CHAPTER 3

MITIGATING CLIMATE CHANGE—GROWTH- AND DISTRIBUTION-FRIENDLY STRATEGIES

Without further action to reduce greenhouse gas emissions, the planet is on course to reach temperatures not seen in millions of years, with potentially catastrophic implications. The analysis in this chapter suggests that an initial green investment push combined with steadily rising carbon prices would deliver the needed emission reductions at reasonable transitional global output effects, putting the global economy on a stronger and more sustainable footing over the medium term. Carbon pricing is critical to mitigation because higher carbon prices incentivize energy efficiency besides reallocating resources from high- to low-carbon activities. A green investment push up front would strengthen the macroeconomy in the short term and help lower the costs of adjusting to higher carbon prices. The transitional costs of carbon pricing consistent with net zero emissions by mid-century appear manageable and could be reduced further as new technological innovations develop in response to carbon pricing and green research and development subsidies. Governments can protect those most affected by mitigation by providing targeted cash transfers financed by carbon revenues.

Introduction

Global warming continues apace. The increase in the average temperature over the surface of the planet since the industrial revolution is estimated at about 1°C and is believed to be accelerating. Each successive decade since the 1980s has been warmer than the previous one, the past five years (2015–19) were the warmest ever reported, and 2019 was likely the second-warmest year on record. Rising pressure on Earth systems is already evident from more frequent weather-related natural disasters.[1] Global sea levels are rising, and evidence is mounting that the world is closer to abrupt and irreversible changes—so-called tipping points—than previously thought (Lenton and others 2019).

Scientific studies attribute most of global warming to emissions of greenhouse gases associated with human activity, especially from the carbon released by burning fossil fuels (IPCC 2014, 2018a) (see Box 3.1 for a glossary).[2] Scientists have warned that temperature increases relative to preindustrial levels need to be kept well below 2°C—and ideally 1.5°C—to avoid reaching climate tipping points and imposing severe stress on natural and socioeconomic systems (IPCC 2014, 2018a). The objective of limiting temperature increases by 2100 to 1.5°C–2°C was endorsed worldwide by policymakers in the 2015 Paris Agreement. Sizable and rapid reductions in carbon emissions are needed for this goal to be met; specifically, net carbon emissions need to decline to zero by mid-century (IPCC 2014, 2018a). This means that carbon emissions must be eliminated or that any remaining carbon emissions must be removed from the atmosphere by natural (for example, forests and oceans) or artificial (for example, carbon capture and storage) sinks. Even with such drastic reductions, temperatures may temporarily overshoot the target until the stock of accumulated carbon in the atmosphere is sufficiently reduced by absorption by carbon sinks.

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[1]See also Chapter 2 of the April 2020 *Sub-Saharan Africa Regional Economic Outlook*, Chapter 3 of the October 2017 *World Economic Outlook*, and Kahn and others (2019). Adaptation policies are another critical element of the strategy to reduce losses from climate change and, in some cases, can overlap with mitigation policies (such as for the preservation of rain forests). However, these are beyond the scope of this chapter.

[2]Greenhouse gas is any gas that contributes to the greenhouse effect by absorbing infrared radiation (net heat energy) emitted from Earth's surface and radiating it back to Earth's surface. These gases include carbon dioxide, methane, nitrous oxide, and fluorinated gases. The chapter focuses on carbon emissions from the consumption of fossil fuels, which is a main driver of human-made greenhouse gas emissions. IMF (2019) discusses policies to reduce other important sources of greenhouse gas emissions beyond domestic fossil fuel CO_2 emissions (forestry, agriculture, methane leaks, industrial process emissions, F-gases, international aviation/maritime emissions).

Tangible policy responses to reduce greenhouse gas emissions have been grossly insufficient to date.[3] While the COVID-19 crisis has reduced emissions, it is already evident that this decline will be only temporary. Under unchanged policies, emissions will continue to rise relentlessly, and global temperatures could increase by an additional 2–5°C by the end of this century, reaching levels not seen in millions of years, imposing growing physical and economic damage, and increasing the risk of catastrophic outcomes across the planet (Figure 3.1).[4] Damages from climate change include (but are not limited to) lower productivity due to changes in the yield of agricultural crops and fish farming and hotter temperatures for people working outside; more frequent disruption of economic activity and greater physical destruction of productive capital, infrastructure, and buildings as a result of more frequent and severe natural disasters and (for coastal areas) the rise in sea levels; deterioration of health and possible loss of life due to natural disasters and increased prevalence of infectious diseases; and diversion of resources toward adaptation and reconstruction (see, for example, Batten 2018).[5] The response of temperatures to the accumulated stock of carbon emissions in the atmosphere ("climate sensitivity") and the damages that can be expected for given temperature increases are subject to uncertainty; many of the damages—including damages to the natural world and catastrophic risk—are also insufficiently captured by existing estimates, which are based on small historical variations in temperatures. Nevertheless, by all estimates, damages are expected to be substantial, and more recent studies that take account of the possibility

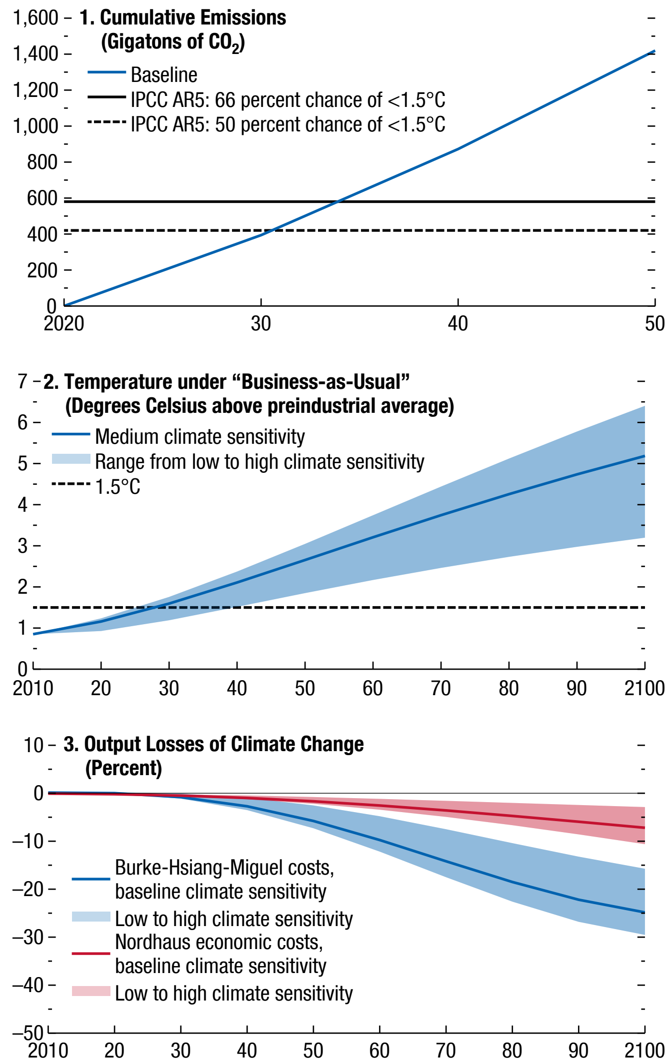
[3]For most countries, the Nationally Determined Contributions pledged under the Paris Agreement are deemed insufficient to meet either the 1.5°C or the 2°C target, and, judging by current policies, unlikely to be met in the first place (see Climate Action Tracker Warming Projections Global Update—December 2019). Views about the shortfalls of stated policies have been echoed by others, such as the International Energy Agency, which points out that significantly more ambitious policies are needed to reach the targets (IEA 2019).

[4]Absent climate change mitigation policies or massive migration, one-third of the global population could experience mean annual temperatures above 29°C by 2070. Such temperatures are currently found in only 0.8 percent of Earth's land surface, mostly in Africa, and are projected to cover 19 percent of land by 2070 (Xu and others 2020).

[5]Climate change will also complicate the management of macroeconomic stability, as climatic changes and natural disasters increase output and price volatility and, with the costs of natural disasters—from reconstruction to investment in adaptation—put pressure on fiscal sustainability. Last but not least, it will increase poverty and inequality because lower-income countries and lower-income people in any given country tend to be not only more exposed to but also less able to handle shocks or adapt to climate change.

Figure 3.1. Risks from Unmitigated Climate Change

Under the current trajectory of emissions, the probability of keeping global warming below 1.5°C would drop to 50 percent in about 15 years. Global temperatures under business-as-usual would increase to levels not seen in millions of years, triggering substantial income losses and raising the risk of catastrophic outcomes.



Sources: Burke, Hsiang, and Miguel 2015; IPCC 2014, 2018a; Nordhaus 2010; and IMF staff estimates.
Note: Baseline in panel 1 represents cumulative emissions under the unmitigated climate change scenario based on the G-Cubed model; dashed lines correspond to the emission ceilings needed to limit global warming. AR5 = the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Panel 2 shows global average temperature under business-as-usual. Solid line assumes a climate sensitivity (the long-term increase in temperature caused by a long-term doubling of the atmospheric carbon stock) of 3; the shaded area assumes a range of climate sensitivity from 1.5 to 4.5 (see Heal 2017; Hassler, Krusell, and Olovsson 2018). Panel 3 shows economic losses from climate change relative to holding temperatures fixed at current levels. Solid lines assume a climate sensitivity of 3; the shaded area assumes a range from 1.5 to 4.5 (see Heal 2017; Hassler, Krusell, and Olovsson 2018). Economic costs of given temperature rises are based on either Nordhaus (2010) or Burke, Hsiang, and Miguel (2015).

of nonlinear effects and long-lasting reductions in economic growth (for example, Burke, Hsiang, and Miguel 2015) point to much higher damages than previously projected. Various changes that global warming is setting in motion, such as the melting of the ice caps and rise in sea levels, and the acidification of oceans could themselves reinforce global warming and would be very hard to reverse over human timescales (IPCC 2014, 2018a).

The COVID-19 crisis creates both challenges and opportunities for the climate change mitigation agenda. Though mitigation is likely to boost incomes in the long term by limiting damages and severe physical risks, the economic transformation it requires may lower growth during the transition, especially in countries heavily reliant on fossil fuel exports and in those with rapid economic and population growth. The current global recession makes it more challenging to enact the policies needed for mitigation and raises the urgency of understanding how mitigation can be achieved in an employment- and growth-friendly way and with protection for the poor. However, there are also opportunities in the current context to put the economy on a greener path (see also the October 2020 *Fiscal Monitor*).[6] The crisis has led to a major retrenchment in investment and policies can seek to ensure that the composition of the recovery in capital spending is consistent with decarbonization by providing correct price signals and other financial incentives. In addition, fiscal stimulus—which will likely be needed in the aftermath of the pandemic—can be an opportunity to boost green and resilient public infrastructure.

This chapter takes the goal of reducing net carbon emissions to zero by 2050 as given and looks at possible ways of designing mitigation policies, being mindful of constraints related to political feasibility.[7] Specifically, the chapter asks the following two questions:

- Which combination of policy tools—carbon pricing, a public and private investment push, research and development subsidies—would allow the world to reach net zero carbon emissions by 2050 in a growth-, employment-, and distribution-friendly way?
- Can well-designed and sequenced mitigation policies help with the economic repair from the COVID-19 crisis?

While issues of international coordination are important, the depth of emission reductions targeted in this chapter (reaching net zero emissions) limits the room for differentiation of mitigation efforts across countries, especially across the large ones. Each country/region is thus assumed to reduce emissions to the same extent (with the exception of a group of selected oil-exporting and other economies where emissions are assumed to remain at current levels).

A deep decarbonization of human activity will require both energy efficiency and the share of low-carbon sources in energy supply to increase radically more than in recent decades. Incentivizing these changes will require carbon-intensive energy to become much more expensive relative to both low-carbon energy and other goods and services than it is today. Fossil fuels are now massively underpriced, reflecting undercharging for production and environmental costs—including for air pollution and global warming. Coady and others (2019) estimate global energy subsidies—the gap between existing and efficient prices (that is, prices warranted by supply costs, environmental costs, and revenue considerations)—at a striking $4.7 trillion in 2015, or about 6.3 percent of global GDP. A narrower subsidy measure, reflecting only differences between the amount consumers actually pay for fuel use and the corresponding opportunity cost of supplying the fuel, was estimated by Coady and others (2019) at $305 billion globally in 2015.

Governments can use various measures to raise the relative price of carbon-intensive activities. The first set of policies consists of raising the price of carbon through either carbon taxes or carbon emission trading programs to price the emission externality. Correctly pricing carbon would reduce its use while boosting the supply of low-carbon alternatives. While the chapter focuses on a carbon tax as a way to raise carbon prices, introducing feebates or imposing direct mandates and regulations on emissions are alternative or complementary tools that are less efficient but raise the implicit price of carbon and may face less political resistance (see the October 2019 *Fiscal Monitor* for a discussion

[6]For discussions on this, see Batini and others (2020), Bhattacharya and Rydge (2020), Black and Parry (2020), and Hepburn and others (2020).

[7]Almost all countries are revising their climate strategies under the Paris Agreement (Nationally Determined Contributions) ahead of the 2021 UN Climate Change Conference (COP 26) meeting. About 70 countries have committed to net zero emissions by 2050. Under net zero emissions, positive emissions would need to be offset by negative emissions (such as co-firing biofuels in power generation with carbon capture and storage, expanding forest carbon storage, and direct air capture technologies).

of efficiency/feasibility trade-offs).[8] The second set of policies directly aims at making low-carbon energy sources more abundant and cheaper and tackles broader market failures (such as knowledge spillovers, network externalities, and scale economies) in their provision. The toolkit for this approach includes subsidies and price guarantees to increase demand, investment, and supply in the low-carbon energy sector; direct public investment in low-carbon technologies and infrastructure; and research and development subsidies to spur innovation.[9]

Other policy options include the further development and adoption of negative emission technologies, such as carbon capture and storage, which are assumed to play a role in the modeling of emission reduction strategies in the chapter, and solar radiation modification measures, which can be effective in theory but in practice involve large uncertainties, risks, and knowledge gaps.[10]

The optimal mix and sequencing of mitigation policy tools, along with their macroeconomic implications, are still matters of much debate. Some commentators argue that reining in climate change through carbon pricing, while boosting output and welfare in the long term, could weaken growth in the short to medium term, as higher energy prices raise living costs (especially for the poor), displace workers, and reduce profits in carbon-intensive activities. However, some of these effects can be reduced if carbon pricing revenues are used to boost growth (for example, through funding productive investment or reducing distortionary taxes). Others stress the possibility of "green growth," arguing that government support for sustainable investment and technologies—together with higher expected carbon prices—can stimulate activity in the short to medium term through higher net investment, especially when the economy is operating below potential.[11] Another argument is that decarbonization policies focused on innovation policy (such as research subsidies) could trigger waves of technological change that would boost productivity and growth in the medium to long term.

