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EXECUTIVE BOARD MEETING

EBS/20/142

September 16, 2020

To: Members of the Executive Board

From: The Secretary

Subject: **October 2020 World Economic Outlook—Analytical Chapter 3 and Online Annex**

Board Action:	Executive Directors' **consideration** (Formal)
Tentative Board Date:	**Wednesday, September 30, 2020**
Publication:	Yes, it is intended that the full set of the World Economic Outlook documents will be released to the public at the time of the World Economic Outlook press conference, tentatively scheduled for **Tuesday, October 13, 2020.** The analytical chapters will be made available to the public on the IMF website in advance of the publication of the full document.
Questions:	Mr. Mohommad, RES (ext. 36332) Ms. Jaumotte, RES (ext. 36191)
Additional Information:	The paper will be revised for publication in light of the Executive Board discussion. If Executive Directors have additional comments, they should notify Mr. Mohommad and Ms. Jaumotte by **5:30 p.m. on Friday, September 25, 2020**.

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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 emissions reductions at reasonable transitional global output effects, putting the global economy on a stronger and more sustainable footing by 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 would be small in comparison to projected growth of the global economy over the next three decades 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) have been the warmest ever reported, and 2019 is likely to have been 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 to be met; specifically, net carbon emissions

The authors of this chapter are Philip Barrett, Christian Bogmans, Benjamin Carton, Johannes Eugster, Florence Jaumotte (lead), Adil Mohommad, Evgenia Pugacheva, Marina M. Tavares, and Simon Voigts, in collaboration with external consultants Warwick McKibbin and Larry Weifeng Liu for modeling simulations. Eric Bang, Jaden Kim, and Srijoni Banerjee provided research support, and Daniela Rojas Fernandez provided editorial assistance.

[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.

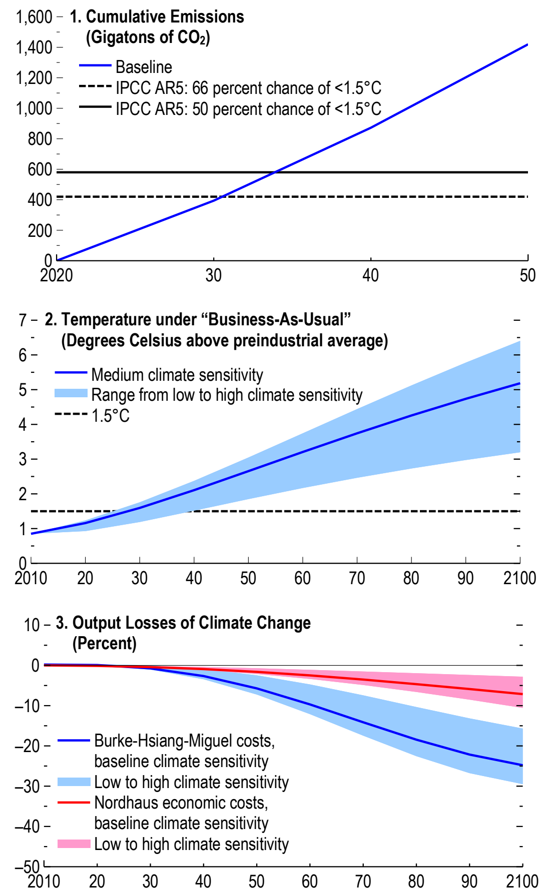
[2]Greenhouse gas is any gas that contributes to the greenhouse effect by absorbing infrared radiation (net heat energy) emitted from Earth's surface and reradiating it back to Earth's surface. They include carbon dioxide, methane, nitrous oxide, and fluorinated gases. The chapter focuses on carbon emissions 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).

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, 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.

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 only be 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

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); Intergovernmental Panel on Climate Change (2014, 2018); Nordhaus (2010); and IMF staff estimates.
Note: Baseline in panel 1 represents the level of 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 (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 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).

[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 polices has been echoed by others, such as the International Energy Agency, which points out that significantly more ambition is 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 only in 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).

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 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. The changes 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 in the transition, especially in countries heavily reliant on fossil fuel exports and 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 us 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?

[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 but also less able to handle shocks or adapt to climate change.

[6]For discussions on this, see Batini and others (2020), Black and Parry (2020), Hepburn and others (2020), and Bhattacharya and Rydge (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 in some sectors would need to be offset by negative emissions in others (such as co-firing biofuels in power generation with carbon capture and storage, expanding forest carbon storage, direct air capture technologies).

While issues of international coordination are important, the depth of emissions reductions targeted in the 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 the Organization of the Petroleum Exporting Countries).

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)—accounting for the full range of externalities—estimates global energy subsidies in 2015 are a striking $5.3 trillion, or about 6.5 percent of global GDP.

Governments can take 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 emissions 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 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]

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[8]Feebates are sectoral measures (for example, on transport, industry, 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—where low-carbon energy sources were available at 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 future.

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

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 the 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 beyond, and immediately yield substantial domestic "co-benefits" from mitigation policies—mainly due to reduced mortality and morbidity from lessened environmental pollution.[12] An initial green investment push combined with initially moderate and gradually rising carbon prices would deliver the needed emissions reductions at reasonable output effects. A green fiscal stimulus would support global GDP and employment in the recovery from the COVID-19 crisis, and lay the ground for higher carbon prices by boosting productivity in low-carbon sectors. As the

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[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 energies, but they are land and resource/material intensive. The same holds for other low-carbon sources of energy, such as hydro or nuclear power, and points to the issue of problem-shifting in a world characterized by many environmental crises. 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.

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

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 both the expected growth of the world economy over the same period and the expected income gains from avoided climate damages in the second half of the century and beyond. Growth in the medium and long term would be harmed considerably unless climate change is addressed, making the benefits from mitigation much higher than the temporary ones 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 damages 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 Tool Kit: 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.

[13]See also Stern (2007) and Hassler and others (2018).

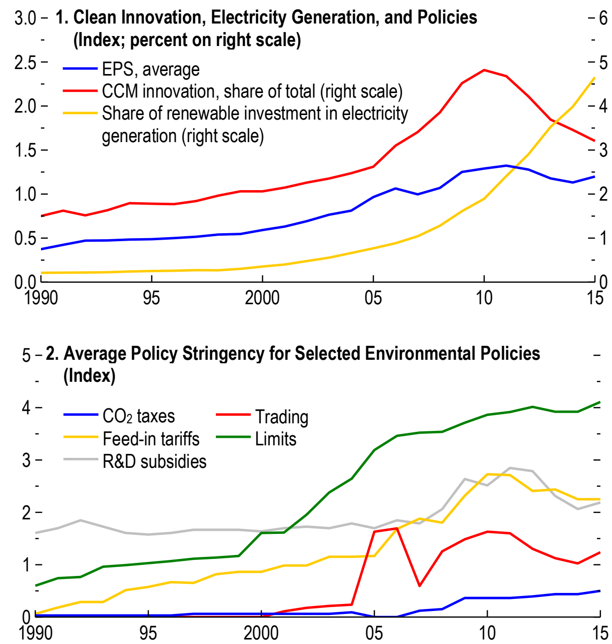
[14]The chapter uses the Organisation for Economic Co-operation and Development's Environmental Policy Stringency Index, as published in OECD (2018). For more details, see Botta and Koźluk (2014).

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]

Over the same period, clean energy innovation (measured by patent applications)[16] doubled in share of total energy innovation, while 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 6½ percent in 2020, with much higher shares attained in some European Union countries. Furthermore, the transition in electricity generation is accelerating: whereas the global renewable share increased by about ½ percentage point a year by 2010, that number had increased to 1 percentage point by 2017.

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.

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] More specifically, more stringent environmental policies are estimated to have contributed to:

- 30 percent of the increase in global clean energy innovation, equivalent to the effect of a permanent increase 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

[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 amount of emission permits is allocated or sold by a central institution, while 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.

[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 over 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.

policies increased the share of innovation in clean and "gray" electricity technologies (where 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).

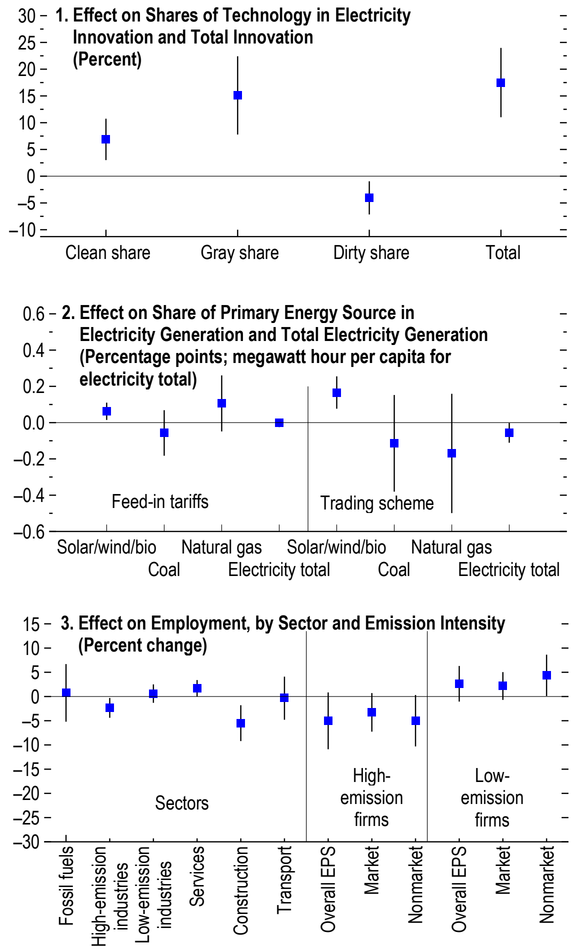
- 55 percent of the increase in the share of renewables in electricity generation. Tighter environmental policies were associated with declines in the share of coal and an ambiguous effect on the share of natural gas—often a complement to renewable energy (Figure 3.3, panel 2). The intermittent nature 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 renewable investment.

