy consumption 6,800 PJ of domestic biomass/gas for process heat (28% of industrial energy consumption)	Passenger transport (pkm) • 41% by train and bus • 50% by electric cars[2] Freight transport (tkm) • 41% by train and bus • 26% by train • 10% by electric trucks[2]	–37% via energy efficiency (i.e., efficient appliances, insulation) Space and water heating: Heat pumps and solar thermal replace oil and biomass boilers; heat pumps serve increasing cooling demand	Manure fermentation, efficient application of fertilizers, less landfilling, less fugitives from fossil fuel use	280 Mt in industry (steel, ammonia, cement, waste)	No synfuels consumption	16% GHG increase vs. 2015 Remaining emissions • 32% (1,190 Mt) in "Other" • 38% from process industries • Rest from fossil fuel use under the given budget

Source: BCG analysis.
Note: PJ = petajoule; pkm = person kilometers; tkm = ton kilometers.
[1]Waste, agriculture, fugitives.
[2]Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

- In the **transportation sector**, railways could cover 40% of passenger and 25% of freight transport by 2050. Road transportation is forecast to grow tenfold by 2050, putting great pressure on infrastructure development. Electric mobility could reach a 50% market share in passenger transport and a 10% share in freight transport. In 2050, the remaining road traffic and aviation will still rely on hydrocarbon fuels, which will make up 70% of energy demand for transportation in 2050.

- The **buildings sector** in India is challenged by population growth, urbanization, and increasing living standards. Average dwelling space will increase from 19 m² per person to 32 m² by 2050. Penetration of energy-efficient electric appliances and new low-energy buildings could reduce total energy consumption by 37% (including a reduction in heating and cooling demand of 40%) from the current-policies path. For space and water heating, heat pumps and solar thermal energy could supply about 55% of the demand by 2050, mainly displacing biomass, which could be channeled to the industrial sector. Fossil fuels would still cover some 15% of heating, cooling, and cooking demand, primarily LPG for cooking in rural areas, which today rely almost exclusively on biomass.

- In **other sectors**, conventional GHG abatement measures in fertilizer use and manure management will reduce agricultural emissions by 23%. Other measures include efficient waste management and reduction of fugitive emissions.

The Full 2°C Path. Eliminating 280 Mt CO_2e (or 8% of the gap to 2°C) requires CCS.

- After exploiting the feasible potential of proven technologies, the deployment of **carbon capture and storage technologies** could avoid at least 280 Mt CO_2, which corresponds to 8% of the remaining emissions.

- Reaching India's national contribution to the global 2°C path in a cost-efficient way would not require the use of synfuels before 2050, provided that the measures under the proven technology path and CCS are applied as described above.

- In 2050, about 30% of **the remaining 3.8 Gt CO_2e under the 2°C path** would be emitted in agriculture and waste, and another third in the industry sector. Due to current expectation of burden sharing, the emissions budget for India would allow for fossil emissions that stemmed mostly from the industry and transportation sectors.

The Price Tag. India requires $6.0 trillion in investment for the proven technology path and an additional $0.3 trillion for the full 2°C path.

- **Investment:** India's national contribution to the global 2°C path can be met to a large extent by the deployment of proven technologies. The investment of $6 trillion represents an average of **1.8% of GDP per year** under the proven technology path and an additional **0.1% of GDP per year** for employing CCS to fully close the gap to the 2°C path.

- **Costs:** After energy cost savings, the resulting macroeconomic costs would be **$1.1 trillion** (**1.1% of GDP per year**) under the proven technology path and an **additional $0.5 trillion** (**0.1% of GDP per year**) to fully close the gap to the 2°C path.

RUSSIA

Current Status: In the aftermath of the Soviet Union's collapse, GHG emissions decreased by one-third from 3 Gt in 1990 to 1.9 Gt in 1997. Since then, emissions have increased by only 8%, to 2.15 Gt in 2015. The energy sector, including fugitive emissions, represents 62% of total GHG emissions.

Trajectory: Despite a stagnating economy and decreasing population, GHG emissions will increase by **3%, to 2.2 Gt CO_2e in 2050**. GDP growth is expected to slowly pick up from near zero to 2.4% per year over time. Russia's population is forecast to decline from 144 million to 129 million by 2050. Increasing energy demand in buildings and industry is hardly affected by efficiency measures; rather, it is met by growth in fossil-fuel district heating and electricity.

The 2°C Gap: In order to meet its 2°C contribution, GHG emissions in Russia would need to decrease by 75% (versus 2015 levels) by 2050. This leaves a gap of **1.67 Gt CO_2e** between the current-policies and 2°C paths. (See the exhibit.)