This chapter approaches these questions in three ways. The first takes stock of the mitigation policies implemented in a large sample of countries over the past 25 years or so, and examines their roles in the shift from high- to low-carbon activities and what impact that had on overall activity. The analysis focuses on the power sector, which was the target of many of these policies. The second uses three macroeconomic models to examine mitigation policies needed to get to net zero emissions by 2050 and how to design them to be as growth friendly as possible. The third part of the approach examines the distributional effects of mitigation policies by modeling their impact on both consumption and labor income of households. It also looks at different ways of using carbon revenues to mitigate the adverse effects on those whose livelihoods would be the most affected.

The chapter finds that climate change mitigation policies have made important contributions to reallocating innovation, electricity generation, and employment toward low-carbon activities, broadly without harming overall activity. Supported by these empirical results, the chapter's model simulations suggest that getting to net zero emissions by 2050 is still within reach, though the window to keep temperature increases to safe levels is closing rapidly. This would put the global economy on a sustainable growth path in the second half of the century and

[8]Feebates are sectoral measures (for example, on transport, industry, or power) that impose a sliding scale of fees on firms/goods with emission rates (for example, CO_2 per kilowatt-hour) above a "pivot point" level and corresponding subsidies for firms/goods with emission rates below the pivot point. They are a hybrid between carbon pricing and green supply policies and may be more politically acceptable as they avoid an increase in the price of energy. Feebates can be used on their own or play a reinforcing role by complementing other instruments (see the October 2019 *Fiscal Monitor*).

[9]A broad package of measures is likely ideal, as the two types of policies can be expected to work in synergy. For instance, higher carbon prices would be more acceptable to the public—and so more sustainable—if low-carbon energy sources were available at a reasonable cost. Conversely, subsidies may not encourage strong private investment in low-carbon technologies if they are not coupled with expectations of a sufficiently high carbon price in the future.

[10]Solar radiation modification attempts to offset the warming from emissions accumulated in the atmosphere, while carbon capture and storage directly limits atmospheric greenhouse gas accumulation.

[11]While the terms "low" and "high" carbon refer to a specific metric (CO_2), the term "green" originates in the environment literature and generally refers to activities that have a (very) small impact on the environment. While "green" is commonly used to refer to low-carbon activities, these may not be strictly green, but just greener. For instance, wind and solar are low-carbon energy sources, but they are land and resource/material intensive. The same holds for other low-carbon sources of energy, such as hydro or nuclear power, which points to the issue of problem-shifting in a world characterized by multiple environmental problems. "Renewable energy" refers to wind and solar energy and to the fact that these technologies do not require fossil fuels, which are nonrenewable on human timescales.

beyond and immediately yield substantial domestic co-benefits from mitigation policies—mainly thanks to reduced mortality and morbidity from less environmental pollution.[12] An initial green investment push combined with initially moderate and gradually rising carbon prices would deliver the needed emission reductions at reasonable output effects. A green fiscal stimulus would support global GDP and employment during the recovery from the COVID-19 crisis and lay the ground for higher carbon prices by boosting productivity in low-carbon sectors. As the recovery takes hold, preannounced and gradually rising carbon prices become a powerful tool to deliver the quick and substantial reductions in carbon emissions required to reach net zero emissions by 2050.

Along the transition, higher carbon prices would entail global output losses, but these losses would be moderate relative to the expected income gains from avoided climate damage in the second half of the century and beyond. Growth in the medium and long term will be harmed considerably unless climate change is addressed, making the benefits from mitigation much higher than the temporary benefits from inaction.[13] The transitional economic costs would be reduced further if new low-carbon technologies were developed, and a strong case can be made to complement early on the innovation incentives sparked by carbon pricing with green research and development subsidies that help remove obstacles to developing new technologies.

The economic costs of the low-carbon transition differ across the world. Countries with fast economic and population growth (such as India and, to a lesser extent, China), those with heavy reliance on high-carbon energy (such as China), and most oil producers are likely to bear larger transition costs. However, for fast-growing countries, these costs remain small given their projected growth over the next 30 years (even under mitigation) and need to be weighed against substantial avoided damage from climate change and co-benefits from climate change mitigation, such as reduced local pollution and mortality rates. If advanced economies were to enact mitigation policies on their own, they would not be able to keep global emissions and temperature increases to safe levels; joint action by the largest economies is critical to avoid the worst outcomes of climate change. For fossil fuel producers, the required diversification of their economies will be difficult, but many of them also stand to benefit from global climate change mitigation.

Finally, whereas carbon pricing would disproportionately affect poorer households, recycling one-sixth to one-quarter of carbon revenues as targeted transfers could fully compensate the poorest 20 percent of households. Fully compensating the poorest 40 percent of households would require recycling between 40 and 55 percent of the carbon revenues. In addition, some limited government spending on low-carbon sectors would support job transitions from high-carbon to low-carbon sectors. Conscious and determined action by governments to build inclusion will be key to enhance the social and political acceptability of the transition.

The Mitigation Toolkit: How Have Policies Worked So Far?

Global innovation and investment in clean energy technologies have increased dramatically over the past two decades or so amid tightening environmental policies (Figure 3.2, panel 1).[14] Environmental policies cover a range of instruments used to varying degrees. Emission limits, notably for power (electricity) plants, and research and development subsidies ("nonmarket instruments") have been widely used since the 1990s and have become more stringent over time. The use of "market instruments," such as trading programs and feed-in tariffs, has picked up since the early 2000s, whereas carbon taxes have yet to become binding constraints in most countries (Figure 3.2, panel 2).[15]

[12]See Parry, Veung, and Heine (2015) and the October 2019 *Fiscal Monitor* for details on the unilateral costs and domestic net benefits of a $50/ton carbon tax in the Group of Twenty countries.

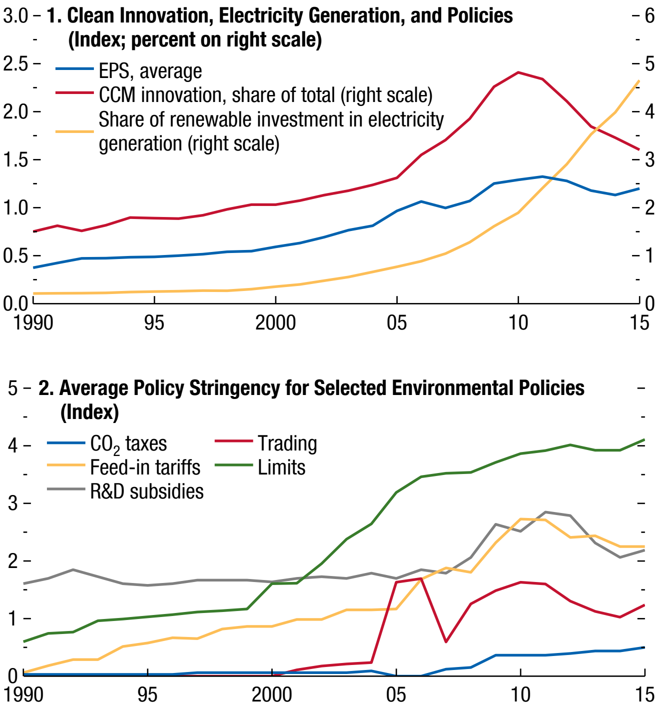
[13]See also Stern (2007) and Hassler, Krusell, and Olovsson (2018).

[14]This chapter uses the Organisation for Economic Co-operation and Development's Environmental Policy Stringency Index, as published in OECD (2018). For more details, see Botta and Koźluk (2014).

[15]Under feed-in tariffs, producers of renewable electricity are offered long-term contracts that guarantee a fixed price for every unit of electricity delivered to the grid. Trading programs include green and white certificates and those covering emissions of various pollutants. Green and white certificates are titles, respectively, for reaching renewable energy targets (portfolio standards) or energy-saving targets. In an emission trading program, a fixed number of emission permits is allocated or sold by a central institution, and the price adjusts to supply and demand. In contrast, a tax on carbon (or other pollutants) defines a price, or more precisely a markup, and lets the quantity of emissions adjust.

Figure 3.2. Environmental Policies and Share of Clean Innovation and Electricity Generation

Clean innovation and electricity generation increased largely in line with tightening environmental policies. The use of carbon taxes has been very limited historically.



Sources: International Energy Agency; Organisation for Economic Co-operation and Development; Worldwide Patent Statistical Database; and IMF staff calculations.
Note: CCM innovation = patents in climate change mitigating technologies; EPS = environmental policy stringency index.

Over the same period, clean energy innovation (measured by patent applications)[16] doubled in share of total energy innovation; and clean electricity innovation now accounts for half of total electricity innovation in the top five innovating countries (up from 15 percent in 1990). The global share of solar and wind power in electricity generation has also increased substantially, from virtually zero in 2000 to 6 ½ percent in 2020, with much higher shares in some European Union countries. Furthermore, the transition in electricity generation is accelerating: whereas the global renewable share was increasing at a pace of ½ percentage point a year by 2010, that number reached 1 percentage point by 2016.

Econometric analysis suggests that the tightening of environmental policies in many countries has played an important role in the changing composition of energy sector innovation and investment toward low-carbon activities (Figure 3.3; Online Annexes 3.1 and 3.2).[17] Specifically, more stringent environmental policies are estimated to have contributed to the following:

- Thirty percent of the increase in global clean energy innovation, equivalent to the effect of a permanent rise in oil prices of $66 a barrel. Higher oil prices explain the rest of the increase up to 2010, though this reversed after 2010. In the electricity sector, environmental policies increased the share of innovation in clean and "gray" electricity technologies (gray innovations reduce the pollution of dirty technologies) at the expense of dirty technologies.[18] Environmental policies contributed to more electricity innovation overall (Figure 3.3, panel 1).
- Fifty-five percent of the increase in the share of renewables in electricity generation. Tighter environmental policies were associated with declines in the share of coal and an ambiguous effect on the share of natural gas—often a complement to renewable energy (Figure 3.3, panel 2). The intermittent nature of renewables requires backup power in the form of batteries or generators that can dispatch electricity to the grid quickly, such as from hydroelectric or natural gas power plants. By and large, environmental policies do not appear to be associated with a discernible negative impact on total electricity generation.

Various policy instruments are found to be effective in spurring both innovation and investment in renewables.

- Both market and nonmarket policies—in particular research and development subsidies, trading programs, emission limits, and feed-in tariffs—were effective in spurring clean innovation. Oil prices

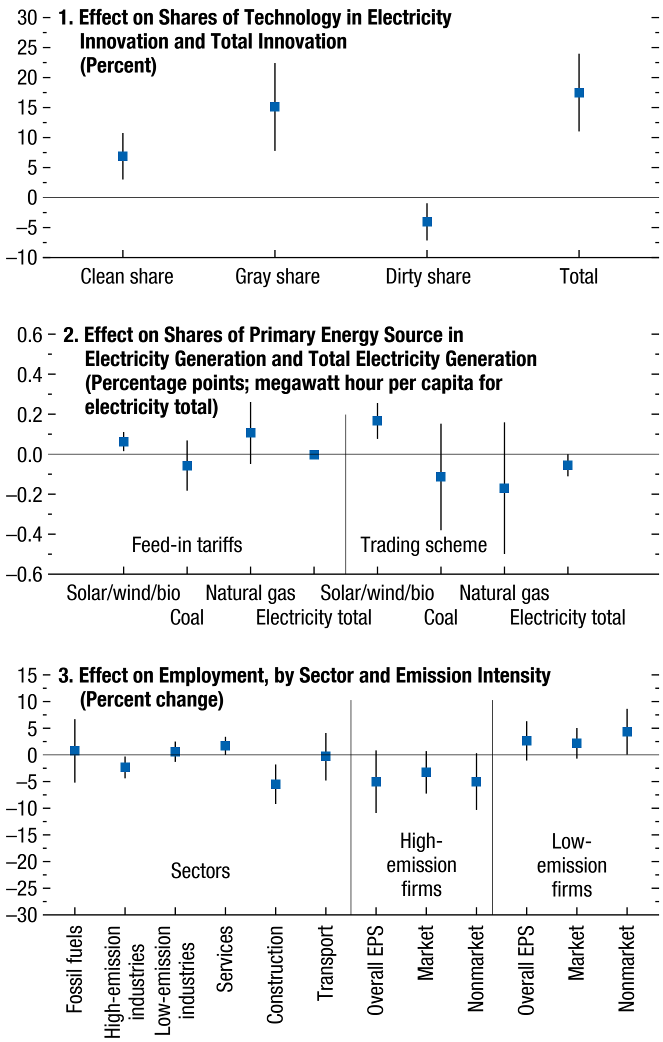
[16]The analysis focuses on clean innovation in the energy sector, given the sector's important contribution to total emissions and innovation in clean technologies and its direct exposure to most of the environmental policies analyzed. Clean energy innovation is defined here as the number of patent applications in climate change mitigation technologies related to energy generation, transmission, or distribution, as classified by Haščič and Migotto (2015).

[17]The analyses cover about 30 advanced economies and emerging market economies during 1990–2015. While the specifications differ somewhat, they generally control for constant country-specific factors and global dynamics (through country and year fixed effects), changes in energy prices, oil and gas reserves, and regulatory changes. All annexes are available at www.imf.org/en/Publications/WEO.

[18]Examples of gray technologies include those that allow the use of heat from fuel or waste incineration or fuels from nonfossil sources. See Dechezleprêtre, Martin, and Mohnen (2017) for details on the classification.