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

Figure 3.3. Effect of Policy Tightening on Total and Relative Electricity Innovation, by Type of Technology

More stringent environmental polices 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; Worldwide Patent Statistical Database; Penn World Tables; Worldscope 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 of 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 nonmarket-based policies, respectively, on employment in firms with high (low) CO_2 emissions (based on a smaller sample of firms that report CO_2 emissions). EPS = environmental policy stringency.

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

[19]The estimation of the effect of oil prices relies on a separate regression, with identical controls but without year fixed effects.

gas boom in the United States that capped oil price increases.[20] Popp and others (2020) also point to the possible role of an earlier clean-tech bubble and falling returns to 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 schemes (which include green certificates to achieve renewable portfolio standards and carbon emissions trading schemes).[21] Green certificate schemes are being phased out in several countries and carbon tax and carbon schemes 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 manufacturing, or transport.[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 more broadly in the economy. 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-emissions sectors (for example, high-emissions manufacturing, transport) in response to a tightening of environmental policies can be offset by job creation in some low-emissions sectors (for example, low-emissions 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

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[20]Acemoglu and others (2019) discuss 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.

[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 tend 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).

negative in response to changes in nonmarket policies, whereas market policies, such as feed-in tariffs and trading schemes, 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).

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 increasing 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 to access financing due to high uncertainty/risk, a long lag to when 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, the prototype of the internet). More active government involvement—including through

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[26]Another option to recycle revenues 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.

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 of gross emissions by 80 percent, assuming that the expansion of natural emissions sinks (such as forests) and some deployment of negative emissions 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 effort across countries. However, one exception is made for the Organization of the Petroleum Exporting Countries, which are only assumed to keep emissions at current levels because economic activity shrinks substantially due to 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 emissions target; (2) gradually phased-in carbon price increases; and (3) compensatory transfers to households. Specifically, it includes:

- *Green supply policies*. These consist of an 80 percent subsidy rate on renewables production and 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 emissions 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–\$20 a ton of CO_2 (depending on the country), reach between \$10–\$40 a ton of CO_2 in 2030, and between \$40–\$150 a ton of CO_2 in 2050.[30]

[28]IEA (2020a) discusses green investment opportunities in the energy sector, transport sector, and 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 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 (IPCC) 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 emissions reductions is large (see, for instance, IPCC2014, 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 emissions reductions; (2) the high assumed growth rate of carbon prices, which backloads 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.

- *Compensatory transfers*. Households receive compensation equal to ¼ of carbon tax revenues, which should allow to protect the purchasing power of poor households through targeted cash transfers (see the "How to Build Inclusion" section).

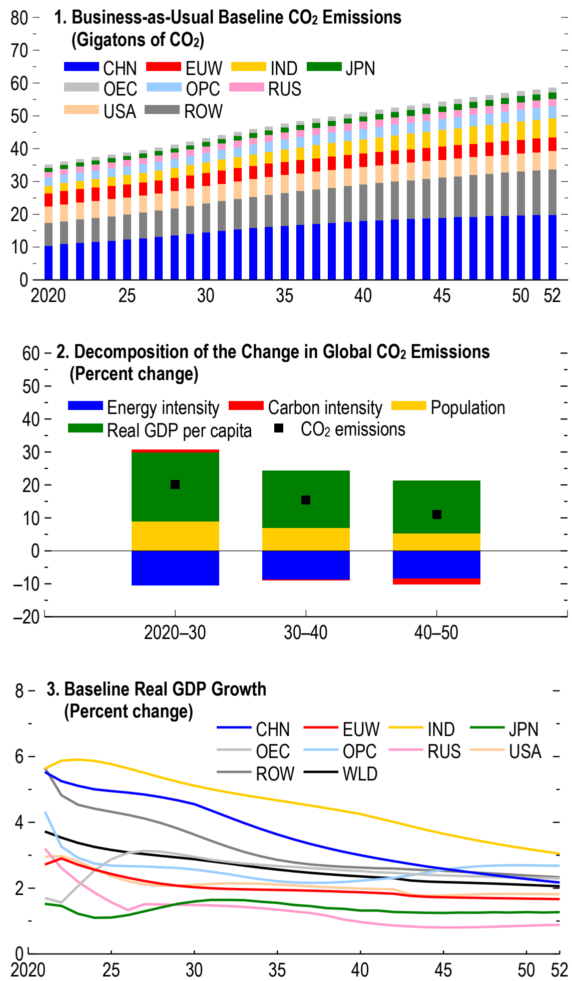
- *Supportive macroeconomic policies*. The policy package outlined above implies a fiscal easing that requires debt finance for the first decade and occurs amid low-for-long interest rates, given the current context of low inflation.

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 terms. 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.[31] 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.

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 global macro model G-Cubed 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 = oil-exporting countries and the Middle East; ROW = rest of the world; WLD = world. Data labels use International Organization for Standardization (ISO) country codes.

In the absence of new climate change mitigation policies, global carbon emissions are projected to continue rising at an average annual pace of 1.6 percent and reach 59 gigatons by 2050 (Figure 3.4).[32] Improvements in energy efficiency and some penetration of renewables—

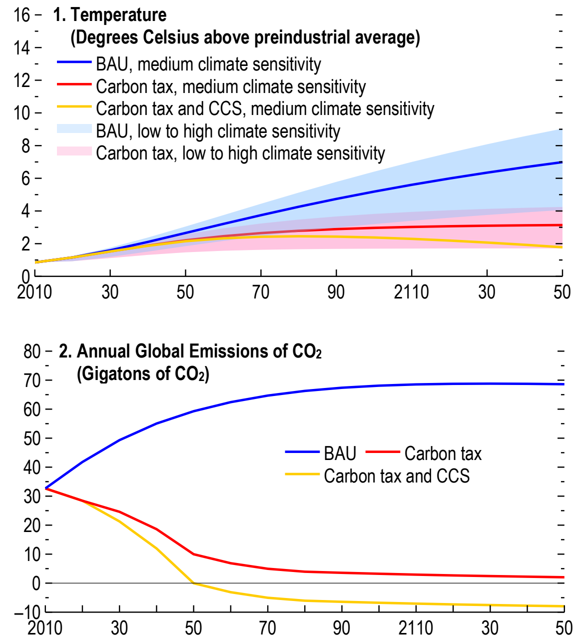
[31]The real price of carbon continues to grow until 2080.

[32]Black and Parry (2020) finds that the required emissions 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

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, still remain relatively small when compared to advanced countries. 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 of economic growth over the next 30 years determine the expected growth of future emissions, and therefore the scale of efforts 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 upon in the Paris Agreement and raising the risk of catastrophic damages for the planet.

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 2050 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 carbon tax, and a carbon tax 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.

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

Under the policy package, global carbon emissions are reduced by about 75 percent from current levels, reaching 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 to avoid 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).

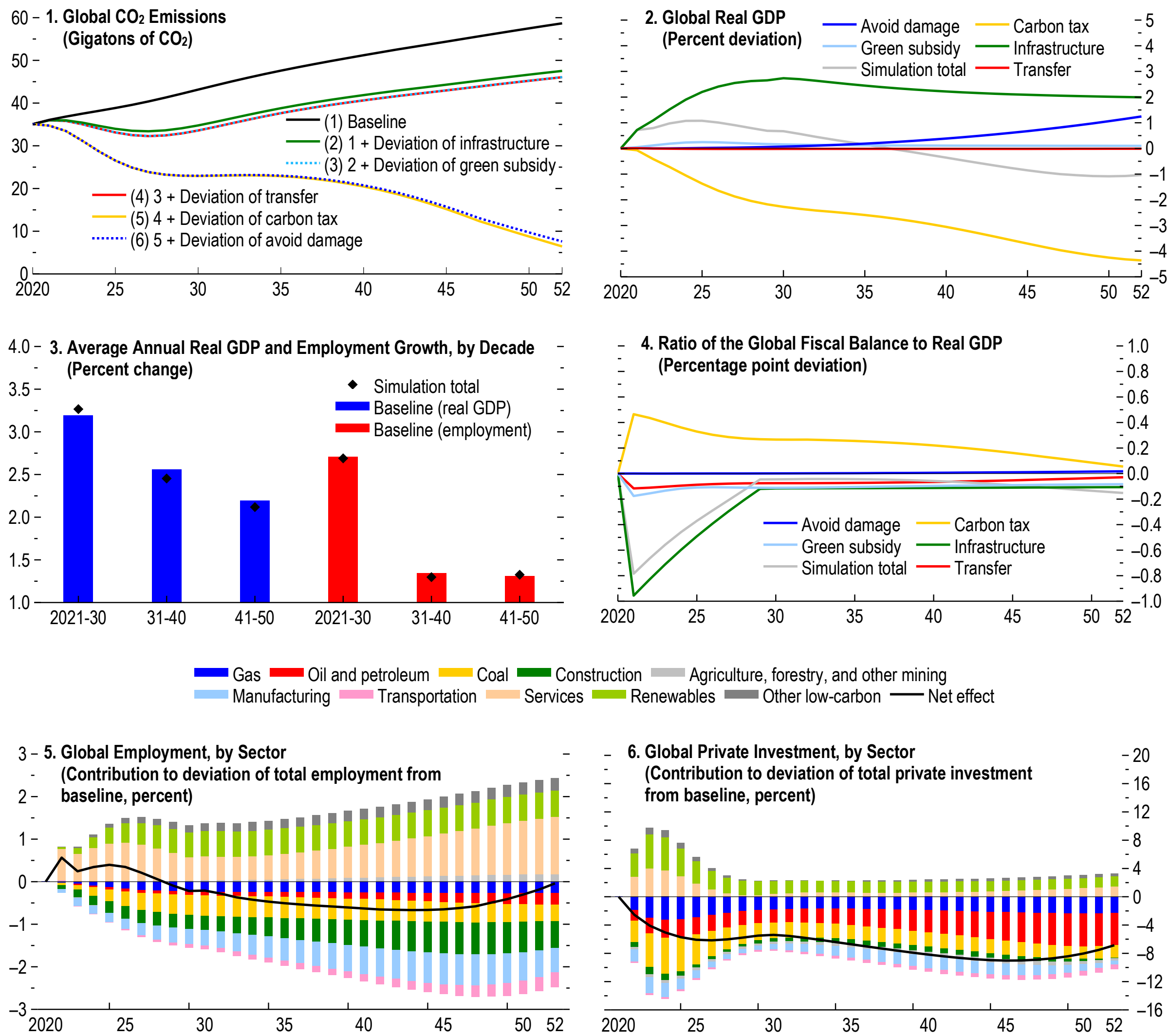
A closer look over the next 30 years shows that the costs of the transition are moderate and that both a green fiscal stimulus and carbon pricing play key roles (Figure 3.6). The policy