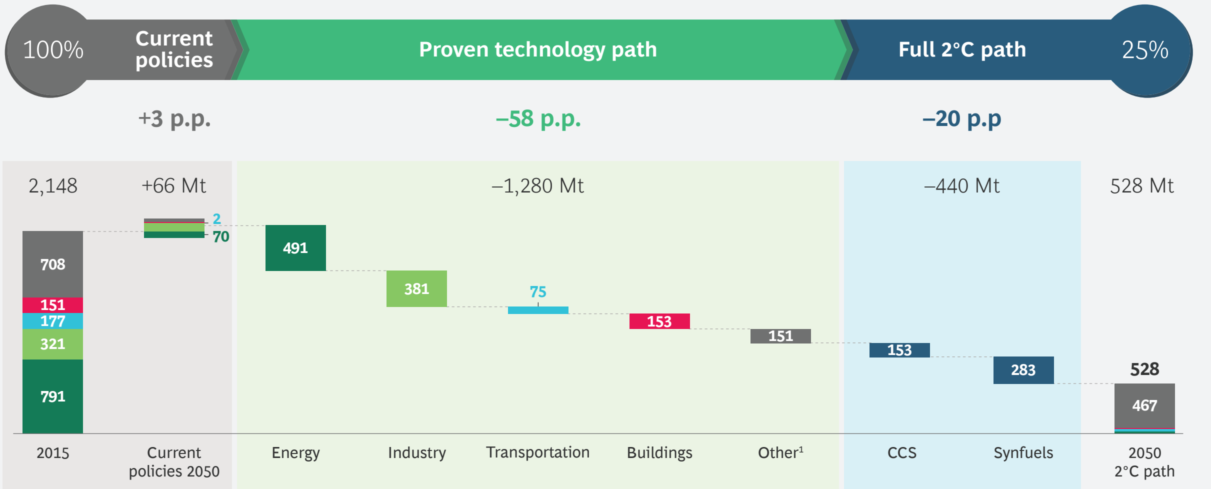
Proven Technologies. Deploying proven technologies can reduce emissions by 1,250 Mt CO_2e (74% of the gap).

- In the **power sector**, Russia has vast resources for hydro, wind, and solar, as well as domestic production of natural gas and coal, and abundant biomass. High penetration rates for these energy sources are primarily an economic issue. By 2050, a largely decarbonized power sector could be supplied by a mixture of 30% nuclear, 29% hydro, and 30% solar and wind. The remaining 11% would be covered by a mixture of biomass and natural gas. Such transformation would require nuclear and hydro capacities to grow two and a half times, to 71 GW and 136 GW respectively, and the construction of a total of 225 GW of wind and solar capacity. This would have spillover implications for space heat and water heating in the buildings sector. In the absence of large CHP (combined heat and power) plants, large district heat systems would be increasingly served by alternative sources such as industrial waste heat, waste incineration plants, biomass, geothermal, power to heat, and to some extent nuclear.

- In the **industrial** sector, best-in-class efficiency technologies that are already available could curb energy demand by 39% compared with the current-policies path. The biggest potential reductions are in the iron and steel and petrochemicals sectors. Additionally, 40% of the resulting energy demand could be covered by substitution of solid biomass for fossil fuels in process heat applications below 500°C.

Russia's 2°C Path Requires 75% GHG Emissions Reduction Between 2015 and 2050

GHG emissions in Mt CO_2e



2015	Current policies 2050	Energy	Industry	Transportation	Buildings	Other[1]	CCS	Synfuels	2050 2°C path
Population 144M, 74% urban GDP $2B Dwelling space 22 m²/person Mobility (in pkm) 6k/person	 129M, 81% urban $3B 22 m²/person 6k/person	Generation mix (1,700 TWh) • 25% wind and solar • 30% nuclear • 39% biomass, hydro, storages • 6% gas Gas replaces coal in backup generation	Efficiency: 39% efficiency gain, yielding –16% energy consumption 2,800 PJ of domestic biomass/gas for process heat (42% of industrial energy consumption)	Passenger transport (pkm) • 24% by train and bus • 60% by electric cars[2] Freight transport (tkm) • 68% by train • 8% by electric trucks[2]	–32% via energy efficiency (i.e., efficient appliances, insulation) Space and water heating: Heat pumps and district heat replace gas boilers	Manure fermentation, efficient application of fertilizers, less landfilling, less fugitives from fossil fuel generation and use	130 Mt in industry (steel, ammonia, cement, waste) 20 Mt in diverse energy transformation (refineries, waste, power generation from blast furnace gases)	150 TWh in national transport 560 TWh in power, buildings, industry	75% GHG reduction vs. 2015 Remaining emissions • 88% (470 Mt) in "Other" • 2% from process industries • Rest from fossil fuel use under the given budget

Source: BCG analysis.
Note: PJ = petajoule; pkm = person kilometers; tkm = ton kilometers.
[1]Waste, agriculture, fugitives.
[2]Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

Biomass penetration is limited only by economic and logistical availability. Only 49% of Russia's sustainable national available biomass resources would be used.