Figure 3.3. Effect of Policy Tightening on Electricity Innovation, Electricity Generation, and Employment, by Type of Technology

More stringent environmental policies stimulated innovation in climate-change-mitigating energy technologies and raised the share of renewable electricity generation. They also raised employment in the "green" sectors and lowered it in the "brown" sectors.



Sources: Dechezleprêtre, Martin, and Mohnen 2017; International Energy Agency; Organisation for Economic Co-operation and Development; Penn World Tables; Worldscope database; Worldwide Patent Statistical Database; and IMF staff calculations.
Note: All panels show point estimate and 90 percent confidence bands. Panel 1 shows the effect of a one-unit tightening in the environmental policy index on innovation in the respective types and total electricity innovation. Panel 2 shows the effect of a one-unit tightening in the policy indicator on the electricity share of the respective primary energy sources and on total electricity generation per capita. Panel 3 shows the effect of tightening policies by one standard deviation on employment. The six bars on the left show the impact of tightening market-based policies on employment among firms in select sectors. The six bars on the right show the impact of tightening aggregate, market-based, and non-market-based policies, respectively, on employment in firms with high (low) CO_2 emissions intensity (based on a smaller sample of firms that report CO_2 emissions). EPS = environmental policy stringency.

were also found to be important determinants of clean energy innovation.[19] Whereas both the tightening in environmental policies and rising oil prices contributed to boosting clean energy innovation up to 2010, the expansion of clean innovation has stalled since then. This has coincided with the partial reversal of regulatory tightening and the shale oil and gas boom in the United States, which capped oil price increases.[20] Popp and others (2020) also point to the possible role of an earlier clean-tech bubble and falling returns on clean innovation. Though the estimated effect of higher carbon prices was far from statistically significant—likely reflecting limited take-up of this instrument and limited statistical power—the significant impact of oil prices on clean innovation suggests that policies that increase the cost of dirty energy may be a strong incentive for clean innovation.

- Instruments that seem to have a clear positive impact on investment in renewable electricity generation are feed-in tariffs and trading programs (which include green certificates to achieve renewable portfolio standards and carbon emission trading programs).[21] Green certificate programs are being phased out in several countries, and carbon tax and carbon trading programs are expected to become more important. As the share of renewables in electricity generation increases, addressing their intermittency will become increasingly relevant, likely requiring significant public investment in grids and innovation (such as storage technologies).

Finally, the analysis examined the impact of tighter environmental policies on employment in high- and low-carbon sectors (see Online Annex 3.3). A concern with decarbonization policies is that they will lead to job losses in carbon-intensive activities, such as coal mining, shale oil and gas production, carbon-intensive

[19]The estimation of the effect of oil prices relies on a separate regression, with identical controls but without year fixed effects.
[20]Acemoglu and others (2019) discusses how the shale gas revolution has set back clean innovation.
[21]Under feed-in tariffs, producers of renewable electricity are offered long-term contracts that guarantee a fixed price for every unit of electricity delivered to the grid. Green certificates are a means to implement government-mandated renewable portfolio standards, measured as the percentage of electricity that utilities need to source from renewables.

manufacturing, or transportation.[22] But the net effect of decarbonization policies on jobs also depends on how many new jobs are created in low-carbon activities, in the energy sector (such as solar and wind power generation), and in the economy more broadly. Production in renewable energy is more job intensive than electricity generation based on fossil fuels (see below).[23] But the substitution may not be full (given that mitigation policies curb emissions in part through reduced energy demand and intensity), and the net effect can be insignificant or negative. Evidence from firms suggests that job losses in some high-emission sectors (for example, high-emission manufacturing, transportation) in response to tighter environmental policies can be offset by job creation in some low-emission sectors (for example, low-emission manufacturing and services).[24] The net effect on aggregate jobs is typically small and indeterminate, depending on the extent of substitution between high- and low-emission activities (Figure 3.3, panel 3).[25] In general, the job effects seem larger and net negative in response to changes in nonmarket policies, whereas market policies, such as feed-in tariffs and trading programs, have a more muted and net positive effect. The impact on fossil fuel industry employment is not significant and reflects the opposing effects of tax-based policies (negative) and trading-based policies (positive). All in all, the evidence indicates that environmental policies have succeeded in reallocating jobs from high- to low-carbon sectors. However, job transitions can involve costs for the workers affected, and it will be important to examine distributional consequences arising from the labor market effects of climate policies (see the "How to Build Inclusion" section).

[22]The literature suggests that tighter climate change mitigation policies, such as carbon taxation, have led to job losses among the low-skilled and workers in high-emission industries, though effects on overall employment are less clear. See Kahn (1997) and Yamazaki (2017) for employment effects across different sectors, Yip (2018) and Marin and Vona (2019) for effects across skill types, and Metcalf and Stock (2020) for aggregate employment effects. Notably, Yamazaki (2017) shows that a revenue-neutral carbon tax can have a small positive and significant employment effect.

[23]Renewables production and installation tends to be more labor intensive than fossil fuel technologies, as capacity investments in renewable electricity generation tend to be more modular and come in relatively small increments.

[24]High-emission manufacturing sectors include chemicals, metals and minerals, paper and packaging, and food.

[25]Policy tightening would increase costs for high-emission firms and, depending on elasticity of demand, reduce output (and employment). Conversely, labor demand could increase in sectors/firms where energy is substitutable with labor, for example among services (see Yamazaki 2017).

How to Reach Net Zero Emissions by 2050

This part of the chapter examines the combinations of climate change mitigation policies needed to bring net carbon emissions to zero by 2050 and how they may impact the macroeconomy. General equilibrium model analysis is required to simulate the effects of ambitious mitigation policies, given that these affect the economy through various channels and come with both negative and positive effects on output as some sectors contract and others expand. Their net effects cannot be predicted with certainty and depend on the relative strength of various channels.

Mechanisms

At a broad level, mitigation policies affect carbon emissions and the macroeconomy through the difference between the prices of fossil fuel and clean energy and the overall energy price.

Relative Price of Fossil Fuel and Low-Carbon Energy

Both carbon pricing and green supply policies increase the price of fossil fuel energy relative to low-carbon energy by raising the price of carbon and/or lowering the price of renewables and other low-carbon energy. The increase in the price of fossil fuel energy relative to clean energy raises demand for renewable energy and, more generally, activities with low carbon intensity and hence leads to a reallocation of investment, innovation, and employment in that direction. The net effect on economic activity will depend on the relative speed at which high-carbon sectors contract and low-carbon sectors can be scaled up (costs of adjusting capital can hinder a rapid scaling up). The net effect on investment and employment also depends on the relative capital- and labor intensity of the sectors. High-carbon sectors (such as fossil fuel energy and heavy manufacturing) are typically more capital intensive, whereas low-carbon sectors (such as renewable energy and many services) are more labor intensive. All else equal, the net effect of the reallocation of activity from high- to low-carbon sectors could therefore be more positive (less negative) for employment than investment. Finally, widening differences between the price of fossil fuel energy and clean energy can lead to wealth effects and stranded assets. Carbon-intensive activities have large footprints on financial portfolios in advanced economies and the net worth of fuel exporters. In an aggressive decarbonization scenario, early obsolescence of carbon-intensive capital would lead to wealth losses and drag down aggregate demand in some economies. Chapter 5 of the October 2020 *Global Financial Stability Report* examines the potential financial stability implications of defaults of carbon-intensive businesses as a result of an increase in carbon prices. At the same time, countries with comparative advantage in renewable energy and low-carbon technologies could experience positive wealth effects.

Overall Energy Price

Carbon pricing and green supply policies affect the overall energy price differently. While a carbon tax increases the overall energy price and can hurt economic activity, it also encourages energy efficiency and discourages energy usage. That said, revenues from carbon pricing could be used to offset these costs, for instance by directly incentivizing the supply of clean energy or financing green public infrastructure that helps reduce the energy intensity of economic activity or raises the efficiency of renewable power.[26] Revenues can also be used to provide transfers to households to avoid hurting the poor and increase political acceptability (October 2019 *Fiscal Monitor*). In contrast, green supply policies lower the overall price of energy and could potentially boost GDP, depending on how the policy support is financed (taxes versus borrowing). But green supply policies do not incentivize energy efficiency and can be accompanied by greater energy consumption, including of carbon-intensive sources (given the intermittency of renewable power). These differences explain both the greater efficacy of carbon taxes at reducing emissions and their greater output cost.[27] When combined, green supply policies and carbon pricing can, in principle, prompt declines in emissions consistent with substantial climate change mitigation, without major shrinkage of output and consumption during the transition.

In addition to providing price signals through carbon pricing and green supply policies, governments can directly stimulate green technologies by providing incentives for research. Innovation is driven by market size; as such, higher carbon prices (which expand markets for low-carbon activities and shrink those for carbon-intensive ones) would incentivize a shift toward greener research and development, lowering the prices of green technologies over time and amplifying decarbonization. Importantly, the presence of this amplifying mechanism would mean that a given decline in emissions could be delivered with lower carbon prices. The use of green research and development subsidies alongside carbon taxes is justified on economic grounds to resolve multiple market failures (for example, Acemoglu and others 2012, 2016; Stiglitz and others 2014). These may include knowledge spillovers from innovation that are not taken into account by private firms; path dependency of research, which gives the established technologies an advantage and creates entry barriers (through economies of scale, sunk costs, and network effects); and difficulty accessing financing due to high uncertainty/risk, a long lag until innovation pays off, and lack of knowledge and information among investors. As with other green supply policies, green research and development subsidies would lower the energy price overall, boosting output but also partly offsetting the reduction in emissions through higher energy consumption. Historically, government research programs have had key roles in the development of large technological breakthroughs (for example, landing on the moon, or the prototype of the internet). More active government involvement—including through international cooperation—may be needed to assist in the development of technologies that can support the low-carbon transition.

A Comprehensive Mitigation Package

The goal of bringing net carbon emissions to zero by 2050 in each country can be achieved through a comprehensive policy package that is growth friendly (especially in the short term) and involves compensatory transfers to households to ensure inclusion. The 2050 objective is operationalized as a reduction in gross emissions by 80 percent, assuming that the expansion of natural emission sinks (such as forests) and some deployment of negative emission technologies (for example, carbon capture and storage technologies) will help absorb the remaining carbon emissions (IPCC 2018a, b). To implement such deep reductions in emissions at the global level, each country/region needs to reduce its own emissions by 80 percent, and there is little room for differentiation of mitigation efforts across countries. However, one exception is made for the group of selected oil-exporting and other economies, which are assumed to keep emissions at current levels because economic activity shrinks substantially due to

[26]Another option for recycling revenue from carbon taxes is to cut distortionary taxes on labor and capital (for example, Goulder 1995 and Goulder and Parry 2008).

[27]Carbon taxes are a very effective way of reducing emissions also because they automatically impose the highest penalties on the most-polluting fuels.

the fall in global oil demand. The policy package is designed with macroeconomic policy goals and political feasibility in mind and includes (1) a green fiscal stimulus that boosts demand and supply in the economy, supporting the recovery from the COVID-19 crisis, and helps reduce the level of carbon prices required to reach the emission target; (2) gradually phased-in carbon price increases; and (3) compensatory transfers to households. Specifically, it includes the following:

- *Green supply policies*: These consist of an 80 percent subsidy rate on renewables production and a 10-year green public investment program (starting at 1 percent of GDP and linearly declining to zero over 10 years; after that, additional public investment maintains the green capital stock created). Public investment is assumed to take place in the renewable and other low-carbon energy sectors, transport infrastructure, and services—the latter to capture the higher energy efficiency of buildings (see Online Annex 3.4 for more details).[28]
- *Carbon pricing*: Carbon prices are calibrated to achieve the 80 percent reduction in emissions by 2050, after accounting for emission reductions from the green fiscal stimulus. A high annual growth rate of carbon prices (7 percent) is assumed to ensure low initial levels of the carbon price and a gradual phase-in of carbon prices.[29] The needed carbon prices start at between \$6 and \$20 a ton of CO_2 (depending on the country), reach between \$10 and \$40 a ton of CO_2 in 2030, and are between \$40 and \$150 a ton of CO_2 in 2050.[30,31]
- *Compensatory transfers*: Households receive compensation equal to one-fourth of carbon tax revenues, which should protect the purchasing power of poor households through targeted cash transfers (see the "How to Build Inclusion" section).
- *Supportive macroeconomic policies*: The policy package outlined above implies a fiscal easing that requires debt financing for the first decade and occurs amid low-for-long interest rates, given the current context of low inflation.

Model Simulations

Policy simulations are run using the G-Cubed global macroeconomic model (McKibbin and Wilcoxen 1999, 2013; Liu and others 2020; see Online Annex 3.4). The model features 10 countries/regions, detailed energy sectors, forward-looking agents, real and nominal rigidities, and fiscal and monetary policies. It is suited to examining the effect of mitigation policies on carbon emissions related to the burning of fossil fuels and on the macroeconomic dynamics in the short, medium, and long term. The long-term dynamics of temperatures and estimates of the avoided damages from climate change are simulated using the integrated assessment model of Hassler and others (2020) and different climate change damage functions. The goal of the simulations presented in the chapter is to illustrate the main mechanisms at work and provide some order of quantification. The exact magnitudes in these long-term projections are unavoidably subject to substantial uncertainty.

In the absence of new climate change mitigation policies, global carbon emissions are projected to continue to rise at an average annual pace of 1.7 percent and reach 57.5 gigatons by 2050 (Figure 3.4).[32] Improvements in energy efficiency and some penetration of renewables—reflecting a continuation of current policies and some autonomous increases (for example, reflecting consumer preferences)—cannot offset the forces of population and economic growth that are driving emissions. Whereas advanced economies have historically contributed the lion's share of emissions, China and India, as large and fast-growing emerging market economies, are significant emitters and are expected to continue to account for growing shares of carbon emissions. Their per capita emissions, however,

[28]IEA (2020a) discusses green investment opportunities in the energy and transportation sectors and in energy efficiency (for example, retrofitting of buildings). See also McCollum and others (2018) for an estimate of energy investment needs for fulfilling the Paris Agreement and achieving the United Nations Sustainable Development Goals.