reduced usage of public transport and greater reliance on individual vehicles, or the greater use of digital communications leading to reduced commuting to offices and less travel. The baseline assumes (somewhat above) trend increases in energy efficiency.

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 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 120 percent cumulative expected growth of global GDP over the next 30 years (Figure 3.6, panels 2 and 3). From mid-century onward, the benefits of climate mitigation in the form of avoided damages grow larger, and the policy package boosts GDP and growth substantially above their baseline levels (Figure 3.7).

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 generate a boost to global GDP, supporting the recovery from the COVID-19 crisis, followed by moderate output losses in the medium term. Over 30 years the output losses would add up to only 1 percent out of a 120 percent projected increase in real GDP. As a result of the reduction in emissions, the global economy would be on a higher and more sustainable income path in the long term.



Source: IMF staff estimates.
Note: The simulations are run using the global macro model G-Cubed 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 to 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.

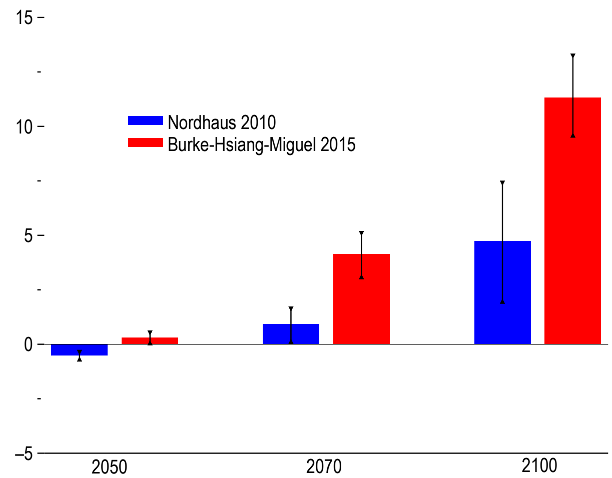
Closer examination of the effects of different tools employed in the policy package shows their complementary roles:

- *Emissions 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 emissions 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 but, after 15 years, the drag from the carbon tax is larger, resulting in small net output losses. The net drag on output—on the order of 1 percent over 2020-2050—is small compared with an expected cumulative increase in real GDP of 120 percent over the same period. Average annual growth, after being higher in the 2020s thanks to the green fiscal stimulus, is lower by only a tenth of a percentage point in the 2030s and by less than a 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 (e.g., 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,

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: 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 Buke, 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 mid-point of 3 (see text for discussion).

[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 and others 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.

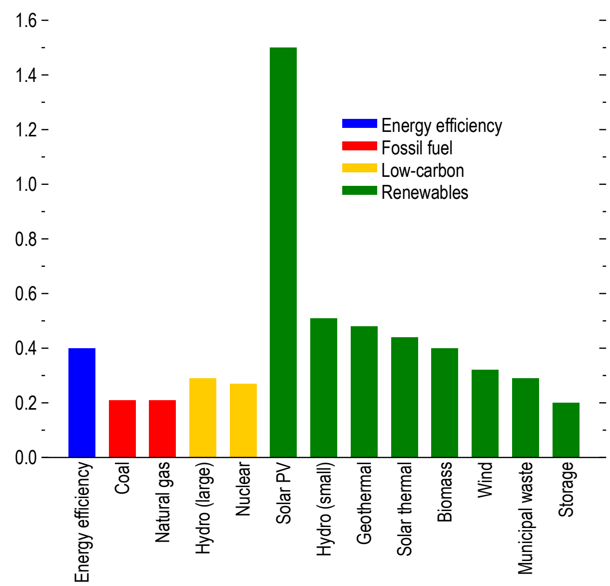
even these estimates are likely to understate benefits from mitigating climate change as they imperfectly take account of—or do not incorporate—some of the damages related to temperature increases, such as a higher frequency and severity of natural disasters, a rise in sea levels, and the risk of more 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). There is a boost to employment in the short term, and a small decline relative to baseline during the transition until the economy reaches a higher output and growth path. Despite the small decline relative to baseline, employment keeps growing strongly throughout the period (Figure 3.6, panel 3). Expanding low-carbon sectors, such as renewable energies, 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).

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.

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 only imply 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 nonfossil fuel capital, and the investment reductions from these industries offset the investment in renewables, which face large 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 small relative to baseline growth for most. For example, with the policy package, India's GDP would be 276 percent higher in 2050 than today, only moderately below what it would have been with

[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 to renewable production would allow the needed carbon price to be reduced. The new European Union Recovery Fund explicitly aims to address climate change.

unchanged policies (278 percent). But more important, these economic costs also need to be weighed against avoided damages 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 (due 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 and others 2015) indicate that many countries would experience substantial economic gains from co-benefits—which would be of the order of 2.5 percent of GDP per year for China and 1 percent for India.[37] Combining real GDP 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 under the policy package in the second half of the century. 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 damages 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 under-estimations as they do not include a number of damages (for example, rise in sea levels, natural disasters, damages to infrastructure from thawing of permafrost in Russia) and negative global spillovers from large economic disruptions that would occur 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 22 percent in 2050 from 32 percent of global

[37]Parry and others (2015) estimates a price on CO_2 that would internalize domestic non-climate-related external costs associated with fossil fuels around the world. The nationally efficient level of CO_2 price 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 per cubic meter in PM10 (particulate matter under 10 micrometers in size) reduces life expectancy by 0.64 years 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 benefits 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 of 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).

[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—as even the informal sector must buy energy from the formal sector, these mechanisms can lead to welfare-enhancing expansion of the formal sector.

emissions under unchanged policies. And in a scenario where only advanced economies enact mitigation policies, the decline in their emissions would be partly 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 performed in advanced economies are likely to relocate to countries where carbon is not taxed.

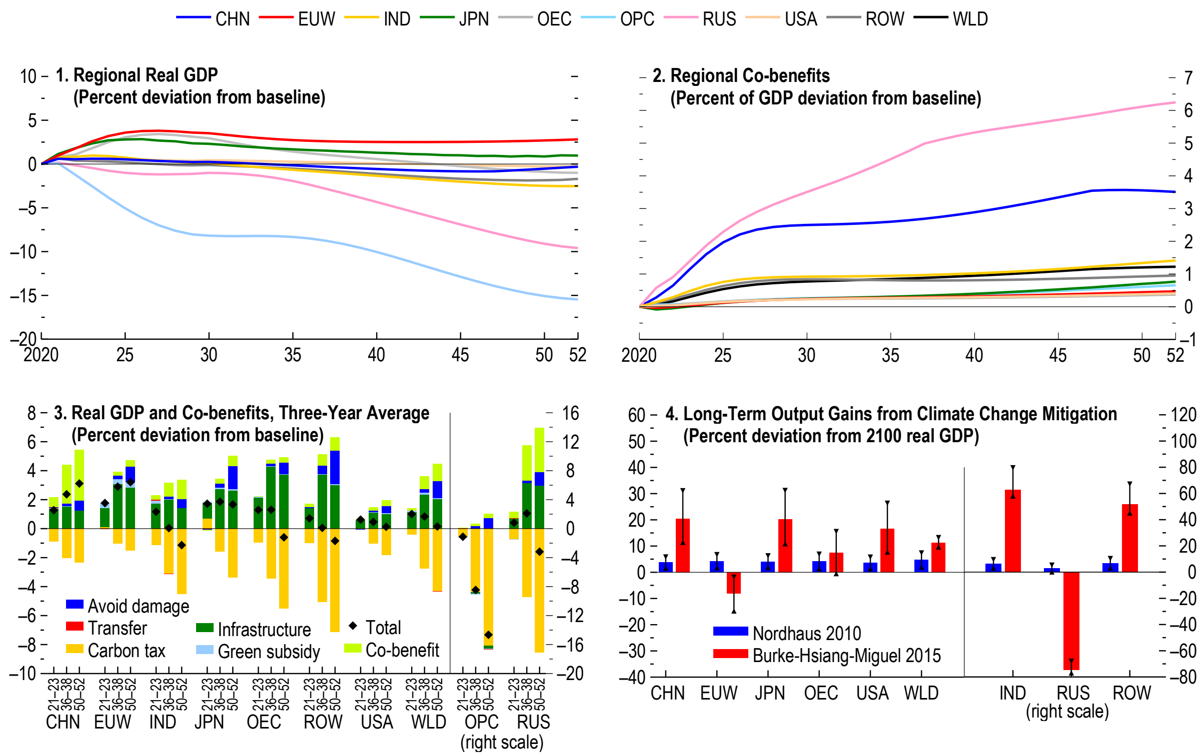
In a scenario where advanced economies are the only ones that reduce their gross carbon emissions by 80 percent by 2050, global emissions still increase to 48 gigatons by 2050, well above current levels (Figure 3.10).[39] In contrast, if the United States, Europe, China, Japan, and India—as the five 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 very similar effect on global GDP and each participating country's GDP, as in the 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—can maximize the revenue that can be 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 even hotter, where water scarcity is already a growing concern.