- In the **transportation sector**, freight relies to a great extent on the rail system. By 2050, up to 70% of freight would move by train, leaving only 8% to electric trucks, largely for short-distance transport around large cities. We expect the bulk of long-distance road freight traffic to be covered by diesel trucks, because the low transport density on Russian roads is unlikely to justify e-mobility infrastructure for trucks. In passenger transport, railways could take up 25% of the load, and the market share of electric road vehicles could reach 60%. Hydrocarbon fuels for road transport and aviation would still make up 70% of energy demand for transportation in 2050.

- The **buildings sector** in Russia faces a great challenge to accelerate refurbishment and adopt efficient building standards. Decreasing population and the substantial penetration of district heating offers good potential to decarbonize centralized-heat supplies. Adoption of efficient refurbishment standards could curb energy demand by 40%, compared with the current-policies path. For space and water heating, district heating could have a 70% share by 2050, heat pumps 20%, and biomass 5%. The remaining 5% would come from diverse sources, including natural gas.

- In **other sectors**, conventional GHG abatement measures in fertilizer use and manure management will reduce agricultural emissions by 18%. Other measures include efficient waste management and reduction of fugitive emissions, which in Russia are largely dependent on global demand for fossil fuels.

The Full 2°C Path. Covering the remaining 440 Mt CO_2e (26%) of the gap to the 2°C path requires CCS and synfuels.

- After exploiting the feasible potential of proven technologies, the deployment of **CCS technologies** could avoid 153 Mt CO_2, or 16% of the remaining emissions.
- Fully closing the gap to the 2°C path would require the use of **710 TWh synfuels**, of which about 20% would be used in the transportation sector to replace oil in cars, trucks, and airplanes. The remaining 80% would be used to replace all remaining natural gas for power generation and to supplant fossil fuels in industry.
- In 2050, about half of **the remaining 528 Mt CO_2e under the 2°C path** would be emitted in agriculture and waste, with the rest being fugitive emissions from fossil fuels in upstream and midstream operations and from uncaptured CO_2. Fugitive emissions will be dependent on global demand for fossil fuels. Further GHG reduction would require tapping into the potential in agriculture and land use.

The Price Tag. Russia needs to invest $2.0 trillion for the proven technologies path through 2050 and an additional $3.6 trillion for the full 2°C path.

- **Investment:** Cumulative investments correspond to an average of **2.2% of GDP per year** under the proven technology path and an additional **3.9% of GDP per year** to fully close the gap to 2°C. Among all countries analyzed, Russia would need to shoulder the largest investment burden in relation to its economic capacity, reflecting the very high carbon intensity of the Russian economy.
- **Costs:** Given the factors of high capital costs and cheap domestic fuels, an aggressive Russian climate change mitigation agenda would need to overcome massive obstacles. After energy cost savings, the resulting macroeconomic costs would be **$1.4 trillion** (**1.5% of GDP per year**) under the proven technology path and an additional **$6.4 trillion** (**5.1% of GDP per year**) to fully close the gap to the 2°C path.

BRAZIL

Current Status: Brazil has experienced modest and linear emissions growth of 2.7% per year since 1990, emitting 1.1 Gt in 2015. Fully 40% of current GHG emissions originate from the agricultural sector, followed by 18% from the transportation sector. Thanks to abundant hydropower and a relatively small industrial sector, total emissions from these two sectors amount to only 230 Mt.

Trajectory: On the current-policies path, GHG emissions are forecast to increase by 12% by 2050, driven by population and economic growth and agriculture, where emissions will increase by 26%, to 560 Mt, by 2050.

The 2°C Gap: In order to meet its 2°C contribution, GHG emissions in Brazil would need to decrease by 55% (compared with 2015) by 2050. This leaves a gap of about **0.8 Gt CO_2e** between the current-policies and 2°C paths. (See the exhibit.)