[29]Gollier (2018a, b) finds that, contrary to the Hotelling rule (according to which greatest efficiency is achieved when the carbon tax grows at a rate equal to the interest rate), most scenarios from the Intergovernmental Panel on Climate Change involve a rate of growth in the carbon tax higher than the interest rate, to reflect political constraints on the initial level of carbon taxes.

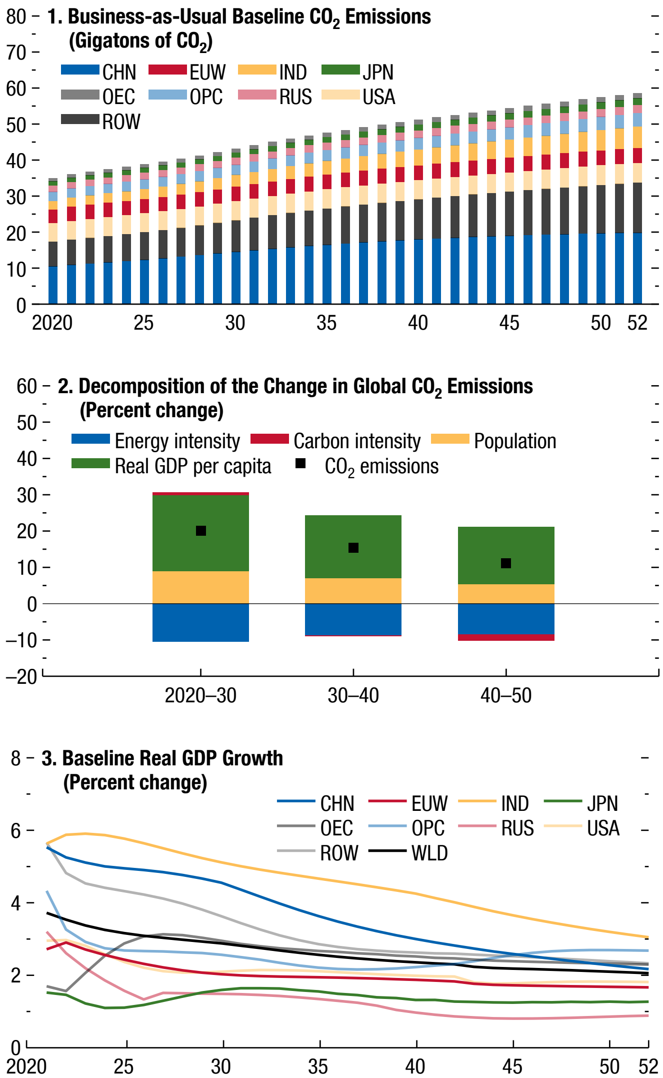
[30]The range of estimates of carbon prices needed to reach a certain level of emission reduction is large (see, for instance, IPCC 2014, Figure 6.21.a, or Stiglitz and others 2014). The relatively low levels of carbon prices in this chapter's simulations reflect (1) the combination of carbon prices with other instruments (green infrastructure investment and green subsidies), which achieve part of the emission reduction; (2) the high assumed growth rate of carbon prices, which back-loads their increases; and (3) the fact that the G-Cubed model embeds more substitutability between high- and low-carbon energy (based on econometric evidence) than engineering-based models.

[31]The real price of carbon continues to grow until 2080.

[32]Black and Parry (2020) finds that the required emission reductions for meeting temperature stabilization goals are essentially unchanged by the current economic crisis. But the COVID-19 crisis could lead to long-term behavioral changes that would raise or lower emissions—such as reduced use of public transportation and greater reliance on individual vehicles or greater use of digital communication, leading to reduced commuting and less travel. The baseline assumes (somewhat above) trend increases in energy efficiency.

Figure 3.4. G-Cubed Model Simulations, Baseline

Under unchanged policies, global carbon emissions would keep rising due to economic and population growth. Continued declines in energy intensity would not be sufficient to offset these forces.

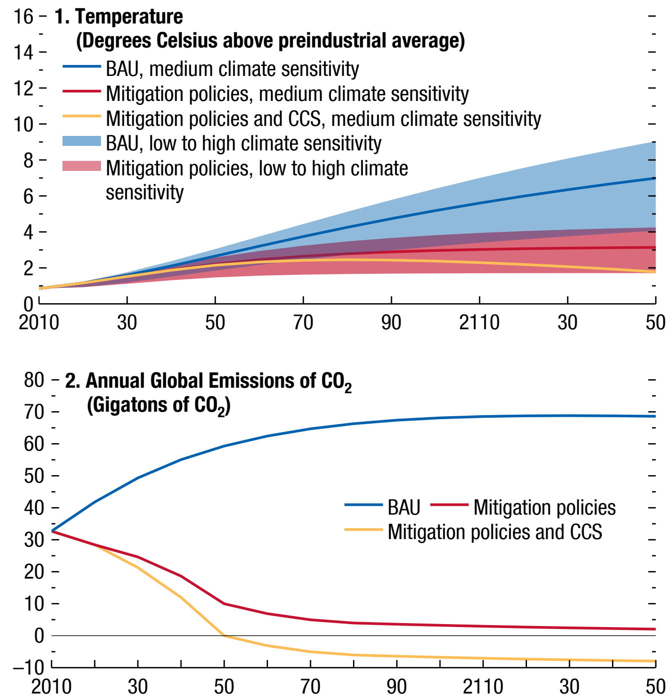


Source: IMF staff estimates.
Note: The baseline simulations are run using the G-Cubed global macroeconomic model of McKibbin and Wilcoxen (1999, 2013) and Liu and others (2020). See Online Annex 3.4 for a description of the baseline assumptions. EUW = EU, Norway, Switzerland, United Kingdom; OEC = Australia, Canada, Iceland, Liechtenstein, and New Zealand; OPC = selected oil-exporting countries and other economies; ROW = rest of the world; WLD = world. Data labels use International Organization for Standardization (ISO) country codes.

still remain relatively small when compared with those of advanced economies. Global growth is assumed to progressively decline from 3.7 percent in 2021 to 2.1 percent in 2050, reflecting a tapering off of growth in emerging market economies as they catch up toward the income levels of advanced economies. Projections

Figure 3.5. Global Temperature and CO_2 Emissions

The policy package, combined with some deployment of carbon capture and storage, brings carbon emissions to net zero by mid-century and helps keep temperature increases to 2°C in the long term.



Source: IMF staff estimates.
Note: The calculations use an integrated assessment model with exogenous technical change. Panel 1 shows global average temperature under three policy scenarios: business-as-usual, a mitigation policy package, and a mitigation policy package plus carbon capture and storage (CCS). Solid lines assume a climate sensitivity (the long-term increase in temperature caused by a long-term doubling of the atmospheric carbon stock) of 3; the shaded areas are a range from 1.5 to 4.5 (see Heal 2017; Hassler, Krusell, and Olovsson 2018). BAU = business-as-usual.

of economic growth over the next 30 years determine the expected growth of future emissions and therefore the scale of effort needed to keep temperature increases to 1.5–2°C. However, most existing scenarios (IPCC 2014, 2018a) indicate that, under unchanged policies, carbon emissions will continue growing strongly, leading to temperature increases well above the safe levels agreed to in the Paris Agreement and raising the risk of catastrophic damage for the planet.

As the simulations show, however, an initial green investment push combined with steadily rising carbon prices would deliver the needed emission reductions at reasonable output effects.

Under the policy package, global carbon emissions are reduced by about 75 percent from current levels, reaching about 9 gigatons by mid-century (Figure 3.5). This brings net emissions to zero around mid-century and to negative levels thereafter with the deployment of carbon capture and storage. Over the long term, temperature increases are kept down to 2°C after some modest initial overshooting. Thus, the policy package allows avoiding much of the severe damage from climate change and especially the risk of catastrophic outcomes, putting the global economy on a higher and sustainable income path from the second half of the century (see below).

A closer look over the next 30 years shows that the costs of the transition are moderate and that both a green fiscal stimulus and carbon pricing play key roles (Figure 3.6). The policy package delivers a net positive effect on global growth in the initial years, suggesting that it can support the recovery from the COVID-19 crisis. After 15 years, GDP is lower by up to about 1 percent relative to its baseline level under unchanged policies. The estimated transitional GDP costs in this chapter's simulation are within the range of other studies (1–6 percent of GDP by 2050), albeit on the lower side of estimates—reflecting the support to activity from green infrastructure investment and higher substitutability between high- and low-carbon energy in G-Cubed than in engineering-based models (see Chapter 6 of IPCC 2014). These are moderate output losses in the context of the expected 120 percent cumulative global GDP growth over the next 30 years (Figure 3.6, panels 2 and 3). From mid-century on, the benefits of climate mitigation in the form of avoided damage grow larger, and the policy package boosts GDP and growth substantially above their baseline levels (Figure 3.7).

Closer examination of the effects of different tools employed in the policy package shows their complementary roles:

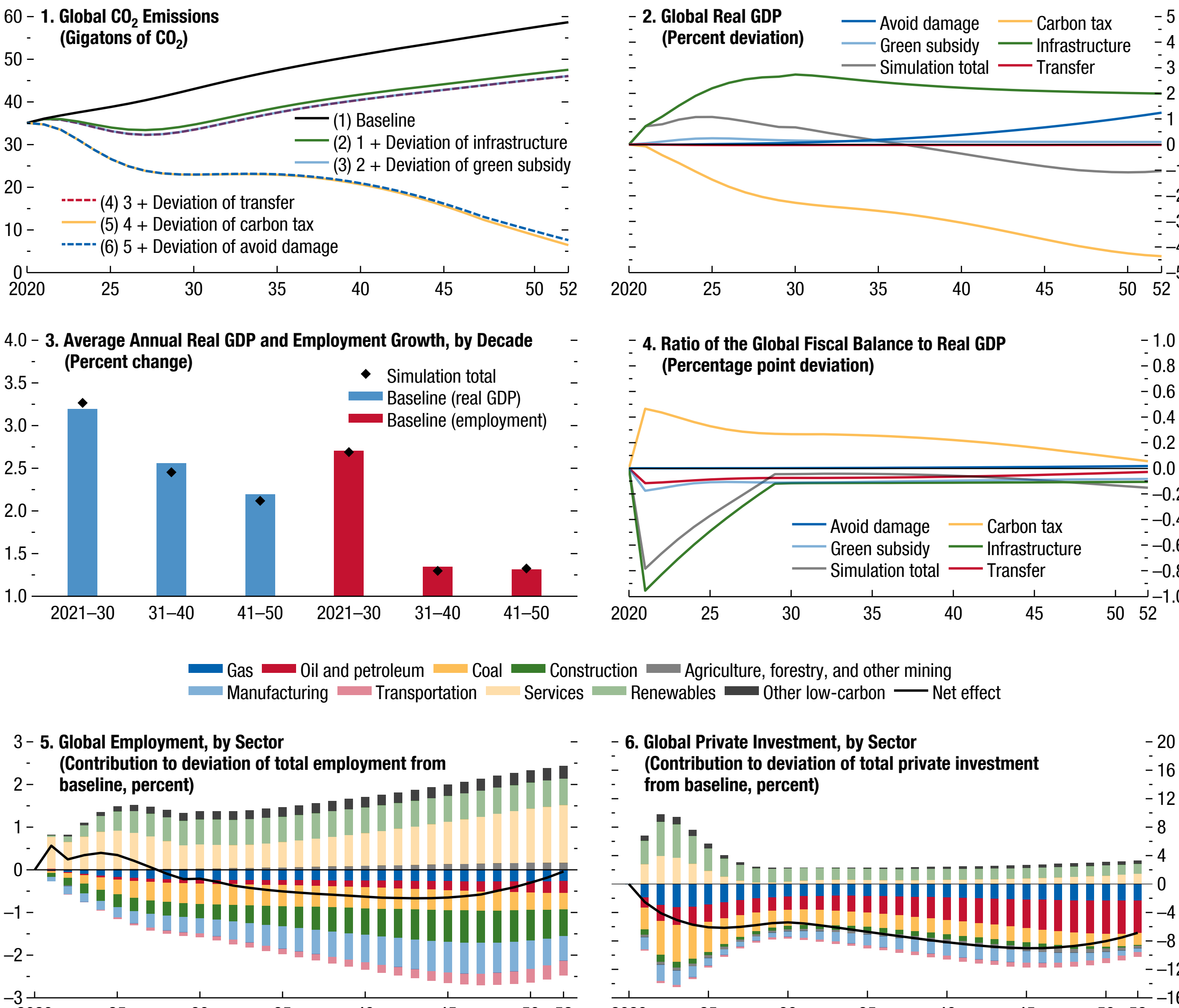
- *Emission reductions:* While the green fiscal stimulus helps reduce emissions meaningfully, its effect is much smaller than that of carbon pricing. The latter is a powerful tool to generate rapid and substantial emission reductions because it is effective at increasing energy efficiency, while green supply policies lower the overall energy price and boost energy consumption (Figure 3.6, panel 1).
- *Economic costs:* Whereas carbon pricing lowers real GDP by increasing the cost of energy, the green fiscal stimulus boosts it, both directly and indirectly (Figure 3.6, panel 2). First, the green fiscal stimulus directly adds to GDP through higher investment spending. Second, it indirectly reduces the output costs of the transition to a low-carbon economy by lowering future carbon emissions and the level of carbon taxes needed to meet the emission reduction targets. The green stimulus first boosts economic activity by increasing aggregate demand; thereafter the green infrastructure investment boosts the productivity of the low-carbon sectors, incentivizing more private investment in these sectors and increasing the potential output of the economy. Its effects are large enough to comfortably offset the economic cost of the carbon tax in the initial years. As a result, the policy package raises output in the first 15 years by about 0.7 percent of global GDP each year (on average over that period). After 15 years the drag from the carbon tax is larger, resulting in small net output losses. The net drag of the policy package on global output—of about 0.7 percent, on average, between 2036–50, and slightly more than 1 percent by 2050—appears manageable in the context of an expected cumulative increase in real GDP of 120 percent over the next 30 years. Average annual growth, after being higher in the 2020s thanks to the green fiscal stimulus, is lower by only one-tenth of a percentage point in the 2030s and by less than one-tenth of a percentage point in the 2040s (Figure 3.6, panel 3). Over time, the economy benefits from avoiding damages from climate change—such as lower productivity due to higher temperatures and more frequent natural disasters—meaning that output would be higher relative to what it would have been under unchanged policies. Estimates of damages from climate change vary with the assumed response of temperatures to the accumulated carbon stock and with methodologies used to relate economic damages to temperatures. The more recent studies (for example, Burke, Hsiang, and Miguel 2015) point to much larger damages than previously estimated and are more in line with the substantial risks scientists have warned about.[33] Based on these estimates, the projected net output gains from mitigating climate change increase rapidly after 2050, reaching up to 13 percent of global GDP by 2100 (Figure 3.7). However, even these estimates are likely to understate benefits from mitigating climate change as they imperfectly take account of—or do not incorporate—some of the damages related to temperature increases, such as

[33]The large difference between the various measures comes from uncertainty over two aspects of the costs of climate change: first, whether temperature increases affect the level of output (as in Nordhaus 2010) or its growth rate (as in Dell, Jones, and Olken 2012; and Burke, Hsiang, and Miguel 2015); second, whether the relationships observed in historical data between temperature and output can be relied upon in the future (especially when these are nonlinear). Over long forecast horizons, different stances on these two aspects can lead to very big differences in the costs of climate change and the gains from climate mitigation.