[39] See IMF (2020) for a discussion of the potential role of border carbon adjustment in climate mitigation strategies.

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

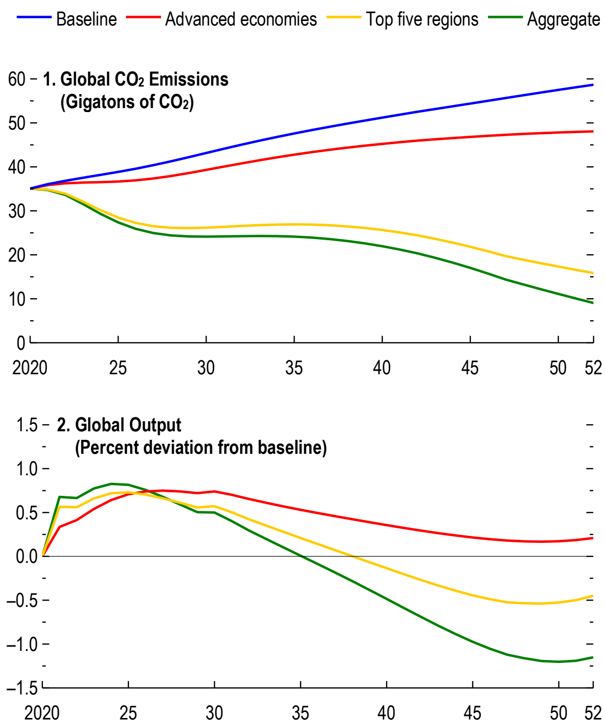
There are large cross-country differences in output effects, with most oil producers and countries with fast economic and population growth bearing larger costs in the medium term. However, these countries also stand to benefit more from avoided damages from climate change and co-benefits.



Source: IMF staff estimates.
Note: Panels 1, 2, and 3 are based on simulations run using the global macro model G-Cubed 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 comprise: (1) gradually rising carbon taxes, (2) a green fiscal stimulus consisting of green infrastructure investment and a subsidy to 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 Buke, 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 mid-point of 3 (see text for discussion). EUW = European Union, Norway, Switzerland, United Kingdom; OEC = Australia, Canada, Iceland, Liechtenstein, New Zealand; OPC = oil-exporting countries and the Middle East; ROW = rest of the world; WLD = world. Data labels use International Organization for Standardizatioon (ISO) country codes.

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

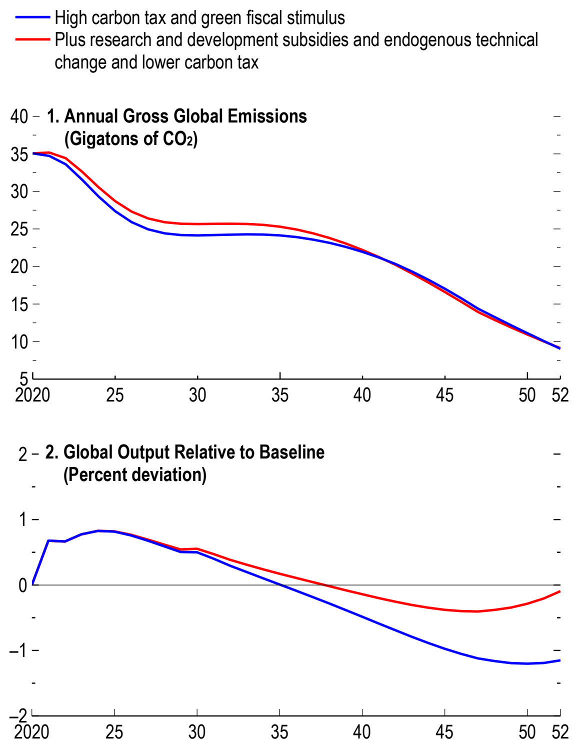
Advanced economies mitigating alone cannot keep temperature increases to safe levels. But joint action by the top five emitters would make a large dent in global emissions.



Source: IMF staff estimates.
Note: This figure is based on simulations run using the global macro model G-Cubed 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 by 2050 and comprises (1) gradually rising carbon taxes, (2) a green fiscal stimulus consisting of green infrastructure investment and a subsidy to renewables production, and (3) compensatory transfers to households. The figures also show 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 regions" assume that only advanced economies and five regions with the largest GDP (China, European Union, India, Japan and the United States) act to mitigate.

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 emissions reductions can be achieved with a lower carbon tax and at a lower cost to output.



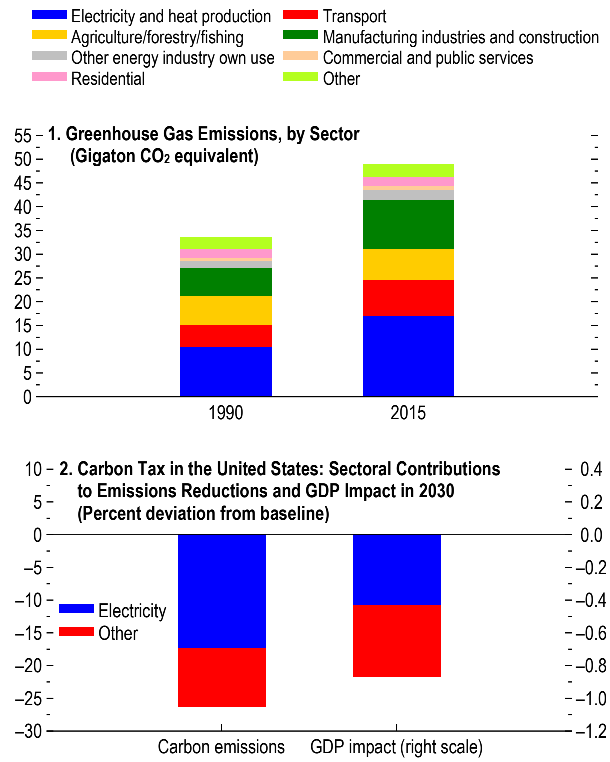
Source: IMF staff estimates.
Note: The panels compare the G-Cubed simulation of the comprehensive policy package with a simulation run using an extension of the Hassler and others (2020) integrated assessment model with endogenous technological change. The second simulation features a lower carbon tax 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, the 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) to green research and development, allows for a similar emission target to be reached by a carbon price path that is about half of the prices needed 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.

Figure 3.12. Potential for Emissions Reductions in the Electricity Sector

The electricity sector offers substantial scope for emissions reductions and better emissions–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.

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.[40] Overall, the analysis suggests that a lower carbon price, if combined with an early use of green research and development subsidies, might be able to achieve the same lower emissions 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.[41]

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

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

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

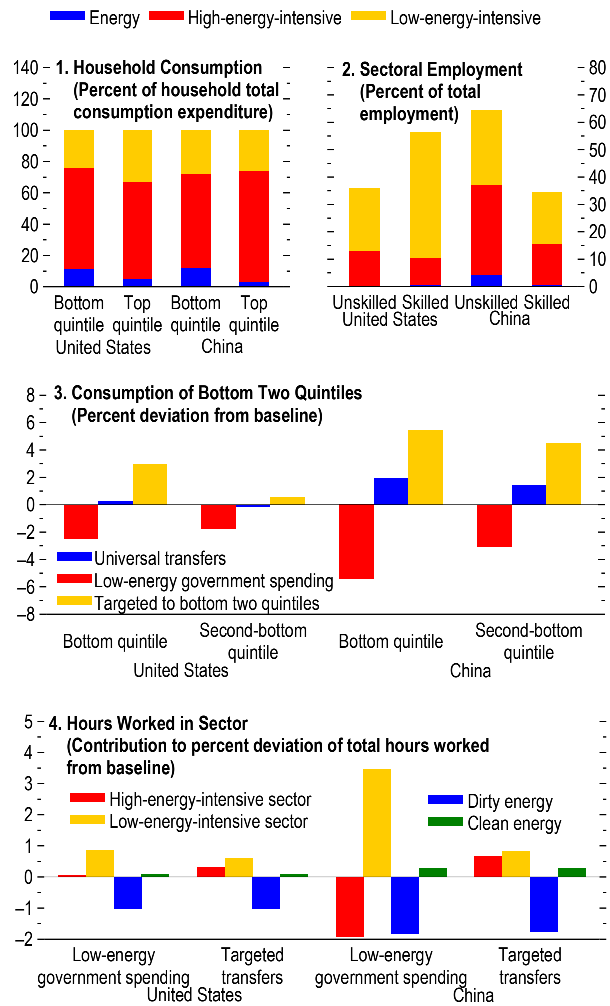
decarbonization because substitute low-carbon technologies are already available and are economically competitive as a result of a dramatic decline in prices in the past decade—for example, the costs of electricity from wind have declined by 70 percent (Lazard 2019). This makes near-term emissions-output trade-offs particularly favorable in this sector, which is also reflected in the G-Cubed simulation, where about ⅔ 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- or 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 than boosting

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: 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 show the result of the multisector heterogeneous agent model simulation of a \$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.