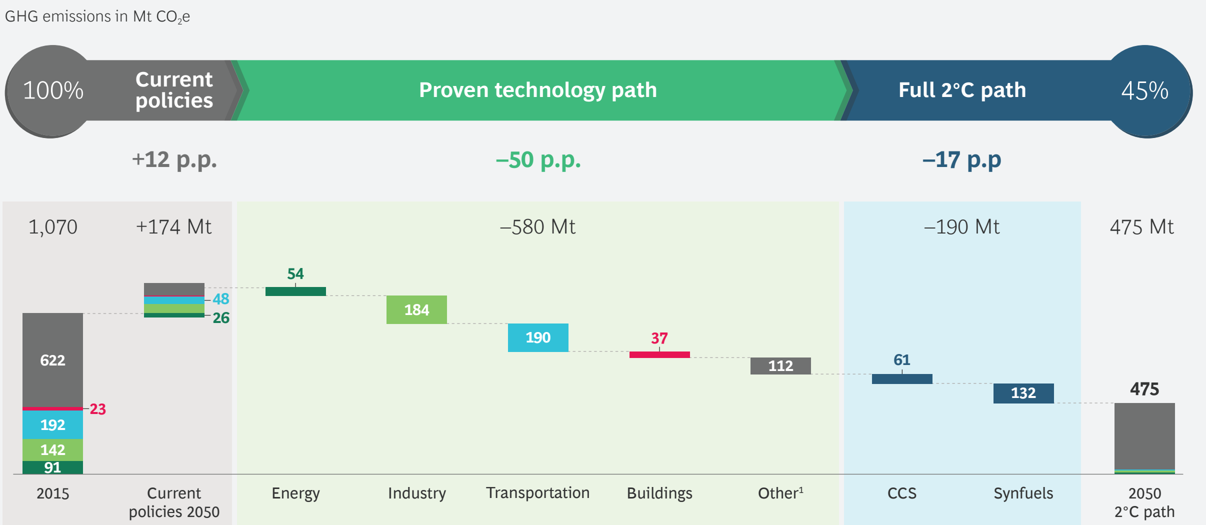
Proven Technologies. 580 Mt CO_2e (75% of the gap) could be reduced by deploying proven technologies.

- The **power sector** in Brazil is already almost carbon neutral; less than 10% of electricity comes from fossil sources. Given excellent conditions for wind and solar, as well as untapped hydropower potential, meeting increasing demand with zero-carbon technologies should be only a moderate challenge. The primary hurdle to overcome will be the environmentally and socially sustainable development of new hydropower dams and wind power in coastal areas. The hydropower market share would remain near today's 60%, increasing from 360 TWh to 650 TWh. Wind power would grow to 240 TWh and solar power to 100 TWh, together covering 30% of electricity supply. The remaining 12% would be covered by biomass, nuclear, and natural gas, in that order.

- In the **industrial** sector, best-in-class efficiency technologies that are already available could curb energy demand by 11% compared to the current-policies path. The largest potential will be in the food and tobacco and iron and steel sectors. Additionally, 64% of the resulting energy demand could be covered by substitution of solid biomass for fossil fuels in process heat applications below 500°C. Abundant biomass limits the need for costly efficiency retrofits. Less than half of Brazil's sustainable nationally available biomass resources would be used.

- The **transportation sector** in Brazil is largely dependent on road transportation; railway infrastructure is underdeveloped. Roughly 20% of people transport and 15%

Brazil's 2°C Path Requires 55% GHG Emissions Reduction Between 2015 and 2050



	2015	Current policies 2050
Population	206M, 86% urban	333M, 91% urban
GDP	$2B	$6B
Dwelling space	22 m²/person	35 m²/person
Mobility (in pkm)	7k/person	9k/person

Energy	Industry	Transportation	Buildings	Other[1]	CCS	Synfuels	2050 2°C path
Generation mix (1,100 TWh) • 30% wind and solar • 4% nuclear • 64% biomass, hydro, storages • 2% gas Gas replaces coal in backup generation	Efficiency: 11% efficiency gain, yielding +55% energy consumption 3,900 PJ of domestic biomass/gas for process heat (71% of industrial energy consumption)	Passenger transport (pkm) • 23% by train and bus • 40% by electric cars[2] Freight transport (tkm) • 14% by train • 15% by electric trucks[2]	–29% via energy efficiency (i.e., efficient appliances, insulation) Space and water heating: Solar thermal replaces oil boilers; heat pumps satisfy increasing cooling demand	Manure fermentation, efficient application of fertilizers, less landfilling, less fugitives from fossil fuel generation and use	61 Mt in industry (steel, ammonia, cement, waste)	180 TWh in national transport 100 TWh in power, buildings, industry	60% GHG reduction vs. 2015 Remaining emissions • 92% (440 Mt) in "Other" • 4% from process industries • Rest from fossil fuel use under the given budget

Source: BCG analysis.
Note: PJ = petajoule; pkm = person kilometers; tkm = ton kilometers.
[1]Waste, agriculture, fugitives.
[2]Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

of freight transport could be on rails by 2050. Electrification of road transport could reach 40% for people and 15% for trucks. Car fleet renewal dynamics, the role of domestic biofuels, and infrastructure constraints would not sustain faster adoption of electric vehicles. More efficient internal combustion vehicles will contribute decreasing emissions. The remaining road traffic and aviation will rely on hydrocarbon fuels, which will make up 45% of energy demand for transportation in 2050.