Figure 3.6. G-Cubed Model Simulations of Comprehensive Policy Package, Global Results

(Deviation from baseline, unless noted otherwise)

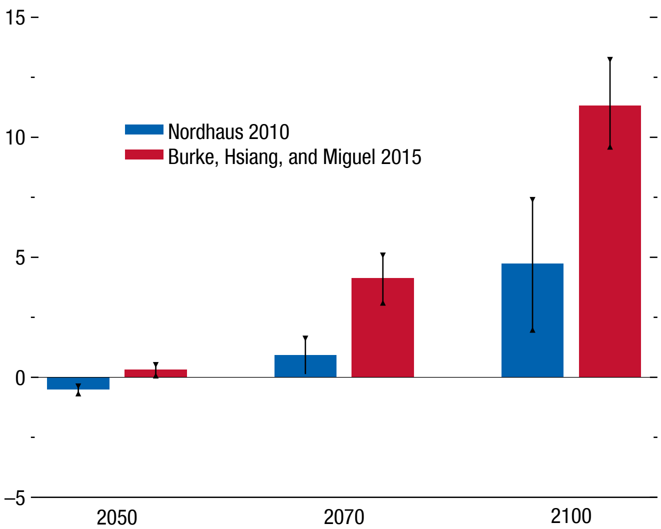
An initial green investment push, combined with steadily rising carbon prices, would deliver the needed emissions reductions at reasonable output effects. The package would initially boost global GDP, supporting the recovery from the COVID-19 crisis, but then weigh on global activity for a period, as the impact of the investment push wanes and carbon prices continue to rise. In the second half of the century, the reduction in emissions would place the global economy on a stronger and more sustainable path.



Source: IMF staff estimates.
Note: The simulations are run using the G-Cubed global macroeconomic model of McKibbin and Wilcoxen (1999, 2013) and Liu and others (2020). The climate change mitigation policy package is calibrated to reduce gross emissions by 80 percent in every country/region by 2050 and comprises (1) gradually rising carbon taxes, (2) a green fiscal stimulus consisting of green infrastructure investment and a subsidy for renewables production, and (3) compensatory transfers to households. The figure also shows the effects of avoided damages from climate change resulting from the implementation of the package. See Online Annex 3.4 for more details on the implementation of the simulation.

Figure 3.7. Medium- to Long-Term Output Gains from Climate Change Mitigation
(Percent of baseline GDP)

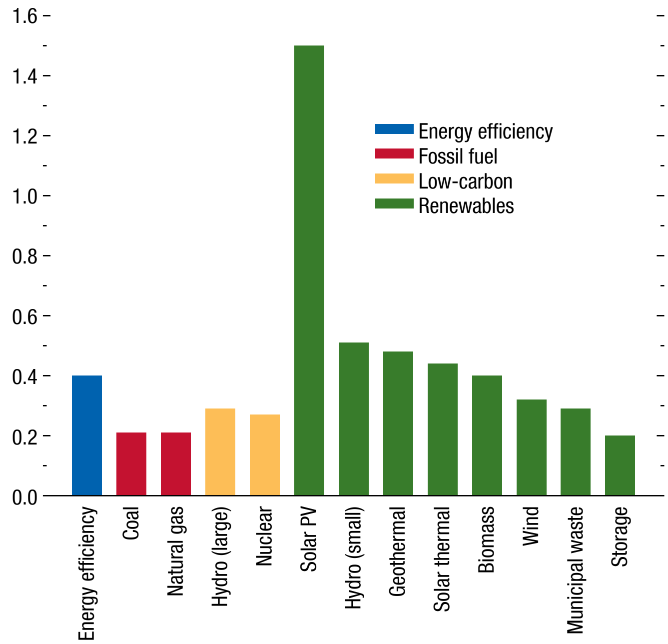
Climate change mitigation results in substantial output gains in the second half of the century.



Source: IMF staff estimates.
Note: The figure shows the variation over output gains from climate change mitigation due to uncertainty from two sources: local costs of higher temperatures, from either Nordhaus (2010) or Burke, Hsiang, and Miguel (2015); and climate sensitivity, measured as the increase in long-term temperature with respect to a doubling in CO_2 concentration, with a range of 1.5–4.5 and a midpoint of 3 (see text for discussion).

Figure 3.8. Job Multipliers
(Job-years per gigawatt hour; levelized over lifetime of utility)

Renewable-based electricity generation and energy-efficiency-enhancing investment are more job-intensive than the generation of electricity from fossil fuels.



Sources: Wei, Patadia, and Kammen 2010; and IMF staff calculations.
Note: Each bar shows the total number of job-years generated per gigawatt hour of capacity. This includes both direct and indirect jobs, and barring energy efficiency, excludes induced job effects (for example, induced by changing relative prices). The jobs created, both in the initial phase of asset creation and in the subsequent operation and maintenance of new capacities, are averaged (levelized) over a typical lifespan of a utility. PV = photovoltaic.

a higher frequency and severity of natural disasters, a rise in sea levels, and the risk of more catastrophic climate change.

- *Fiscal costs:* On the fiscal front, the policy package initially deteriorates the fiscal balance and requires debt financing, given that the carbon revenues are smaller than the initial spending on infrastructure, subsidies, and compensatory transfers to households. Carbon tax revenues are thereafter broadly sufficient to finance the additional green infrastructure and transfers to poor households (Figure 3.6, panel 4).

The effects of the climate change mitigation policy package on global employment follow largely those on output (Figure 3.6, panel 5). Employment is boosted initially. Global employment would be higher by a total of 12 million people, on average, each year between 2021 and 2027, followed by a small decline relative to the baseline employment path during the transition until the economy reaches a higher output and growth path. Despite the decline relative to baseline, employment continues to grow strongly throughout the period (Figure 3.6, panel 3). Expanding low-carbon sectors, such as renewable energy, retrofitting of buildings, electric car production, and the services sector, are typically more labor intensive than the shrinking high-carbon sectors (such as fossil fuel energy, transportation, heavy manufacturing)—both in the short and long term—and can create many jobs (Figure 3.8). However, the policy package scenario entails a substantial reallocation of about 2 percent of jobs from high- to low-carbon sectors, which could cause difficult transitions for some workers and require reskilling and government support (see below).

Turning to private investment, the policy package leads to a sharp global contraction because the carbon tax acts as a negative wealth shock and reduces the long-term desired capital stock (Figure 3.6, panel 6). The expanding low-carbon sectors (renewables, services) are also less capital intensive than the contracting sectors (fossil fuel energy, manufacturing), further reducing demand for capital investment. Finally, the renewable energy sector is smaller than the fossil fuel sector and takes time to expand due to capital adjustment costs, although green infrastructure investment and subsidies help incentivize private investment in renewables and other low-carbon energy sectors.[34] Some variation is seen across countries and regions: reductions in private investment are especially large in countries with larger fossil fuel sectors, whereas the policy package elicits more positive responses from private investment where low-carbon energy sectors are already large and the cost of ramping up physical capital relatively low (for example, Europe and Japan; see below). In the current context of depressed private investment and very low interest rates, green support policies could also have a more positive effect on private investment in the near term than modeled here.

To sum up, a mix of carbon pricing and an initial green stimulus would help with economic recovery from the COVID-19 crisis in the near term while putting the global economy on a sustainable growth path at moderate transitional growth costs. The green fiscal easing would help boost growth and employment in the first few years, when the economy is depressed, despite the introduction of the carbon tax. From a macroeconomic and public finance perspective, the next decade is the best time for governments to invest and borrow, given that interest rates for many large emitters are likely to stay low for long, suggesting that an aggressive investment policy would be affordable and desirable. As the recovery takes hold, further increases in carbon taxes would be essential to generate the needed substantial declines in emissions and would imply only moderate growth costs. Over the longer term, the economy would be on a higher growth and output path because substantial damages from climate change would be avoided.

Cross-Country Differences

While the transitional output costs associated with the policy package are relatively moderate in global terms, they are very different across countries (Figure 3.9, panel 1).

Some of the advanced economies may experience smaller economic costs throughout the transition—or even gain, as does Europe. The more renewables there are already in the economy, the higher the initial capital stocks, so the more they can be ramped up without incurring large adjustment costs.[35] Europe starts with a large renewable sector, implying that the adjustment costs per unit of additional investment are much lower than for other countries.[36] In contrast, the United States and China have a large amount of fossil fuel capital relative to non-fossil-fuel capital, and the investment reductions from these industries offset the investment in renewables, which face larger adjustment costs to ramp up.

Countries with fast economic or population growth (India, especially; China, to a lesser extent) and most oil producers are bound to experience larger economic costs by forgoing cheap forms of energy, such as coal or oil. These output costs nevertheless remain modest relative to baseline growth for most. For example, with the policy package, India's GDP would be 277 percent higher in 2050 than today, only moderately below what it would have been with unchanged policies (287 percent). But more important, these economic costs also need to be weighed against avoided damage from climate change and co-benefits from climate change mitigation.

The countries for which economic costs are larger are also the ones that would enjoy immediate substantial co-benefits from acting to curb carbon emissions (Figure 3.9, panel 2). These are reductions in mortality risks and improved health from less air pollution (thanks to lower use of coal and natural gas) and reduced road congestion, traffic accident risk, and road damage (associated with taxation of gasoline and road diesel). While the value of saving lives goes well beyond economic gains and quantifying the economic value of human life and health is difficult, existing valuations (see, for example, the October 2019 *Fiscal Monitor;* and Parry, Veung, and Heine 2015) indicate that many countries would experience substantial economic gains from co-benefits—on the order of 0.7 percent of GDP immediately and 3.5 percent of GDP by 2050 for China, and 0.3 percent immediately and 1.4 percent by 2050 for India.[37] Combining real GDP

[34]In the G-Cubed model, investors are forward looking, and substitutability is high relative to other models (McKibbin and Wilcoxen 1999, 2013; Liu and others 2020).

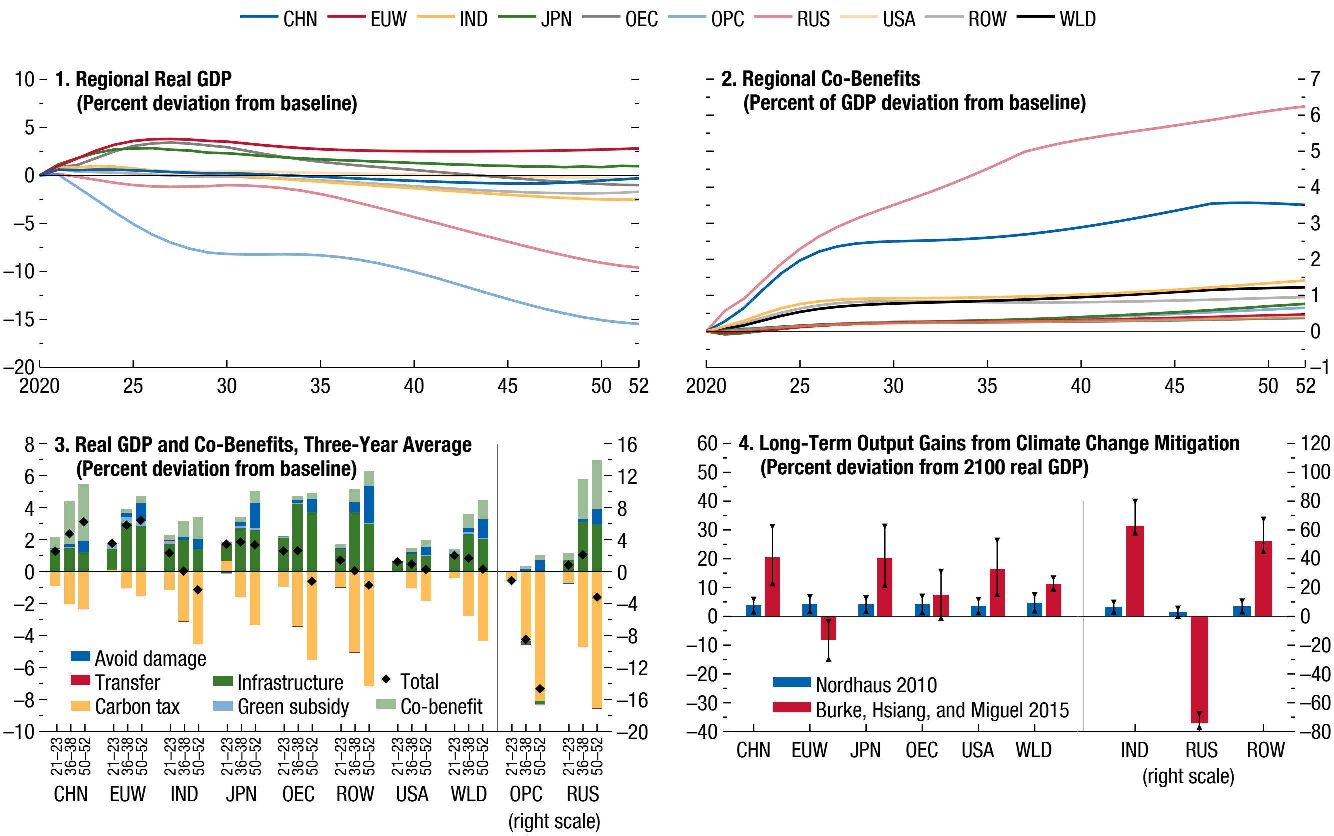
[35]This is because adjustment costs are quadratic in the rate of investment.