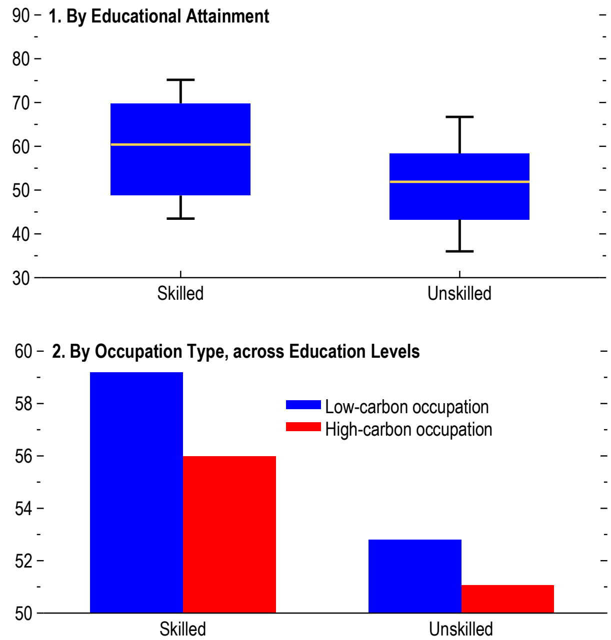
economic growth; and support for protecting the environment is the lowest for lower-skilled workers employed in carbon-intensive sectors (Figure 3.14).[42]

The distributional impacts of carbon pricing are likely to vary by country. Carbon pricing is not always regressive, especially in emerging market and developing countries, 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 be used to 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 (their consumption levels kept broadly constant) by redistributing about one-quarter and one-sixth of the carbon revenues to this group of households, respectively, in the United

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. The low-skill 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.

[42]See also IMF (forthcoming).

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.[43]

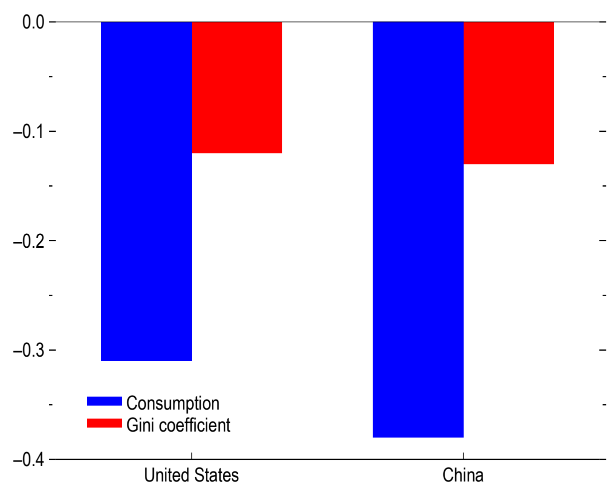
While they both protect private consumption, neither universal nor targeted cash transfers help materially ease job transitions. By contrast, increasing government spending on low-carbon goods and services—similar in spirit to the "green supply policies" studied in the previous section—would fail to protect the consumption of poorer households, but they 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 being spent on subsidies to promote the consumption of clean energy. The revenue-raising component (carbon tax) is similar.

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

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



Source: IMF staff calculations.
Note: The figure shows the result 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).

[43]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 (2010) and Carl and Fedor (2016).

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 employs more unskilled labor than the dirty energy sector).

Finally, mitigation policies are likely to affect some communities more than others, adding a geographical 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.

Conclusion

The window for attaining net zero emissions by 2050 and maintaining 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 emissions 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 small in comparison to projected growth of the global economy over the next three decades and could be reduced further as new 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 economic countries/regions—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 rates. 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 that of international coordination, which could offer scope for a 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; Lessman 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 avoiding climate-change-induced events, such as crop-loss, rise in sea levels, and extreme weather.

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

Carbon tax. A tax imposed on CO_2 releases emitted largely through the combustion of carbon-based fossil fuels. Administratively, the easiest way to implement is through 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, or 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 any negative effects resulting from the policy on consumption (or some other measure of household well-being) of low-income groups.

Economies of scale. Cost advantages that enterprises obtain due to their scale of operation, with cost per unit of output decreasing with increasing scale.

Emissions 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 emissions content in fuels. The total quantity of allowances is fixed, and market trading of allowances establishes a market price for emissions. Auctioning the allowances provides 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 consider.

Feebate. This policy would impose 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, the feebate might 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 tariff. 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.

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

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.

Gray technologies. Technologies that tend to improve the pollution efficiency of "dirty" technologies. Examples of gray technologies include technologies that allow the heat usage from fuel or waste incineration or fuels from nonfossil origins.

High-carbon. Activities that are either engaged in generation of carbon-based energy or are relatively high emitters 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 finance. 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 hydro-electric sources. The latter is often subdivided into large and small hydro, due to the large environmental impact of the former.

Research and development. Innovative activities undertaken by corporations or governments in developing new products or technologies.

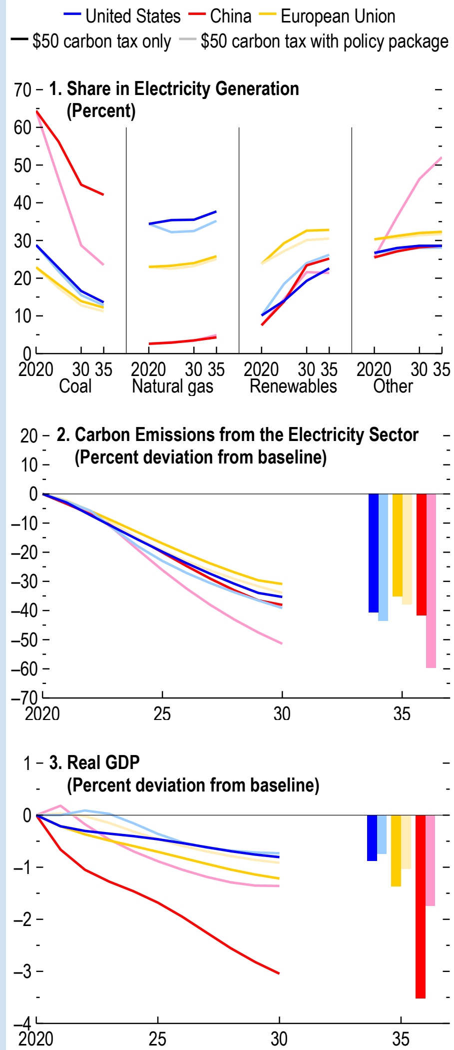
Revenue recycling. Use of (carbon) tax revenues to, for example, lower other taxes on households and firms or fund public investments.

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, nuclear, and hydro. The constraints that intermittency of renewables (the undesired output variation from the varying availability of sun and wind) poses 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 introducing gradually a $50 carbon price over 10 years in the electricity sector, flanked by a frontloaded 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 debt financed, leading to a total increase of the debt-to-output ratio of roughly 1 percent of GDP. The carbon price discriminates by 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.

Figure 3.2.1. Decarbonization of the Electricity Sector



Source: IMF staff estimates.
Note: The figure is based on the GIMF-E 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.

While investment and employment decline in the coal sector, the subsidy triggers a surge in investment in renewables, offsetting large parts of 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 a 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 insufficient 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 macro 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. A storage technology for renewable electricity, which might become feasible in the near term, would amplify the penetration of renewables resulting from the carbon price. As 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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Annex 3.1. The Impact of Environmental Policy on Clean Innovation

This note describes the empirical model and the data and presents more detailed results on the influence of climate mitigating policies on innovation in climate mitigating technologies. It starts with a selective presentation of the most closely related papers, followed by a brief explanation of the conceptual basis and the estimation strategy, before introducing the key variables and the main results.

Related Literature

The most closely related paper to this analysis is Johnstone et al. (2010).[1] Similar to our paper, it analyses in a cross-country setup the effect of broad policy measures on climate-change mitigating innovation. Our analysis however benefits from a much more recent sample,[2] a more precise technological classification and more standardized policy indicators, namely the environmental policy stringency (EPS) indicator published by the OECD.[3] This allows us to better capture the dramatic increase in clean innovation of the early 2000s, but also the flattening and partial reversal since 2010.[4] Our analysis relies on the environment-related technology (ERT) classification proposed by Haščič and Migotto (2015). However, rather than relying on all ERT technologies, we focus on the climate change mitigation technologies related to energy. These are among the technologies with the biggest potential for emissions reductions and most closely targeted by climate-related policies. Unlike the technologies investigated by Johnstone et al. (2010), they include not only renewable energy, but also technologies related to improved efficiency in energy generation, transmission and distribution. In addition, we use a technological specification proposed by Dechelepretre and others (2017) to look more closely at technologies related to electricity. The classification has the advantage of not only identifying clean technologies, but also dirty as well gray one, where the latter are innovation that improve the environmental impact of dirty technologies (e.g. biofuel, waste incineration plants). This allows us to study the relative benefits from tightening environmental policies for these different types of technologies, as well as the impact on electricity innovation overall.

[1] Other relevant papers using cross-country analysis of similar questions include Popp (2006) and De Vries and Withagen (2005).

[2] The sample in Johnstone et al. (2010) is limited to 25 countries over the time frame of 1978-2003, while our sample covers 33 countries from 1990-2015.