- Energy consumption in the **buildings sector** is relatively low but expected to grow by a factor of 2.5 under current policies, mainly due to cooling and other electric appliances. Penetration of energy-efficient electric appliances and new low-energy buildings could reduce total energy consumption by 29%. For space and water heating, heat pumps and solar thermal energy could supply about 60% of the demand by 2050. For cooking, biomass would cover 35% and fossil fuels 5%.

- In **other sectors**, conventional GHG abatement measures in fertilizer use and manure management will reduce agricultural emissions by 20%. Another 20% reduction could be achieved by slower growth in enteric fermentation. Other measures include efficient waste management and reduction of fugitive emissions.

The Full 2°C Path. Eliminating 190 Mt CO_2e (25%) of the gap to 2°C requires synfuels and CCS or, alternatively, methane pills.

- After exploiting the feasible potential of proven technologies, the deployment of

CCS technologies could avoid 61 Mt CO_2e, which corresponds to 9% of Brazil's remaining emissions.

- Fully closing the gap to the 2°C path would require the use of **280 TWh synfuels**, of which about 65% would be used in the transportation sector to replace oil in cars, trucks, and airplanes. The remaining 35% would supplant fossil fuels in industry and buildings.

- In 2050, about 80% of **the remaining 475 Mt CO_2e under the 2°C path** would be emitted in agriculture, mainly by cattle. These methane emissions represent a large untapped potential, should methane pills be a preferred solution over CCS or synfuels.

The Price Tag. Brazil requires $1.4 trillion in investment for the proven technology path through 2050 and an additional $900 billion for the full 2°C path.

- **Investment:** These figures correspond to average investments of **1.0% of GDP per year** under the proven technology path and an additional **0.7% of GDP per year** to fully close the gap to 2°C.

- **Costs:** After energy cost savings, the resulting cumulative macroeconomic costs would be **$0.6 trillion** (**0.5% of GDP per year**) under the proven technology path. The high cost of capital in Brazil results in relatively high cumulative costs of **another $0.9 trillion** (**0.6% of GDP per year**) to fully close the gap to 2°C.

GERMANY

Current Status: Comprehensive efforts have already reduced Germany's GHG emissions by **28%**, from 1,251 Mt CO_2e in 1990 **to 902 CO_2e in 2015**. A major part of this decline is attributable to the phaseout of inefficient lignite in the power and industrial sectors after reunification. Since 2010, emissions have been declining in all sectors except power generation, where the decision to phase out nuclear power kept emissions stable, despite a high increase in renewable generation. Germany has adopted ambitious climate mitigation goals; versus 1990 levels, the country aims to reduce GHG emissions **by 80% to 95%** by 2050. The latter target is consistent with the German 2°C contribution.

Trajectory: At currently projected macroeconomic development (declining population, economic growth slightly above 1% per year), with currently existing regulations (on power generation and building and vehicle efficiencies, for example), and with foreseeable technology trends (such as LED lighting), Germany would achieve approximately **45% GHG** emissions reductions by 2050 under current policies.

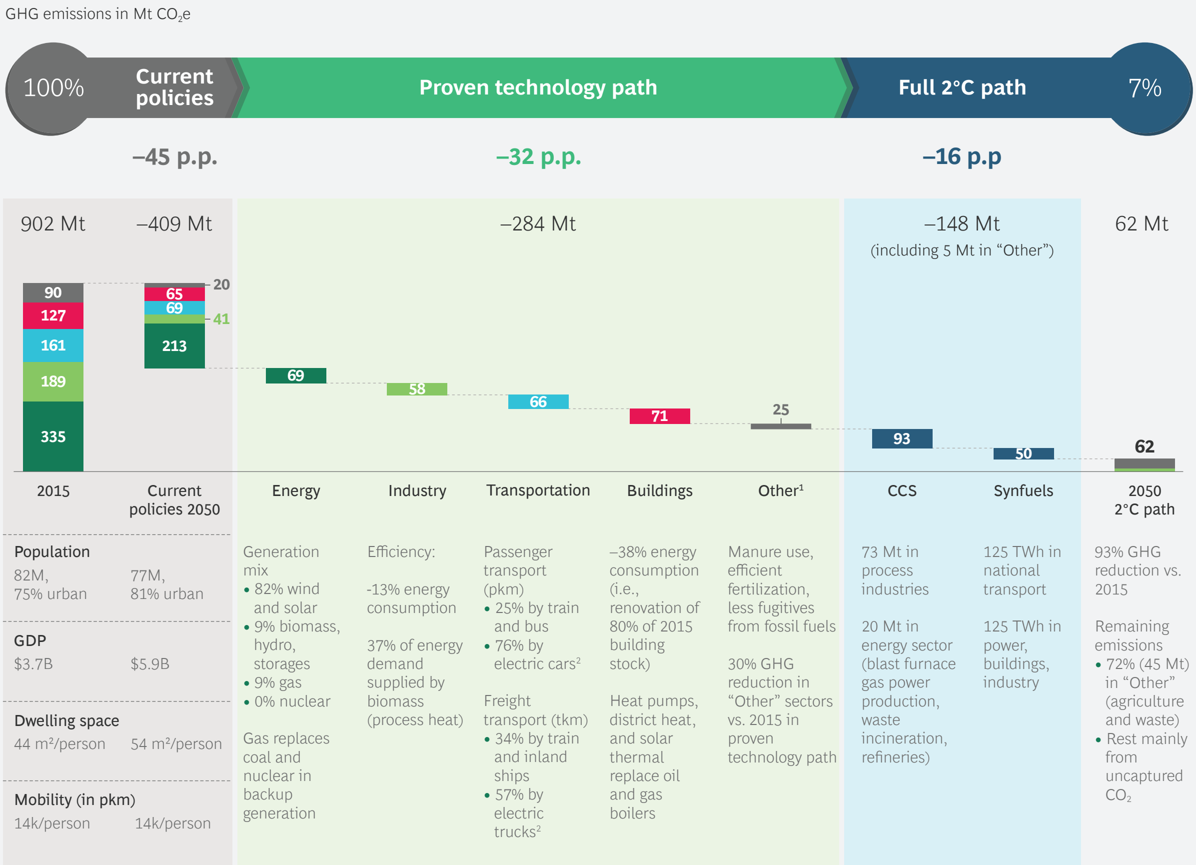
The 2°C Gap: In order to meet the 2°C contribution, GHG emissions in Germany would need to decrease by 93% (compared with 2015) by 2050. This leaves a gap of **432 Mt CO2e** between the current-policies and 2°C paths. (See the exhibit.)