[36]IMF (2020a) examines climate mitigation scenarios for the European Union using the Envisage CGE model. It concludes that a higher carbon price is needed for Europe's climate mitigation objectives and that a subsidy for renewables production would allow the needed carbon price to be reduced. The new European Union recovery fund explicitly aims to address climate change.

[37]Parry, Veung, and Heine (2015) estimates a price on CO_2 that would internalize domestic non-climate-related external costs

Figure 3.9. G-Cubed Model Simulations of Comprehensive Policy Package, Cross-Country Differences

There are large cross-country differences in output effects, with most oil producers and countries with fast economic and population growth bearing larger costs in the medium term. However, these countries also stand to benefit more from avoided damages from climate change and co-benefits.



Source: IMF staff estimates.
Note: Panels 1, 2, and 3 are based on simulations run using the G-Cubed global macroeconomic model of McKibbin and Wilcoxen (1999, 2013) and Liu and others (2020). The climate change mitigation policy package is calibrated to reduce gross emissions by 80 percent in every country/region by 2050 and comprises (1) gradually rising carbon taxes, (2) a green fiscal stimulus consisting of green infrastructure investment and a subsidy for renewables production, and (3) compensatory transfers to households. The figure also shows the effects of avoided damages from climate change resulting from the implementation of the package. See Online Annex 3.4 for more details on the simulation. Panel 4 shows the variation over output gains from climate change mitigation by 2100 due to uncertainty from two sources: local costs of higher temperatures, from either Nordhaus (2010) or Burke, Hsiang, and Miguel (2015); and climate sensitivity, measured as the increase in long-term temperature with respect to a doubling in CO_2 concentration, with a range of 1.5–4.5 and a midpoint of 3 (see text for discussion). EUW = European Union, Norway, Switzerland, United Kingdom; OEC = Australia, Canada, Iceland, Liechtenstein, New Zealand; OPC = selected oil-exporting countries and other economies; ROW = rest of the world; WLD = world. Data labels use International Organization for Standardization (ISO) country codes.

associated with fossil fuels around the world. The nationally efficient CO_2 price level is, on average, $57.5 a ton (in 2010)—and ranges between $11 and $85 for the countries/regions in the G-Cubed model. These reflect primarily health co-benefits from reduced air pollution at coal plants and, in some cases, reductions in automobile externalities. The co-benefits differ across countries per unit of abatement and are largest for Russia and China. See Karlsson, Alfredsson, and Westling (2020) for a review of available monetary estimates of air quality co-benefits. Based on quasi-experimental evidence from China, Ebenstein and others (2017) finds that an increase of 10 micrograms a cubic meter in PM10 (particulate matter under 10 micrometers in size) reduces life expectancy by 0.64 year and, consequently, bringing all of China into compliance with its Class I standard for PM10 would save 3.7 billion life-years. In addition to the benefit of reduced mortality, studies also show significant benefits from reduced morbidity (that is, lower health care spending) in response to environmental policies. For example, reducing PM2.5 (particulate matter under 2.5 micrometers in size) concentration in China from the prevailing average to the World Health Organization–recommended level (which is about one-sixth the current average level) would reduce health care spending by $42 billion relative to 2015 spending levels, or about 7 percent of national annual health care spending (see, for example, Barwick and others 2018).

effects and co-benefits yields net benefits throughout the transition for China and smaller transitional costs for India, Russia, and others (Figure 3.9, panel 3).[38]

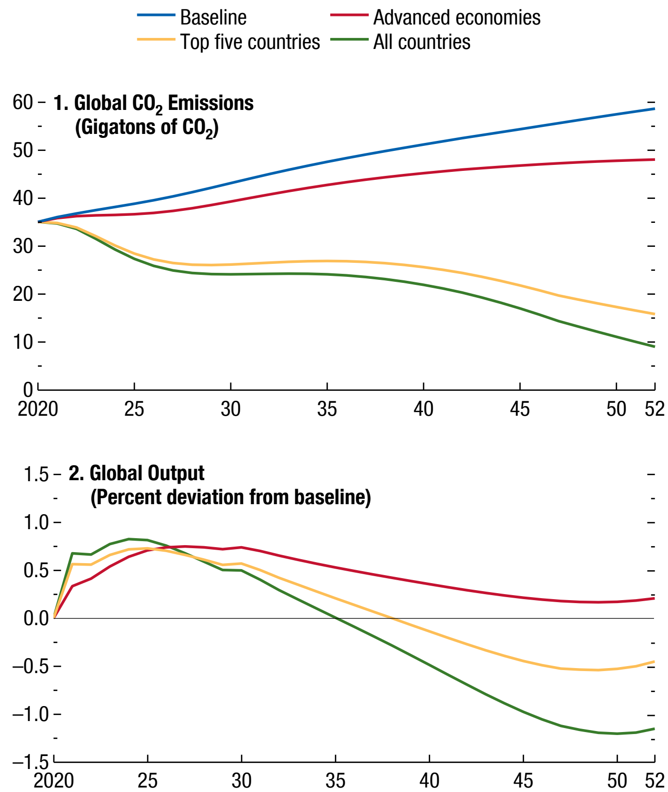
Without global policy action, damages from climate change increase sharply after 2050. Therefore, all countries would experience substantial benefits from avoided climate damages in the second half of the century under the policy package. The benefits from mitigating climate change are expected to be particularly large for some of the countries with higher transitional costs. India is among those likely to suffer the greatest damage from global warming, reflecting its initially high temperatures. For India, the net gains from climate change mitigation—relative to inaction—would be up to 60–80 percent of GDP by 2100 (Figure 3.9, panel 4). While estimates of losses from climate change are somewhat smaller for colder regions (for example, Europe, North America, and east Asia), these are likely underestimations as they do not include a number of damages (for example, rise in sea levels, natural disasters, damage to infrastructure from thawing of permafrost in Russia) and negative global spillovers from large economic disruptions in other parts of the world.

It is sometimes argued that countries that have contributed the bulk of the stock of global carbon emissions—advanced economies—should shoulder a greater part of the mitigation burden. Advanced economies cannot keep global temperatures to safe levels on their own, as their share in global emissions is set to drop to 23 percent in 2050 from 32 percent of global emissions under unchanged policies. And in a scenario in which only advanced economies enact mitigation policies, the decline in their emissions would be partially offset by an increase in other countries' emissions relative to the baseline. This reflects two types of "leakages": first, lower demand from advanced economies for fossil fuels depresses global fossil fuel prices and so increases their consumption by other countries; and second, some carbon-intensive activities previously carried out in advanced economies are likely to relocate to countries where carbon is not taxed.

In a scenario in which advanced economies are the only ones that reduce their gross carbon emissions by 80 percent by 2050, global emissions still increase to 48 gigatons by 2050, well above current levels (Figure 3.10). In contrast, if the United States, Europe, China, Japan, and India—as the five largest countries (economic region)—act together, they can make a large dent in global emissions over the next three decades. Global emissions would be reduced by close to 56 percent from current levels, with a very similar effect on global GDP and on each participating country's GDP, as in the

Figure 3.10. G-Cubed Model Simulations, Partial Participation in Mitigation

Advanced economies mitigating alone cannot keep temperature increases to safe levels. But joint action by the five largest countries (economic region) would make a large dent in global emissions.



Source: IMF staff estimates.
Note: This figure is based on simulations run using the G-Cubed global macroeconomic model of McKibbin and Wilcoxen (1999, 2013), and Liu and others (2020). The climate change mitigating policy package is calibrated to reduce gross emissions by 80 percent in every country/region except OPC (the "All countries" scenario) by 2050 and comprises (1) gradually rising carbon taxes, (2) a green fiscal stimulus consisting of green infrastructure investment and a subsidy for renewables production, and (3) compensatory transfers to households. The figure also shows the effects of avoided damages from climate change resulting from the implementation of the package. See Online Annex 3.4 for more details on the simulation. Scenarios "Advanced economies" and "Top five countries" assume that only advanced economies and five countries/regions with the largest GDP (China, European Union, India, Japan, United States) act to mitigate.

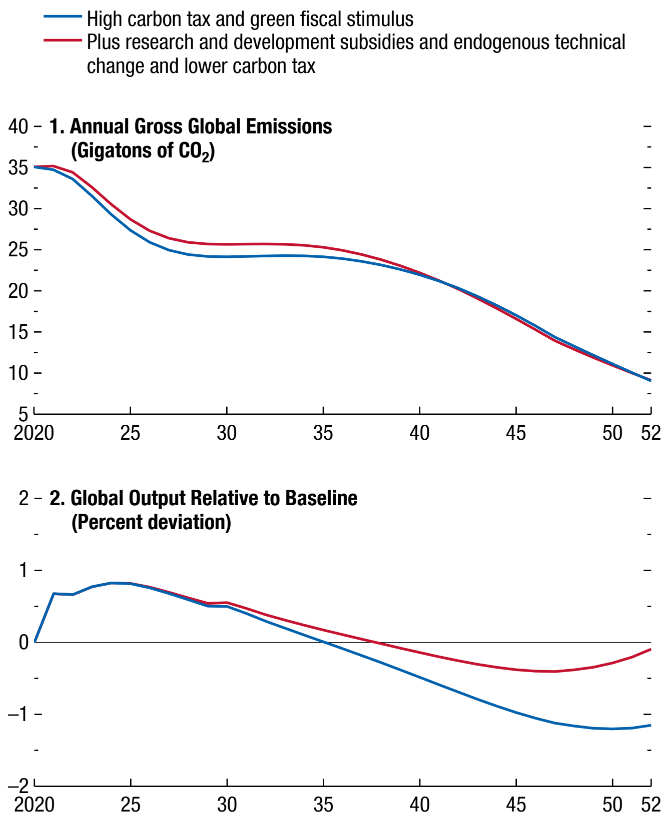
[38]Bento, Jacobsen, and Liu (2018) also points out that the costs of implementing a carbon tax are substantially lower with a large informal sector as the carbon tax lowers the relative distortion between the formal and informal sectors—given that even the informal sector must buy energy from the formal sector, these mechanisms can lead to welfare-enhancing expansion of the formal sector.

scenario of global action. The October 2019 *Fiscal Monitor* discusses how a carbon price floor among the largest emitters—possibly with a lower price floor or transfers for lower-income countries—would be an effective arrangement to scale up Paris Agreement commitments. It would provide a transparent target based on a common measure and help reassure against potential losses in international competitiveness from higher energy costs.

Fossil fuel exporters are bound to experience the largest economic losses from the transition of the global economy to a low-carbon path (see Mirzoev and others 2020 for a discussion of carbon transition risks in Gulf Cooperation Council countries). Even without a domestic carbon tax, the fall in global demand for fossil fuels would significantly lower these economies' fiscal revenues and economic activity. Moreover, the industrial structure in many fuel exporters is reliant on cheap energy, making the required restructuring and diversification of these economies more difficult and painful. Imposing an export tax (royalty) on oil sales—if this could be agreed upon among oil producers—could maximize the revenue extracted from oil reserves (while demand lasts) and at the same time contribute to the decarbonization of other economies (see the October 2019 *Fiscal Monitor*). Many oil exporters, however, also stand to gain from global climate change mitigation measures. For example, rising temperatures will make oil-exporting countries in the Middle East, where water scarcity is already a growing concern, even hotter. Many oil-exporting countries have recognized the challenges that are being created by the energy transition and are actively seeking to diversify their economies away from the reliance on oil. Policies that seek to strengthen the non-oil sector through better business regulation, greater credit availability, and reforms to the labor market, and increase sources of non-oil revenue for the government, are being implemented.

Figure 3.11. Role of Green Technological Progress

Policies that contract markets for dirty fuels and expand markets for clean fuels induce a green technological response so that similar emission reductions can be achieved with a lower carbon tax and at a lower cost to output.



Source: IMF staff estimates.
Note: The panels compare the G-Cubed simulation of the comprehensive policy package with a simulation run using an extension of the Hassler and others (2020) integrated assessment model with endogenous technological change. The second simulation features a lower carbon tax and a green research and development subsidy and includes the endogenous response of technology to policies. See Online Annex 3.5 for more details.