[3] OECD (2018), "Environmental Policy Stringency index (Edition 2017)", OECD Environment Statistics (database), https://doi.org/10.1787/b4f0fdcc-en (accessed on 28 July 2020).

[4] For a discussion of possible reasons behind the relative decline in clean innovation post-2010, see Popp et al. (2020) and Acemoglu et al. (2019). Among a partial relaxation in environmental standards in some countries, technological progress especially related to hydraulic fracturing, energy prices and reduced investor appetite after a possible technology bubble in the previous years may have diminished returns to clean research.

Conceptual Framework

The conceptual basis for the empirical estimation is a multiplicative production function of new innovation in country i in technology j along the lines of the one specified in Acemoglu and others (2016).

$$X_i^j = \theta \left(H_i^j\right)^{\beta} \left(u_i^j\right)^{\gamma}$$

where u_i^j stands for the accessible stock of knowledge and H_i^j stands for the research effort. The equation can be re-written as an equation that can be estimated with empirical count models.

$$X_i^j = \exp\left(\alpha + \beta \ln\left(H_i^j\right) + \gamma \ln\left(u_i^j\right) + \epsilon_i^j\right)$$

where $\alpha = \ln(\theta)$ and ϵ_i^j is the residual. Acemoglu and others (2016) assume that new innovation X_i^j follows a Poisson distribution.

In our empirical estimation, the flow of innovation X_i^j is proxied by the number of climate change mitigating patent families associated with a particular country, and where the first patent application was made in a given year. A patent family is associated with a given country if it is the most common country of residence of the first inventors of the different patents.

The key line of investigation is how environmental policy affects the flow of innovation. Consistent with the conceptual framework, the baseline includes the stock of knowledge[5] as well as overall innovation. The latter controls for policies related to education and research as well as changing patenting cultures.[6] In addition, the model includes both country- as well as year fixed effects, to control for time-invariant country characteristics, as well as global dynamics, including the effects of the global business cycle. The year fixed effects also capture the influence of changes in the oil prices as well as part of the common trend towards tighter environmental standards. In a subsequent analysis of the fixed effects, we try to shed light on the relative importance of these two factors in driving the global trends. The equation is estimated using the fixed effects Poisson estimator with clustered robust standard errors, in line with today's best practices. All control variables are lagged by one year, as they are in part pre-determined (e.g., the knowledge stock) and to account for time lags in knowledge production.

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[5] The inclusion of the stock of knowledge creates an indirect link between policies and innovation as a higher effort u_f^j today creates a bigger knowledge stock tomorrow H_f^j, which provides a bigger base for innovation in the future. The patent stock in the specific ERT technology is constructed using the perpetual inventory method. The 1965-1975 growth rate in patenting, a 10 percent annual depreciation rate and a geometric series are used to determine the stock in 1965. If the depreciation rate is $\sigma = 0.1$ and δ is the annual growth rate in patenting, the initial stock $S_{1965} = \frac{1}{1-r} P_{1965}$, where $r = (1-\sigma)/(1+\delta)$ and P_{1965} the initial level of patenting.

[6] The incentives to patent a given technology differ across countries, but also change over time. For example, patent promotion policies in China or the historical requirement in Japan to have a separate application for each claim have resulted in a relative inflation in the numbers of applications in some countries. The inclusion of overall patenting controls for such differences.

Main Results

The table below shows the main results (Annex Table 3.1.1). The effect of the aggregate EPS indicator is reasonably stable across specifications and highly statically significant. In the various columns, the different specifications control respectively for the evolution of oil and gas reserves, the electricity prices at the household level, as well as indicators for labor and electricity market regulation. The control variables have the expected sign and are often statistically significant. As the inclusion of additional controls rapidly reduces the size of the sample, column 1 is used to calculate illustrative examples. Its coefficient of the EPS variable is at the lower end of the range over the different specifications. The illustrations below would thus produce stronger effects, if the we relied on a specification with additional controls.

Annex Table 3.1.1. Aggregate Effect of Environmental Policy on Clean Innovation

Dependent variable: CCM energy patent families	(1)	(2)	(3)	(4)	(5)	(6)
EPS_{t-1}	0.174***	0.237***	0.179***	0.223***	0.154***	0.201***
	(4.05)	(5.04)	(5.50)	(5.62)	(4.40)	(5.33)
Log tech $stock_{t-1}$	0.551***	0.581***	0.455***	0.444***	0.486***	0.264*
	(11.63)	(5.39)	(10.28)	(3.69)	(8.06)	(1.80)
Log all $tech_{t-1}$	0.468***	0.473***	0.656***	0.704***	0.286**	0.640***
	(9.09)	(4.56)	(8.85)	(6.12)	(2.46)	(3.45)
Log oil and gas reserves $(bb)_{t-1}$		-0.111		-0.0596		-0.0837
		(1.25)		(0.49)		(0.70)
Price of electricity for households $(USD)_{t-1}$			0.278***	0.252**		0.408***
			(3.35)	(2.19)		(3.86)
ETCR $electricity_{t-1}$					-0.0782**	-0.0669
					(2.02)	(1.28)
Labor market $regulation_{t-1}$					0.0143	-0.0276
					(0.60)	(0.89)
Number of observations	762	724	589	560	417	345

Source: IMF staff calculations.

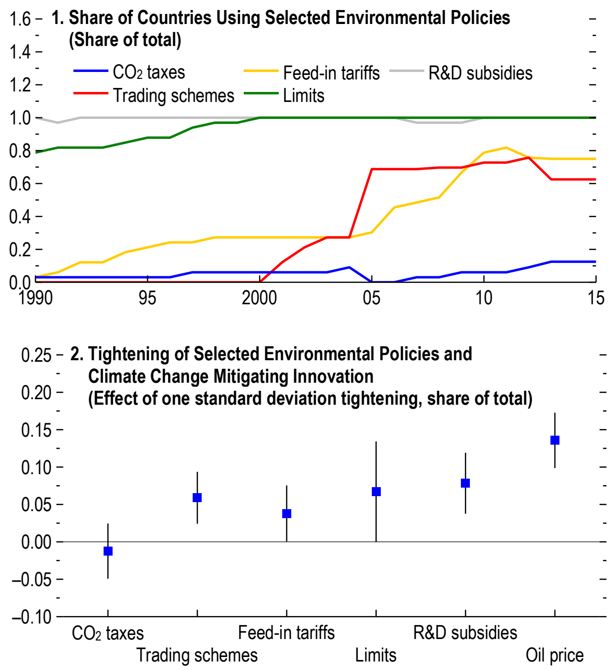
Note: All regressions include country and year fixed effect. T-statistics in parentheses. EPS = environmental policy stringency; CCM = climate change mitigating; tech stock = patent stock in specific technology, all tech = total patenting in all technologies; bb = billions of barrels; ETCR = energy, transport and communication regulation. Data on labor market regulation is from the Economic Freedom of the World by the Fraser Institute.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

These effects are not only statistically, but also economically significant. To illustrate this, we compare the predicted level of innovation at the country level, ignoring the global components captured by the year fixed effects, with the same prediction if the EPS indicator had not changed since 1990. This comparison suggests that the change in the EPS directly contributed to roughly 30 percent of the increase in innovation between 1990 and 2010. Given that more innovation leads to a bigger knowledge stock, there would additionally be an indirect, second-round effect, whose magnitude would however be of second order.

By not including the fixed effects in the two predicted values, the above comparison remains consistent with the empirical estimation. It ignores however global factors such as oil prices and the common upward trend in environmental policy stringency. We thus investigate to what extent the year-FE have been driven by these two factors. For this, the retrieved year fixed effects from the baseline regression are regressed on the EPS indicator (country-specific) and oil prices. Based on this second regression we again compare the predicted year fixed effects with the actual EPS indicator and the predictions keeping either the EPS indicator or oil prices at 1990 levels. This suggests that the change in the EPS indicator is responsible for 37 percent of the increase between 1990 and 2010 in global innovation captured by year-FE. This is a significant share but only about half of the contribution from the increase in oil prices. The comparable, but somewhat bigger contribution from energy prices is confirmed by an analysis of the R^2. The individual contribution of the environmental tightening to the variation in the year fixed effects is about 30 percent, compared to an individual contribution of 46 percent from oil prices. The joint contribution of the two amounts to 61 percent.

Annex Figure 3.1.1. Popularity and Effect of Individual Environmental Policies



Sources: International Energy Agency; Organisation for Economic Co-operation and Development; Worldwide Patent Statistical Database; and IMF staff calculations.
Note: Panel 2 shows the effect of one standard deviation change in policy indicator, conditional for all other policies (as in column 6). CCM innovation = patents in climate change mitigating technologies; R&D = research and development.

The Effect of Individual Policies

Going beyond the aggregate EPS indicator, we investigate whether some specific policies are more important than others, using the EPS sub-indicators as the variable of interest. In the table below the policies are first included individually (Annex Table 3.1.2, columns 1 to 5). Column 6 assesses the impact of individual policies on clean innovation, controlling for all others (see also Annex Figure 3.1.1). Although, there has been some co-movement among individual policies, most coefficients barely change when other policies are controlled for. The results suggest that both non-market policies—such as emission limits and R&D subsidies—as well as market policies—such as trading schemes and feed-in tariffs—made a statistically significant contribution to clean innovation. The one major exception are carbon taxes, where the effect is insignificant. This result can be explained by the very limited use of this particular policy tool. While the other policy tools shown here were used by 60-100 percent of the countries in the sample, only slightly more than 10 percent of them used carbon taxes in 2015 (OECD 2018).