Proven Technologies. Roughly 284 Mt CO_2e (67%) of the gap could be cut by deploying proven technologies.

- In the **power sector**, nuclear, hydropower, and biomass have no further deployment potential—nuclear for political reasons and national biomass and hydropower because of physical limitations. Thus, a transition toward a low-emitting power system is viable only through accelerated deployment of **wind and solar**. These technologies would need to make up more than 80% of German net power generation by 2050. As dispatchable backup, **gas plants** will need to replace the country's entire coal power plant infrastructure. This would also require accelerated power grid expansion, more storage (mostly batteries), and more use of electric vehicles, heat pumps, and other technologies to reduce demand. Because wind power generation would be close to its feasible expansion potential in Germany, energy efficiency in all power consuming sectors is key to reaching climate targets.

- In the **industrial** sector, 90% penetration of current state-of-the-art **efficiency technologies** could reduce energy

Germany's 2°C Path Requires 93% GHG Emissions Reduction Between 2015 and 2050



Source: BCG analysis.
Note: pkm = person kilometers; tkm = ton kilometers.
[1]Waste, agriculture, fugitives.
[2]Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

consumption by 16% (compared with the current-policies scenario) by 2050. Additionally, use of available sustainable **biomass** should be concentrated primarily in industry, where it can serve to decarbonize the entire demand for low- and medium-temperature (less than 500°C) heating and at least part of the high-temperature (more than 500°C) demand. From a national perspective, this is significantly more economical than using biomass in the power, building, and transportation sectors because biomass burns with higher efficiency, and few other alternatives exist.

- In the **transportation** sector, the main measures would be an increase of the share of **electric cars** to serve close to 80% of mobility demand. The introduction of **battery trucks** for shorter-range deliveries and **highway overhead lines** for long-range heavy-duty transport could increase the share of electric mobility to more than 50% of road freight transport.

- Reducing emissions from German **buildings** means phasing out fossil oil and gas for space and water heating and process heat generation. This would require continuation of existing **efficiency standards** for new buildings and the refurbishment of about 80% of the 2015 building stock. In parallel, oil and gas boilers must be phased out and replaced predominantly by **heat pumps** in suburban and rural areas and by low-carbon **district heating** in urban areas. Solar thermal can contribute to the heating mix, mainly for seasonal water heating.

- In **other sectors**, emissions in agriculture will decrease by 8%, to 56 Mt, by 2050. Conventional GHG abatement measures—fertilizer use and manure management—will reduce agricultural emissions by 20%. Other measures include efficient waste management and a reduction in fugitive emissions.

The Full 2°C Path. Eliminating 148 Mt CO_2e (the final third of the gap to 2°C) requires synfuels, CCS, and methane pills for cows.

- As residual emissions from **agriculture and waste** and industrial processes fill out the remaining emissions budget in 2050, a German 2°C path requires **zero net emissions in all other sectors**.

- After exploiting the feasible potential of proven technologies, the deployment of **CCS** could avoid 93 Mt CO_2, which corresponds to 44% of the remaining gap.