The Returns to Supporting Technological Innovation

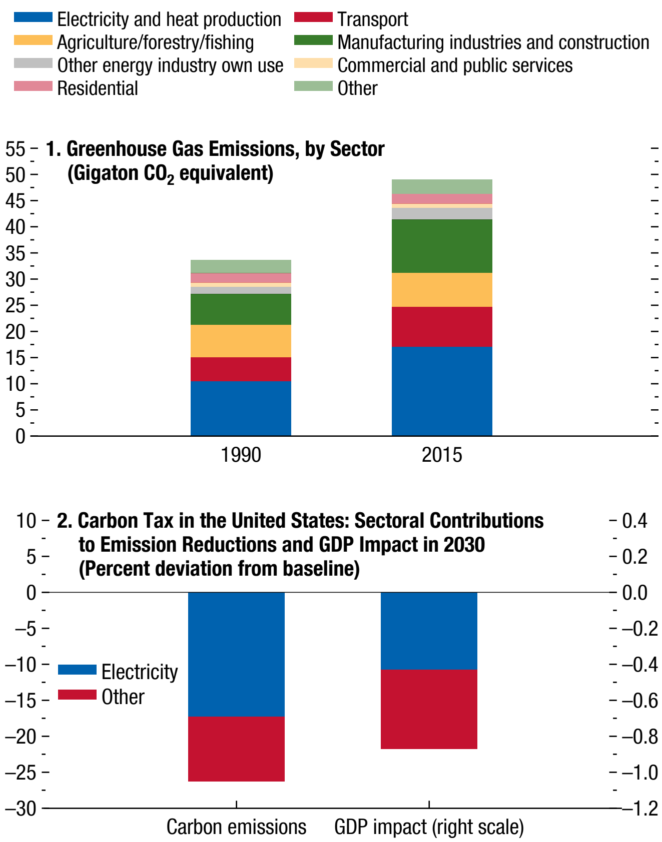
The response of technology ("endogenous technical change") to carbon taxes or research and development subsidies is important in amplifying the effects of carbon pricing and facilitating the low-carbon transition. Given that this mechanism is difficult to integrate into the G-Cubed model, this chapter uses the more stylized representation of Hassler and others (2020) to illustrate the impact of supporting technological innovation (Figure 3.11; see Online Annex 3.5). Assuming a plausible response of technological change to the price of carbon—and combining it with a subsidy (of 70 percent) for green research and development—would allow a similar emission target to be achieved with a carbon price path at about half the prices required in the G-Cubed scenario. In the presence of endogenous technical change and research and development subsidies, the transitional costs of mitigation policies are therefore significantly lower, and global GDP rises toward baseline earlier (around the mid-2040s) than in the absence of innovation.

The beneficial impact of this policy is felt mostly in the medium to longer term (after 2030), as the innovation response and the diffusion of new knowledge through the global economy take time to materialize.[39]

[39]The immediate effects of this policy are limited by the modest initial size of the green energy sector.

Figure 3.12. Potential for Emission Reductions in the Electricity Sector

The electricity sector offers substantial scope for emission reductions and better emission-output trade-offs due to the availability of substitute low-carbon technologies.



Sources: International Energy Agency; and IMF staff estimates.
Note: Panel 2 is based on the carbon tax effect in the G-Cubed simulations of the comprehensive policy package.

Overall, the analysis suggests that a lower carbon price, if combined with early use of green research and development subsidies, may be able to achieve the same lower-emission benefits as a higher tax, at a lower overall transitional cost to output. Research and development subsidies on their own, however, could not generate the quick and substantial reductions in emissions needed to keep temperature increases to safe levels.[40]

A good example of the role of technology in reducing emissions is the electricity sector, which, together with heating, generates roughly 40 percent of total global carbon emissions (Figure 3.12). Three-quarters of these emissions are from coal-based electricity generation. Raising the share of renewables in the electricity sector is considered the first step toward decarbonization because substitute low-carbon technologies are already available and are economically competitive as a result of a dramatic decline in prices in the past decade—for example, the cost of electricity from wind has declined by 70 percent (Lazard 2019). This makes near-term emission-output trade-offs particularly favorable in this sector, which is also reflected in the G-Cubed simulation, in which about two-thirds of emission reductions in the first 10 years are achieved in electricity generation. Moreover, low-carbon electricity production would generate additional benefits for decarbonization as other end-uses of energy (automobiles, heating, and so on) are electrified. Box 3.2 investigates in more detail how emissions in the electricity sector can be reduced with existing technologies (see also Online Annex 3.6).

How to Build Inclusion

Underlying the moderate macroeconomic effects of mitigation policies discussed in the previous section are differentiated impacts on low- and high-income households and on workers in shrinking versus expanding sectors (such as fossil fuel extraction and manufacturing versus clean-energy and services sectors). For instance, in the absence of compensatory measures, low-income households are more likely than high-income households to be hurt by carbon pricing; in many countries the poor spend a relatively larger share of their income on energy-intensive goods, such as electricity and heating (Figure 3.13, panel 1). Low-income households are also more likely to experience losses in labor income, given that they tend to be employed in low-skill occupations in carbon-intensive sectors (manufacturing, transportation, energy; Figure 3.13, panel 2). Opinion surveys suggest that low-skilled workers are less likely than high-skilled workers to favor protecting the environment over boosting economic growth. Support for protection of the environment is lowest among lower-skilled workers employed in carbon-intensive sectors (Figure 3.14).[41]

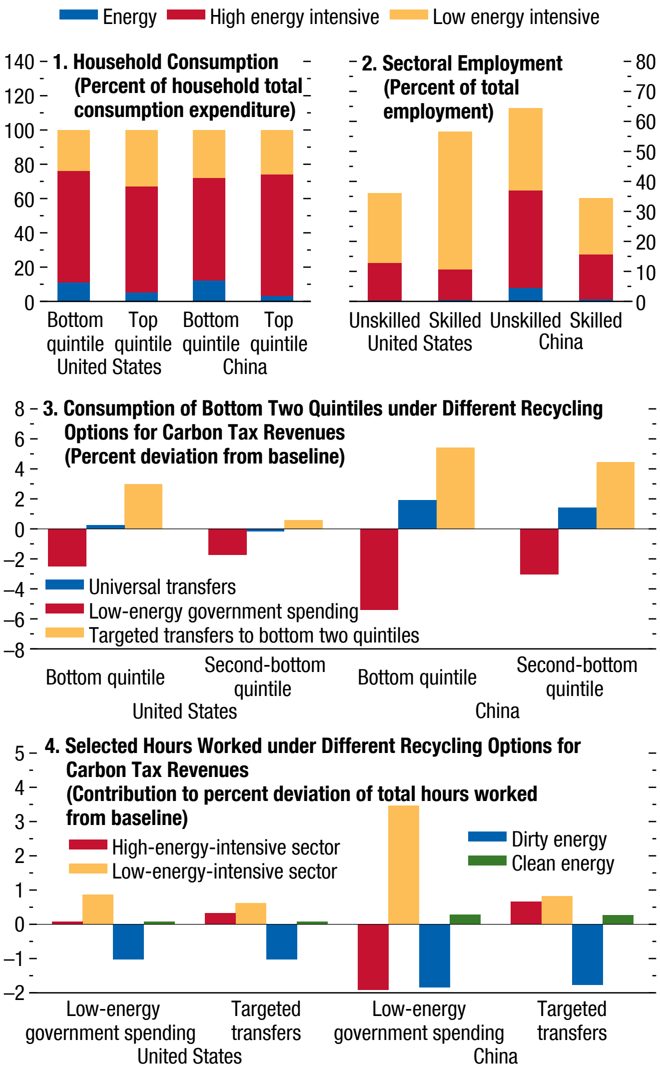
The distributional impacts of carbon pricing are likely to vary by country. Carbon pricing is not always regressive, especially in emerging market and

[40] See also, for example, Bosetti and others (2011), Newell (2015), and Dechezleprêtre and Popp (2017).

[41] See also IMF (forthcoming).

Figure 3.13. Distribution of Consumption, Employment, and Impact of Carbon Taxes

Households at the bottom quintile of the income distribution spend slightly more on energy than their richer counterparts and they are more likely to be employed in high-energy-intensive sectors. Carbon taxes, when accompanied by transfers to households, can reduce poverty and inequality; when accompanied by government spending on low-energy sectors, they can support job transitions to low-energy-intensive sectors.

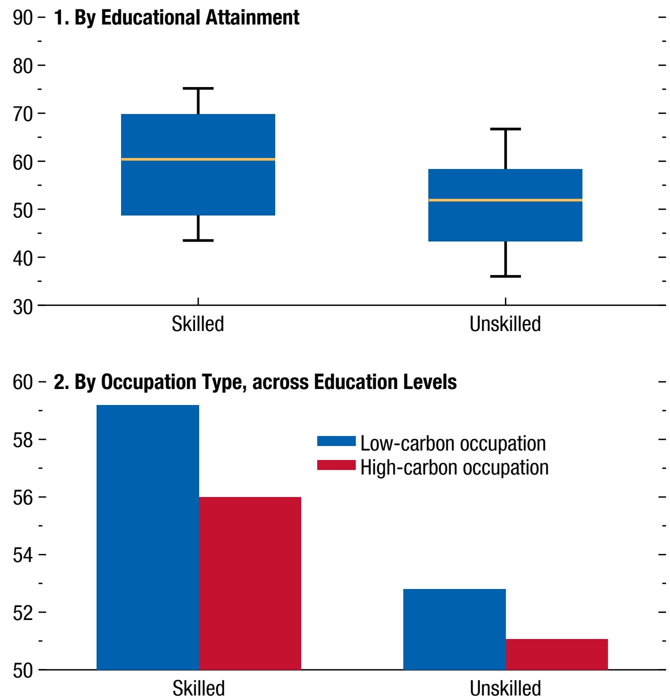


Sources: American Community Survey; China Family Panel Survey; Consumption Expenditure Survey; National Bureau of Statistics of China; and IMF staff calculations.
Note: Panels 1 and 2 are based on survey data. In panel 1, energy goods are electricity, heating, gas, and oil. High-energy-intensive goods are mostly industrial goods and transportation, while low-energy-intensive goods are basically services less transportation. In panel 2, unskilled workers are workers with a high-school education or less, while skilled workers have more than a high-school education. Panels 3 and 4 use a multisector heterogeneous agent model calibrated to generate sectoral output shares to simulate \$50 tax per ton of CO_2, where the revenue is used to finance government spending on (1) low-energy-intensive goods, (2) universal cash transfers, and (3) targeted cash transfers to the bottom two quintiles of the income distribution. In panel 3, each bar shows the quintile percentage change in consumption with respect to the baseline. In panel 4, each bar shows the percentage change in workers' hours weighted by sector employment in the baseline with respect to the baseline.

Figure 3.14. Public Opinion in Support of Environmental Protection

(Percent)

Support for the environment tends to be higher among high-skilled individuals, particularly those working in clean industries. Low-skilled individuals working in high-carbon industries, who represent the group most adversely affected by the changes needed for a transition to a green economy, show the lowest levels of support for environmental policies.



Sources: European Values Study (2017); World Values Survey, wave 7 (2017–20); and IMF staff calculations.
Note: The figure shows the percent of respondents who believe that protecting the environment should be given priority, even if it causes slower economic growth and some loss of jobs. Panel 1 shows the range of values across 77 countries, where the box represents the 25th and 75th percentiles, the whiskers represent the 10th and 90th percentiles, and the horizontal line stands for the median. Educational attainment is used as a proxy for skill level: skilled is post-secondary; unskilled is upper-secondary and below. Panel 2 shows the average across individuals from 47 countries. High-carbon occupations correspond to skilled industry, unskilled, semi-skilled, and farm occupations.

developing economies, where lower access to electricity and ownership of durable goods results in lower direct consumption of energy by poorer households (see the October 2019 *Fiscal Monitor* for additional discussion). Similarly, the distributional impact through the labor income channel can vary across countries. But where carbon pricing is likely to adversely affect vulnerable households and workers, building fairness and inclusion will be crucial to the political acceptability and sustainability of mitigation strategies.

Various policies can limit the adverse effects of higher carbon prices on households. These include fully or partially rebating the carbon pricing revenues through universal or targeted cash transfers—or using some of the revenue to finance higher public spending in low-carbon sectors, which will create jobs and offset employment losses in carbon-intensive sectors. Among the different options for cash transfers, targeted compensation for low-income households is a cost-effective option. Figure 3.13, panel 3, shows the consumption impact of a tax of $50/ton of CO_2 under various revenue recycling options, based on a general equilibrium model with heterogenous agents calibrated to the United States and China that incorporates the carbon tax's impact on consumption and employment (see Online Annex 3.7 and Tavares, forthcoming). Simulations suggest that fully recycling carbon tax revenues in cash transfers targeted to low-income groups (bottom two quintiles) can raise their consumption (see Figure 3.13, panel 3, and Online Annex 3.7 for the impact on the entire consumption distribution). The consumption of households in the lowest quintile could be protected (consumption kept broadly constant) by redistributing about one-quarter and one-sixth of the carbon revenues, respectively, to this group of households in the United States and China. By contrast, it would take, respectively, 55 percent and 40 percent of revenues to protect consumption levels of households in the lowest two quintiles in the United States and China. Fully rebating the carbon revenues through universal transfers would also broadly avert a decline in the consumption of households in the bottom two quintiles, but at a much higher fiscal cost.[42]

While they both protect private consumption, neither universal nor targeted cash transfers help materially ease job transitions. By contrast, increasing government spending on low-carbon goods and services—similar in spirit to the green supply policies studied in the previous section—would fail to protect the consumption of poorer households but would prevent a decline in aggregate employment and spur further reallocation of workers toward low-carbon sectors (Figure 3.13, panel 4).

In practice, governments seeking to introduce carbon pricing will likely face calls to protect low-income households from higher prices and compensate for job losses in carbon-intensive industries. The simulations here show that carbon pricing can produce enough revenue to spend on both goals if income support is well targeted.

Feebates are an essential complement to other mitigation policies. They are systems of fees and rebates on products or activities with above- or below-average emission intensity, or regulations (such as emission rates or energy efficiency standards) that can be used when carbon pricing is not feasible or cannot be imposed on the necessary scale (October 2019 *Fiscal Monitor*). Feebates can be tailored to specific markets, and their impact on emissions depends on the size and energy intensity of the target market. Feebates are modeled broadly here as consisting of a tax of $50/ton of CO_2 imposed on the dirty energy consumption of firms and households, with the revenue used to finance a subsidy to promote the consumption of clean energy. The only way in which this experiment differs from the previous one is that the revenue is spent on subsidies to promote the consumption of clean energy. The revenue-raising component (carbon tax) is similar.