Annex Table 3.1.2. Effect of Individual Policies

Dependent variable: CCM Energy patent applications	(1)	(2)	(3)	(4)	(5)	(6)
Log tech stock$_{t-1}$	0.551***	0.531***	0.596***	0.543***	0.508***	0.519***
	(14.20)	(13.72)	(11.29)	(12.32)	(13.22)	(10.48)
Log all tech$_{t-1}$	0.492***	0.506***	0.438***	0.448***	0.593***	0.525***
	(9.28)	(10.40)	(7.16)	(10.23)	(12.66)	(9.71)
CO_2 taxes	0.0105					-0.016
	(0.47)					(0.55)
Trading schemes		0.0333**				0.0320***
		(2.03)				(2.79)
Feed-in tariffs			0.0278***			0.0207*
			(3.10)			(1.67)
Emission limits				0.0511**		0.0388*
				(2.29)		(1.65)
R&D subsidies					0.0693***	0.0616***
					(5.41)	(3.16)
Number of observations	788	785	788	788	788	785

Source: IMF staff calculations.

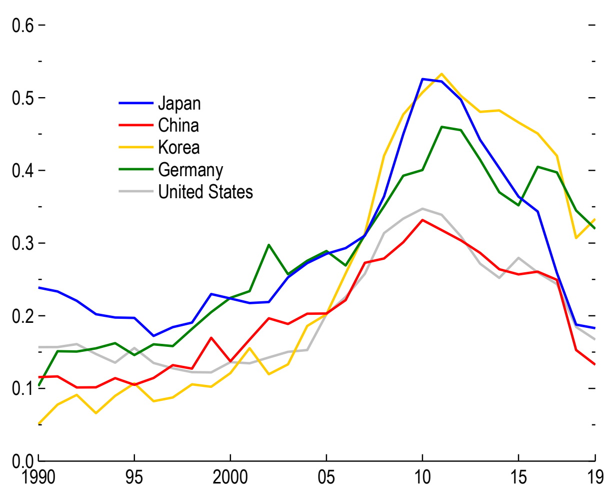
Note: All regressions include country and year fixed effect. T-statistics in parentheses. EPS = environmental policy stringency; CCM = climate change mitigating; tech stock = patent stock in specific technology, all tech = total patenting in all technologies.

*** p<0.01, ** p<0.05, * p<0.1.

Clean, Gray, Dirty and Total Electricity Innovation

After focusing on specific policies, the next analysis looks at a particular set of technologies: electricity. The electricity sector is responsible for a significant share of global emissions and thus targeted by many environmental policies. In addition, focusing on electricity is interesting as, relying on a classification by Dechezlepretre and others (2017), we can distinguish clean electricity innovation from dirty and gray innovation, where gray innovations are technologies that improve the environmental impact of dirty technologies. The classification illustrates that the share of clean innovation in electricity-related technologies has increased dramatically up to about 2010 (Annex Figure 3.1.2). It also allows us to empirically assess the relative effect of policies on the different types of technologies as well the overall effect on electricity innovation.

Annex Figure 3.1.2. Share of Clean Electricity Innovation
(Share of total)



Sources: Dechezleprêtre, Martin, and Mohnen (2017); Worldwide Patent Statistical Database; and IMF staff calculations.

The results suggest that environmental policies have increased the relative share of clean innovation, and even to a larger extent that of gray innovation (Annex Table 3.1.3, column 1 and 2). A possible reason for this is that gray technologies are often less radically new and may thus be closer to the practical application. The effect on overall innovation (column 4) is strong and positive suggesting that the relative decline in dirty innovation (column 3) was more than offset by the increase in the other categories.

Annex Table 3.1.3. Relative and Absolute Electricity

Dependent variables: Patent families related to different types of electricity	(1) Clean	(2) Gray	(3) Dirty	(4) Total
EPS_{t-1}	0.0688***	0.151***	-0.0405**	0.175***
	(0.02)	(0.04)	(0.02)	(0.04)
Log all $tech_{t-1}$	0.0522	-0.338***	0.0543**	0.450***
	(0.10)	(0.10)	(0.02)	(0.07)
Log knowledge stock specific to the type of $electricity_{t-1}$	-0.0255	0.531***	0.0391	
	(0.07)	(0.07)	(0.30)	
Log knowledge stock for all types of $electricity_{t-1}$	-0.00121	0.132	-0.103	0.581***
	(0.17)	(0.21)	(0.30)	(0.10)
Log oil and gas $reserves_{t-1}$	-0.129**	-0.0843	0.0398	
	(0.05)	(0.06)	(0.02)	
Number of observations	738	743	743	781

Source: IMF staff calculations.

Note: Besides the overall EPS indicator, the regression controls for total patenting, the existing knowledge stocks in the specific and overall electricity technology and proven oil and gas reserves. Columns 1 to 3 control for overall electricity innovation with a coefficient constrained at 1. EPS = environmental policy stringency; all tech = total patenting in all technologies.

*** p<0.01, ** p<0.05, * p<0.1.

Conclusion

The evidence suggests that the tightening in environmental policies had a statistically and economically significant effect on clean energy innovation. A closer look at the electricity sector suggests that this resulted in a relative shift away from dirty and towards clean and gray innovation, with a net positive effect on electricity innovation overall.

Annex 3.2. Drivers of the Energy Transition with a Focus on Support Policies and Carbon Pricing

Introduction

The substitution of fossil-fuel power plants with renewable energies such as solar photovoltaic (PV) modules and wind turbines is undoubtedly one of the most important tools countries have at their disposal to mitigate carbon emissions in the electricity sector. From 2001 to 2020 the share of all renewables in nominal global power plant investment increased from 44 percent to 66 percent, with that increase being larger in advanced economies (from 44 to 75 percent) than in developing economies (from 44 to 60 percent) (IEA, 2020b). As the costs of solar PV and onshore wind declined by 82 percent and 63 percent respectively between 2000-2019 (IRENA, 2020), the (real) renewable share in terms of total capacity installed increased even faster.

Main Question & Literature Review

The investment boom in solar, wind and biomass has led to a rapidly increasing share of these renewable energy sources in global power generation, with its share increasing from virtually nil in 2000 to 6.5 percent in 2017, and with much higher shares attained in some EU countries such as Denmark, Germany and the United Kingdom. Furthermore, the pace of this ongoing energy transition is in fact accelerating: while the global share increased by about 0.5 percentage point per year in 2010 that number had increased to 1 percentage point in 2017. To understand whether this transition (and its acceleration) can be sustained, it is important to understand its drivers, especially levers for policy makers. To this end we ask: what has been the role of support policies and carbon pricing in driving the energy transition?

According to Bourcet (2020), who reviews a total of 48 papers studying the drivers of renewable energy development, consensus exists in the literature for the following drivers: (i) renewable energy support policies (positive effect), (ii) lobby effect from pre-existing energy sources (negative effect), (iii) (lagged) CO2 emissions per capita (negative effect for the renewable energy share, especially within Europe), (iv) population size (positive effect, as larger countries are expected to contribute more to a global public good), (v) income (positive effect for developing countries).

Only a few studies, i.e., Burke (2010), Best (2017), and IMF (2018), analyze the share of renewable energy/electricity in conjunction with the share of other (polluting) primary energy sources such as coal. Studying the shares of different energy sources simultaneously can provide for a more complete picture of how policies to support renewables and/or reduce carbon emissions have changed the energy/electricity mix.

Empirical Specification

Since a growing renewable energy share is a necessary (but not sufficient) condition to mitigate greenhouse gas emissions from energy use, the annual change in the share of non-hydro renewable energy in electricity generation is selected as our main dependent variable.[7] Other dependent variables analyzed are: the annual change in the shares of coal and natural gas in electricity generation, and total electricity generation per capita (in MWh/capita).

This analysis contributes to the literature by analyzing the effects of various environmental policies on the shares of various primary energy sources in the electricity mix. It does so by regressing the change in the share of renewable electricity on a package of various environmental policy instruments, which limits omitted variable bias potentially affecting single-policy regressions. As the policies are measured as indexes and the underlying units of measurement differ, it should be noted that one cannot directly compare the effect of one policy instrument with another (see below).

To explain the annual change in the share of renewable electricity generation Δy_{it}, we adopt the empirical specification from Urpelainen and Smith (2014). With *i* indexing countries and *t* indexing years, the equation to be estimated reads as follows:

$$\Delta y_{it} = \beta_1 y_{i,t-1}^{MA} + \beta_2 \boldsymbol{Policy_{it}} + \beta_3 X_{it-1} + \mu_i + \lambda_t + \varepsilon_{it}$$

where $y_{i,t-1}^{MA}$ is the three year-moving average of the share of renewable electricity generation lagged by one period, $\boldsymbol{Policy_{it}}$ is a vector of environmental policies and electricity market reforms, X_{it-1} is a vector of controls including income per capita, the interest rate, the electricity share of hydro and nuclear, and proven reserves of natural gas and oil all lagged by one period. To control for unobservable determinants that are country-specific (e.g., citizens' environmental values), and time-specific (e.g., variations in prices of solar and wind that are common to all countries), we include country fixed effects and year fixed effects, denoted by μ_i and λ_t respectively. As in Verdolini and others (2018) we use the OLS panel fixed effects estimator.

Urpelainen and Smith (2014) also employ an instrumental variable approach to deal with the possible reserve causality between the deployment of renewables and feed-in tariffs. If anything, Urpelainen and Smith (2014) find that OLS underestimates the true effect of feed-in tariffs, but in contrast to our work they do not control for other support policies such as renewable energy certificates or carbon pricing. Rodríguez and others (2015) study the relationship between various environmental policies and private sector investment. They find that 2SLS estimates of the effect of feed-in tariffs and renewable energy standards on private sector investment do not differ much from OLS. In their analysis, a Hausman test confirms the exogeneity of these renewable energy policies. While these considerations and others leave little doubt that some policy instruments have had positive effects, it remains prudent to interpret the results from our analysis as associations rather than causal effects.