- Fully closing the gap to the 2°C path would require the use of **250 TWh of synfuels**. Half of these fuels would be needed for national transportation. The other half would be needed to replace all remaining natural gas for power generation and all remaining fossil fuels for energy use in other sectors.

- To meet its ambitious contribution to the 2°C path, Germany will also need to reduce methane emissions from cattle by 30% (about 5 Mt CO_2e), perhaps via technologies that are today not allowed, such as food additives (methane pills). (These currently do not fall under the proven technology category.)

The Price Tag. Germany requires $1.6 trillion in investment for the proven technology path through 2050 and an additional $800 billion for the full 2°C path.

- **Investment:** These figures correspond to average investments of **1.1% of GDP per year** under the proven technology path and an additional 0.4% of GDP per year to fully close the gap to 2°C.

- **Costs:** A low cost of capital and relatively high fossil fuel costs make climate investments attractive in Germany. After energy cost savings, the resulting cumulative macroeconomic costs would be **$500 billion** (0.5% of GDP per year) under the proven technology path and **an additional $400 billion** (0.3% of GDP per year) to fully close the gap to 2°C.

SOUTH AFRICA

Current Status: In 2015, GHG emissions in South Africa amounted to 520 Mt CO_2e. The power sector, characterized by inefficient, aging coal power plants, represented 58% of the total.

Trajectory: On the current-policies path, emissions from the power sector decrease by 23%, while emissions from the transportation and industrial sectors continue to grow. In total, GHG emissions decrease by 10%.

The 2°C Gap: In order to meet its 2°C contribution, South Africa must decrease its GHG emissions 72% (versus 2015 levels) by 2050. This leaves a gap of **0.3 Gt CO_2e** between the current-policies and 2°C paths. (See the exhibit.)

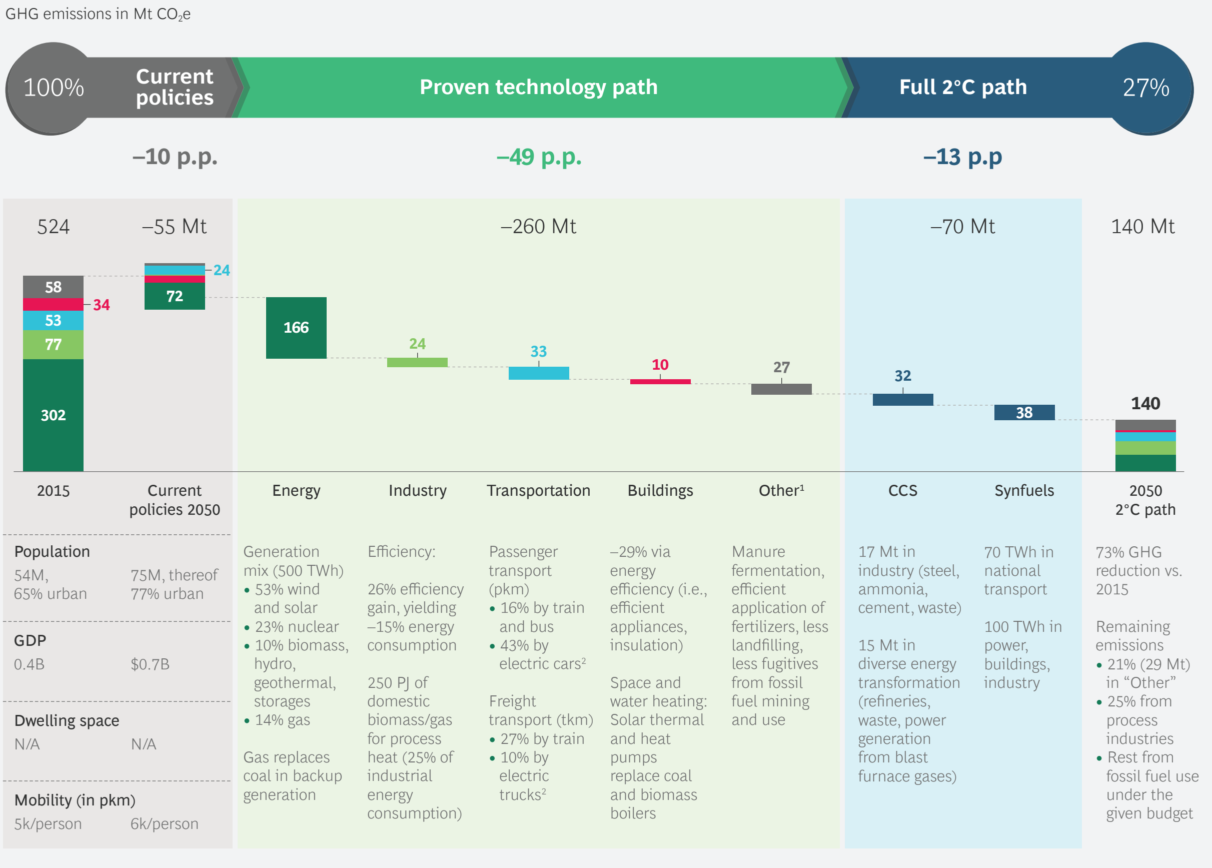
Proven Technologies. Roughly 260 Mt CO_2e (79%) of the gap could be reduced by deploying proven technologies.