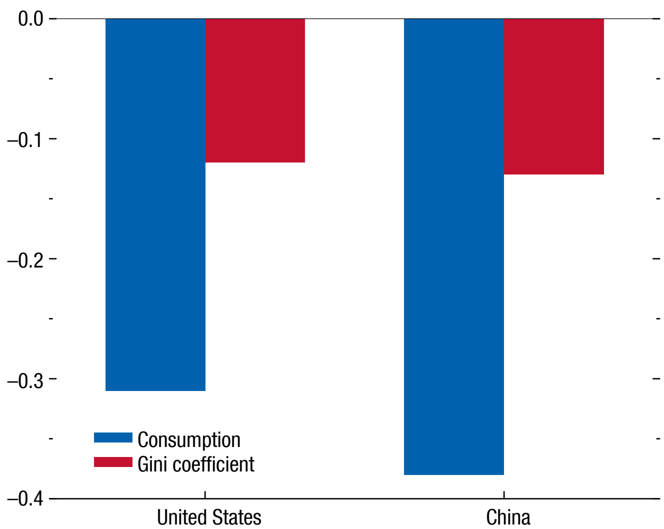
Simulations show that the effects of the feebates on the consumption of the bottom quintile and inequality are smaller than when carbon taxes are imposed, if no action is taken to mitigate the impact on the distribution (Figure 3.15). The effects are smaller because the impact on energy prices is minimal (taxes and subsidies are levied on different varieties of the same good) and because feebates stimulate employment for low-skilled workers, on net (given that the renewable sector is more labor intensive than the dirty energy sector).

Finally, mitigation policies are likely to affect some communities more than others, adding a geographic dimension to inequality. A just transition is needed also for the most hard-hit communities and regions and may require—beyond reskilling of workers—effective government support for those communities.

[42]Iran's 2010 fuel subsidy reform and the introduction of carbon pricing in British Columbia are examples of successful reforms that included compensatory transfers to households (among other measures). See Guillaume, Zytek, and Farzin (2011) and Carl and Fedor (2016).

Figure 3.15. Distributional Impact of Feebates
(Consumption, percent deviation from baseline, and Gini index change)

Feebates can reduce carbon emissions, but they also need to be accompanied by transfers.



Source: IMF staff calculations.
Note: The figure shows the results of the multisector heterogeneous agent model simulation of a \$50 tax per ton of CO_2 levied on dirty energy consumption by households and firms. The revenue is used to finance a subsidy to clean energy. The first bar shows the bottom quintile percentage change in consumption with respect to the baseline, and the second bar shows the change in the Gini coefficient with respect to the baseline. The Gini coefficient is measured on a scale from 0 (perfect equality) to 100 (perfect inequality).

Conclusion

The window for attaining net zero emissions by 2050 and holding temperature increases to safe levels is rapidly closing. The analysis in this chapter suggests that an initial green investment push combined with steadily rising carbon prices would deliver the needed emission reductions at reasonable transitional global output effects. A green fiscal stimulus would strengthen the macroeconomy in the short term and help lower the costs of adjusting to higher carbon prices. Carbon pricing is critical to mitigation because higher carbon prices incentivize energy efficiency in addition to reallocating resources from high- to low-carbon activities. The transitional costs of carbon pricing consistent with net zero emissions by mid-century would be manageable in the context of the projected growth of the global economy over the next three decades and could be reduced further as technological innovations develop in response to carbon pricing and green research and development subsidies. In the medium term, such a strategy would place the global economy on a stronger and more sustainable growth path by avoiding serious damages from climate change and the risk of catastrophic outcomes.

Keeping global temperatures to safe levels requires a global effort. Advanced economies cannot successfully mitigate climate change by themselves, as they account for a declining share of global emissions. By contrast, the five largest countries/economic union—the United States, China, the European Union, Japan, and India—acting jointly can make a large dent in global emissions. While the economic costs of mitigation vary across countries, all stand to gain greatly from avoided damages from climate change and co-benefits from mitigation, such as reduced pollution and mortality. Building sustainably now, rather than having to rebuild infrastructure later, would lower the transitional costs of mitigation. For fossil fuel exporters, smoothing the transition will require accelerating the diversification of their economies. This chapter set out to examine the macroeconomic impacts of climate change mitigation policies. Another important issue is international coordination, which could offer scope for different burden sharing of mitigation costs. International policy coordination on climate change deserves further study—given how elusive it has been for countries to come together and take meaningful action to reduce emissions (see, for example, Barrett 2005, 2013, 2016; Lessmann and others 2015; Nordhaus 2015). Analysis on how to achieve such cooperation is, however, outside the scope of this chapter.

Last but not least, decarbonization involves a structural transformation of economies, with unequal impacts across population subgroups. To build inclusion and ensure the broadest possible support for mitigation policies, governments can use part of their carbon tax revenues to support job transitions and provide targeted cash transfers to protect poorer households against losses in purchasing power. Place-based policies to compensate areas or regions likely to experience more labor shedding due to a retrenchment in high-carbon sectors may also be needed.

Box 3.1. Glossary

Avoided damages. The value of avoided climate-change-induced events, such as crop loss, rises in sea level, and extreme weather.

Carbon dioxide (CO_2). The main greenhouse gas, produced from burning fossil fuels, manufacturing cement, and forestry practices. CO_2 emissions remain in the atmosphere for an average of 100 years.

Carbon tax. A tax imposed on CO_2 emissions released largely through the combustion of carbon-based fossil fuels. Administratively, implementation is easiest by taxing the supply of fossil fuels—coal, oil, and natural gas—in proportion to their carbon content.

Clean energy innovation. The number of patent applications in climate change mitigation technologies related to energy generation, transmission, and distribution.

Co-benefits. Reductions in mortality risks and improved health from less air pollution (as a result of lower use of coal and natural gas) and reduced road congestion, traffic accident risk, and road damage.

Distribution-friendly policy. A policy that attempts to mitigate the policy's negative effects on low-income groups' consumption (or some other measure of household well-being).

Economies of scale. Cost advantages for businesses as a result of their scale of operation, with unit costs of output decreasing with increasing scale.

Emission trading system. A market-based policy to reduce emissions (sometimes referred to as "cap and trade"). Covered sources are required to hold allowances for each ton of their emissions or (in an upstream program) the embodied emission content in fuels. The total quantity of allowances is fixed, and market trading of allowances establishes a market price for emissions. Auctioning the allowances is a valuable source of government revenue.

Externality. A cost imposed by the actions of individuals or firms on other individuals or firms (possibly in the future, as in the case of climate change) that the former does not take into account.

Feebate. A sliding scale of fees on firms with emission rates (for example, CO_2 per kilowatt-hour) above a "pivot point" level and corresponding subsidies for firms with emission rates below the pivot point. Alternatively, a feebate can be applied to energy consumption rates (for example, gasoline per mile driven) rather than emission rates. Feebates can exploit many (but not all) of the mitigation opportunities promoted by carbon taxes but without a large increase in energy prices.

Feed-in tariffs. Long-term contracts that guarantee producers of renewable electricity a fixed price for every unit of electricity delivered to the grid.

Gray technologies. Technologies that tend to improve the pollution effect of "dirty" technologies. Examples include technologies that use the heat from fuel or waste incineration or fuels from nonfossil sources.

Green supply policies. Policies aimed at boosting the supply of renewable energy and energy efficiency, including subsidies and investment programs.

Green/white certificates. Titles, respectively, for reaching renewable energy/energy saving targets.

Greenhouse gas. A gas in the atmosphere that allows incoming solar radiation to pass through but traps and absorbs heat radiated from Earth. CO_2 is easily the most predominant greenhouse gas.

High-carbon activities. Activities that either involve generation of carbon-based energy or emit relatively high amounts of CO_2.

Nationally Determined Contribution (NDC). Climate strategies, including mitigation commitments, submitted by 190 parties to the Paris Agreement. Countries are required to report progress on implementing NDCs every two years and (from 2020 onward) to submit revised NDCs (which are expected to contain progressively more stringent mitigation pledges) every five years.

Paris Agreement. An international accord (ratified in 2016) on climate mitigation, adaptation, and financing. The agreement's central objective is to contain global average temperature increases to 1.5–2°C above preindustrial levels.

Renewable energy. Typically includes energy generated from solar photovoltaic, solar thermal, wind, geothermal, biomass, and hydroelectric sources. Hydroelectric is often subdivided into "large" and "small" because of the major environmental impact of the former.

Research and development. Innovative activities by corporations and governments with the goal of developing new products and technologies.

Revenue recycling. Use of (carbon) tax revenues for purposes such as lowering other taxes on households and firms or funding public investment.

Box 3.2. Zooming In on the Electricity Sector: The First Step toward Decarbonization

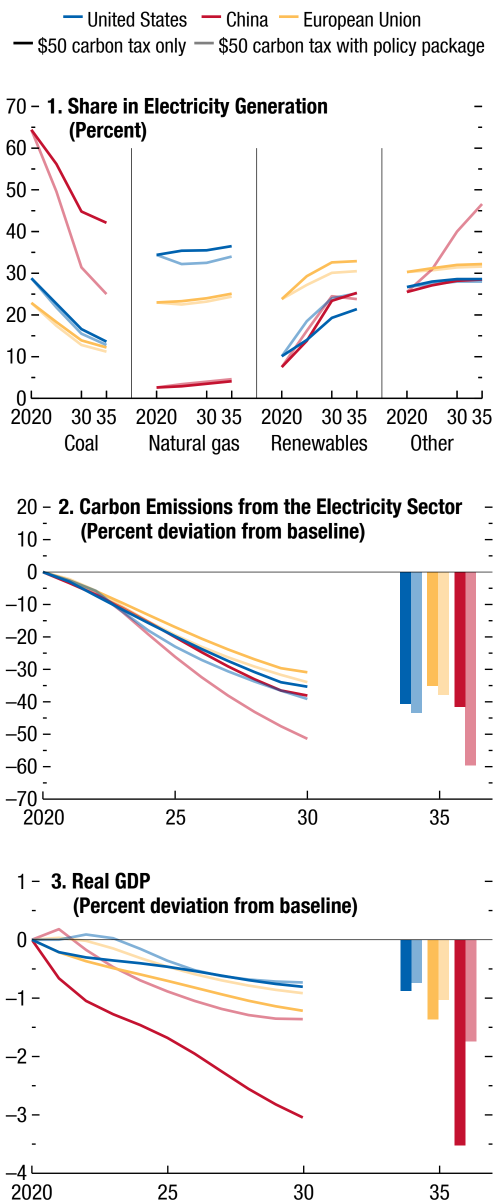
This box investigates in more detail how emissions in the electricity sector—which, together with heating, accounts for roughly 40 percent of global emissions—can be reduced with existing technologies. To this end, the analysis modifies the Global Integrated Monetary and Fiscal model (Laxton and others 2010) to include an electricity sector where power is generated from coal, natural gas, renewables or by nuclear or hydroelectric processes. The constraints that intermittency of renewables (the undesired output variation from the varying availability of sun and wind) pose for their market penetration are captured by pairing renewable electricity generation with a flexible backup capacity that covers output shortfalls (see Online Annex 3.6; all annexes are available at www.imf.org/en/Publications/WEO). Studying the same illustrative $50 carbon price in the United States, Europe, and China allows for highlighting how a country's current electricity mix and economic structure affect the impact of introducing a carbon price.

Simulations for the United States show that even a moderate policy of gradually introducing a $50 carbon price over 10 years in the electricity sector, flanked by a front-loaded subsidy for investment in renewables, would unlock substantial decarbonization of the electricity sector at very small output costs (Figure 3.2.1, panels 1–3). The policy mix is budget neutral when the carbon price is fully in place after 10 years, and its revenues (roughly 0.2 percent of GDP) are enough to finance the subsidy. However, before revenues fully emerge, the subsidy is financed through debt, leading to a total increase in the debt-to-output ratio of roughly 1 percent of GDP. The carbon price discriminates according to the carbon intensity of the different technologies, thereby disadvantaging electricity production using coal (and to a lesser extent gas). Accentuated by a decline in renewable prices due to the subsidy, the change in relative prices leads to a rebalancing of the electricity mix away from coal toward renewables technologies, and electricity sector emissions decline by 35 percent relative to baseline by 2030 as a result. The decline of gas is dampened by its role as a backup capacity for renewable electricity.

While investment and employment decline in the coal sector, the subsidy triggers a surge in investment in renewables, offsetting a large portion of

The authors of this box are Benjamin Carton and Simon Voigts.

Figure 3.2.1. Decarbonization of the Electricity Sector



Source: IMF staff estimates.
Note: The figure is based on the CarMMa (Carbon Mitigation Macro Model). Simulation of a $50 tax per ton of carbon dioxide, phased in over 10 years, alone and together with a policy package. The policy package includes, in each of the three regions, frontloaded renewables investment subsidies and, in the short term, an accommodative monetary policy. For China, the policy package also includes a doubling of nuclear and hydro capacities over 20 years.

Box 3.2 *(continued)*

the losses in coal sector investment. Therefore, the policy mix greatly reduces emissions, while economic damage is mitigated (output declines below baseline by ½ percent over 10 years) as the economy adjusts by reallocating labor and investment from coal toward renewables.

The European Union is comparably advanced in its electricity transition (coal and renewables both have a share of about 20 percent). At the same time, the share of natural gas is considerably smaller than in the United States, which constrains further expansion of renewables by making the grid comparably less flexible to accommodate a rise in intermittent electricity generation. With less room to cut coal output and more limited means for renewables to expand, the carbon price achieves a somewhat milder reduction in emissions.

The high share of coal-generated electricity in China—almost 70 percent—amplifies the increase in electricity costs caused by the carbon price, in turn leading to a more pronounced decline in output. The carbon price increases the share of renewables by about 20 percentage points, which alone is not enough to reduce the share of coal to a sustainable level. With limited availability of natural gas, renewables must be backed up by coal itself (assuming the possibility of flexibility retrofits, as discussed in IEA 2019), reducing the scope for reductions. In addition to renewables subsidies, the macroeconomic package assumes an expansion in nuclear power (accounting for the time it takes to build plants), which crowds out coal-based generation. While the percentage decline in emissions is of the same order as in other regions, in absolute terms, it is about three times greater than in the United States owing to China's greater initial emissions.

Overall, the policy is highly effective at curbing electricity-related emissions at modest macroeconomic costs, especially if labor reallocation can be facilitated. Storage technology for renewable electricity, which could become feasible in the near term, would amplify the penetration of renewables resulting from the carbon price. Given that the macroeconomic costs of a low-carbon electricity transition are modest, it is striking that current policy action and plans for the phasing out of coal generally fall short of what is needed to avoid irreversible climate damage. According to the International Energy Agency, under current and proposed investment plans and policies, power generation from coal alone would use up most of the remaining carbon budget (IEA 2019).

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