- The **power sector** in South Africa faces a great challenge: moving from almost complete reliance on coal power to a mix of renewable energy, nuclear, and gas. The challenge is exacerbated by abundant local coal resources, a fairly poor network infrastructure, and a doubling of demand by 2050. In 2050, 37% of electricity supply could come from solar power, 23% from nuclear, and 16% from wind. Hydropower potential is limited to about 13 TWh, representing only 3% of demand. The remaining 21% would be covered by a mixture of biomass and natural gas. Such transformation requires creation of 80 GW in solar power, 29 GW in wind power, and 28 GW of gas power capacity. Nuclear power would increase from 2 GW to 15 GW.

- In the **industrial** sector, best-in-class efficiency technologies that are already available could curb energy demand by 26% compared with the current-policies path. The largest potential is in the mining sector. Additionally, 24% of the resulting energy demand could be covered by solid biomass, which could substitute for fossil fuels in process heat applications below 500°C. This would require commitment of almost 80% of South Africa's sustainably available biomass resources.

- The **transportation sector** in South Africa is largely dependent on roads. The expansion of the currently inadequate rail infrastructure could put roughly 20% of passenger transport and 15% of freight transport on rails by 2050. Electrification of road transport could reach 40% for cars and 15% for trucks. Electrification will be limited to a few urban areas because of

South Africa's 2°C Path Requires 73% GHG Emissions Reduction Between 2015 and 2050



Source: BCG analysis.
Note: PJ = petajoule; pkm = person kilometers; tkm = ton kilometers.
¹Waste, agriculture, fugitives.
²Battery electric vehicles, plug-in hybrids, fuel cell vehicles, and catenary-hybrid trucks/buses.

infrastructure constraints and low transportation density in rural areas. More-efficient internal combustion vehicles will help decrease emissions. Remaining road traffic and aviation will still rely on hydrocarbon fuels, which will account for 45% of energy demand for transportation in 2050.

- Energy consumption in the **buildings sector** is low and rather stable on the current-policies path. Penetration of energy-efficient electric appliances and new low-energy buildings could reduce total energy consumption by 20%. For space and water heating, heat pumps and solar thermal energy could serve about 60% of the demand by 2050. Clean biomass in rural areas will remain important for cooking, representing 35% of demand. Domestic coal-derived liquid fuels for residential use will not be fully phased out by 2050.

- In **other sectors**, conventional GHG abatement measures in manure management could reduce agricultural emissions by 27%. Other measures include efficient waste management and reduction of fugitive emissions.

The Full 2°C Path. Eliminating 70 Mt CO_2e (21%) of the gap to 2°C requires synfuels and CCS.

- After exploiting the feasible potential of proven technologies, the deployment of **CCS technologies** could avoid 32 Mt CO_2, which corresponds to 15% of the remaining emissions.

- Fully closing the gap to 2°C would require the use of **170 TWh synfuels**, of which about 40% would be used in the transportation sector to replace oil in cars, trucks, and airplanes. The remaining 60% would be used to replace all natural gas for power generation and to supplant fossil fuels in industry.

- In 2050, **the remaining 140 Mt CO_2e under the 2°C path** would be emitted by four sectors in equal portions: electricity, industry, transportation, and agriculture and waste.

The Price Tag. South Africa must invest $400 billion for the proven technology path through 2050 and an additional $300 billion for the full 2°C path.

- **Investment:** These figures correspond to **1.9% of GDP per year** for the proven technology path and an additional **1.6% of GDP per year** to fully close the gap to 2°C.

- **Costs:** Similar to those in Russia, climate investments in South Africa face the burdens of high capital costs and cheap domestic fuels. After energy cost savings, the resulting cumulated macroeconomic costs would be **$20 billion** (**0.8% of GDP per year**) under the proven technology path and **an additional $500 billion** (**2.3% of GDP per year**) to fully close the gap to 2°C.

FOR FURTHER READING

The Boston Consulting Group publishes many reports and articles that may be of interest to senior executives. The following are some recent examples.

Why Coal Will Keep Burning
An article by The Boston Consulting Group, March 2018

Climate Paths for Germany
A report by The Boston Consulting Group and Prognos, January 2018 (Full German report and an English summary are available.)

Preparing for a Warmer World
An article by The Boston Consulting Group, December 2017

NOTE TO THE READER

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