[7] A growing renewable electricity share is a sufficient condition for reducing emissions if and only if total electricity demand growth is zero (or negative).

Data

Dependent Variables

The following dependent variables are all taken from the IEA (2019) and span the period from 1990 to 2017: (i) the annual change in the share of renewable electricity, (ii) the annual change in the share of electricity from natural gas, (iii) the annual change in the share of electricity from coal, and (iv) the annual change in electricity generation per capita. Renewable electricity includes solar PV, solar thermal, onshore wind, offshore wind, geothermal, wave/tidal/current, and biomass.[8]

Independent Variables

To measure the stringency of environmental policies across countries over time, data from the OECD Environmental Policy Stringency (EPS) project is used (see Botta and Koźluk 2014). The OECD EPS is the only long-run time-series of a comprehensive package of environmental policies in existence. The EPS is measured as an index on a scale from 0 to 6. It includes cross-country comparable data for 32 OECD and emerging market countries between 1990-2015 for various policy indicators including: taxes on the pollutants NOx, SO2 and particular matter (PM); trading schemes for CO2, SO2, renewable (or green) energy certificates, and white certificates (which are tradable assets proving that a certain amount of energy savings has been attained relative to some baseline); feed-in tariffs for solar and wind; limits on emissions of PM, SO2 and NOx for newly built coal-fired power plants, and government R&D expenditures for renewable energy technologies.

Two policy instruments of particular interest are feed-in tariffs and green certificate schemes. Under feed-in tariffs producers of renewable energy are provided with long-term contracts that stipulate a fixed price per kWh for every unit of electricity provided to the grid. Green certificates or renewable energy certificates are tradable assets which prove that electricity has been generated by a renewable energy source. Many states and countries have implemented renewable energy standards, under which utilities are obliged to source a certain fraction of their electricity from renewable sources. If utilities cannot generate the renewable electricity themselves, they must buy green certificates from producers who hold them in excess to prove their compliance.

Other independent variables include: proven reserves for oil and gas from BP (2019) (to control for resource endowments); population size and real income from the Maddison Project Database (Bolt and others 2018) (to proxy for higher demand for environmental quality among others); short-term interest rates from the IMF WEO database (to proxy for the opportunity cost of investment); shares of hydropower and nuclear energy in electricity generation from IEA (2019) (to control for other low-carbon energy sources); electricity market regulation from

[8] Hydropower is not considered because although it is a mature and relatively cheap renewable energy technology, most of the world's reserves are utilized except for a few regions such as the Congo basin. Furthermore, utilization comes with considerable negative environmental effects.

OECD (Koske and others 2015); and the price of oil expressed in local currency units relative to the domestic price level from the IMF primary commodity price tables (IMF, 2020b).

Results

Renewable Energy

Our main results are reported in Annex Table 3.2.1. Model 1 tests the role of market-based and non-market based environmental policies. While positive and statistically significant evidence is found for market-based policies, non-market-based policies do not appear to have been effective. Abstracting from variations in environmental policy stringency and prices of solar and wind energy common to all countries in our sample by incorporating year fixed effects, the average tightening of market-based environmental policies between 1990 and 2010 can explain a 0.38 percentage point increase in the share of renewable electricity generation per year. To put this into perspective, 0.38 percentage points is equivalent to (i) 29 percent of the average model-implied increase in the share of renewable electricity in the last year of our sample, 2014, and (ii) 55 percent of the actual increase of 0.69 percentage points in our sample of 32 countries in that same year.

Model 2 unpacks the role of market-based policies by distinguishing between three types of market-based policy indices: feed-in tariffs, taxes, and trading schemes. The effects of feed-in tariffs and trading schemes are statistically and quantitatively significant. A one standard deviation tightening of these policies increases the share of renewable energy by 0.118 and 0.183 percentage points respectively per annum. For a better appreciation of the potency of feed-in tariffs, consider the case of Germany. Between 1997 and 2007 this European frontrunner in renewable electricity generation scored a 4 or higher on the OECD feed-in tariff variable. Based on Model 2 a country implementing such a policy for a decade would add 2.5 percent to its share of renewable electricity. The cumulative indirect effect of such a feed-in tariff—which works through the increasingly higher share level—would add another 7.5 percent over the same decade.

Model 3 digs further into the role of trading schemes by separating between three types of schemes: CO2 trading schemes, green certificates, and white certificates. Somewhat surprisingly, green certificates are the only type of trading scheme for which statistically significant evidence is found. A one standard deviation change in the green certificates variable, while controlling for all other policies, is found to increase the share of renewable electricity generation by 0.116 percentage points per year, which suggests that the significant evidence for trading schemes from Model 2 is mostly picking up the effect of the green certificates policy indicator. We attribute the lack of statistical evidence for an effect of CO2 trading schemes (e.g., the EU ETS) on renewable electricity generation to two (related) aspects: limited sample variation and the fact that these policies on average have been relatively weak compared to other instruments such as green certificates and feed-in tariffs.

Models 4, 5 and 6 extend Models 1, 2 and 3 respectively with additional controls. By and large, the coefficients on the environmental policy variables are not sensitive to the inclusion of these variables. This suggests that the regression coefficients on environmental policies in the parsimonious models 1-3 are not affected by omitted variables. Statistically significant evidence is found for the role of income (negative effect) and the share of nuclear power in electricity generation (negative effect). These findings are in line with the literature. Previous studies confirmed the negative role of income for OECD countries. Likewise, since nuclear power is a low-carbon technology, countries that are heavily dependent on nuclear energy for electricity generation will have an incentive to invest less in renewable energy.

In all models a statistically significant effect is found for the role of electricity market deregulation. This effect is also quantitatively relevant. The average de-regulation of electricity markets that took place in OECD countries between 1990 and 2010 has supported an annual increase of 0.38 percentage point of the share of renewable electricity generation. Stated otherwise, a one standard deviation increase in the degree of deregulation corresponds to a 0.223 percentage point increase in the share of renewable electricity generation per year.

Electricity Mix and Electricity Generation Per Capita

In part due to their relatively stringent package of environmental policies, several countries including Denmark, Germany and the United Kingdom have become renewable energy frontrunners, with their electricity share of wind, solar and biomass exceeding 30 percent in recent years. This begs the question of whether their policies have merely shifted the electricity mix, or whether they also have affected total electricity generation—for example by raising average electricity prices. To this end we turn to explaining the relationship between environmental policies and the electricity shares of coal and natural gas as well as total electricity generation per capita in Annex Table 3.2.2. As before our dependent variable measures the annual change.

By and large, the results in Annex Table 3.2.2 are in line with our hypotheses: while policy indicators such as feed-in tariffs and CO2 schemes have a positive relationship with the share of solar, wind and biomass in electricity generation, such policies do not appear to have had a discernible impact on total electricity generation. The analysis also shows that the relationship between the EPS variable and fossil fuel electricity shares are not statistically significant at conventional confidence levels, but the sign of the regression coefficients often points in the expected direction. For example, the EPS variables tend to have a negative association with the annual change of the coal share, and the effects on the share of natural gas are ambiguous, perhaps because natural gas plants and their ability to dispatch electricity quickly can complement intermittent renewable energies.

Annex Table 3.2.1. Main Results (1990–2014)

Dependent variable: Δ(electricity share of renewables)	(1)	(2)	(3)	(4)	(5)	(6)
Solar wind and biomass share MA_{t-1}	0.0852**	0.0791*	0.0826*	0.0808*	0.0741+	0.0799+
	(0.0304)	(0.0361)	(0.0365)	(0.0361)	(0.0410)	(0.0419)
Policy variables						
Market EPS	0.231*			0.249*		
	(0.0974)			(0.101)		
Non-market EPS	-0.124	-0.147	-0.146	-0.109	-0.140	-0.138
	(0.106)	(0.113)	(0.113)	(0.122)	(0.131)	(0.130)
Market EPS taxes		0.0842	0.0860		0.132	0.133
		(0.151)	(0.147)		(0.163)	(0.155)
Market EPS feed-in tariff		0.0621*	0.0625*		0.0658*	0.0666*
		(0.0287)	(0.0290)		(0.0305)	(0.0307)
Market EPS trading		0.166**			0.174**	
		(0.0543)			(0.0622)	
Market EPS trading green certificates			0.0918*			0.108**
			(0.0373)			(0.0322)
Market EPS trading CO_2			0.0392			0.0298
			(0.0360)			(0.0388)
Market EPS trading white certificates			0.0561			0.0491
			(0.102)			(0.101)
Log electricity PMR_{t-1}	-0.440**	-0.441**	-0.445**	-0.563**	-0.557**	-0.568**
	(0.159)	(0.149)	(0.141)	(0.197)	(0.184)	(0.174)
Controls						
Log GDP per $capita_{t-1}$	0.0607	0.0320	0.113	-0.951+	-0.996*	-0.898+
Short-term interest $rate_{t-1}$				0.000731	0.00247	0.00176
Log crude oil $price_{t-1}$				-0.511	-0.504	-0.542
Proven oil reserves per $capita_{t-1}$				-72.98+	-41.57	-47.24
Proven natural gas reserves per $capita_{t-1}$				847.8	719.7	890.8
Hydropower $share_{t-1}$				-0.00900	-0.0104	-0.0122
Nuclear $share_{t-1}$				-0.00909	-0.0105	-0.00976
Number of observations	652	652	652	558	558	558
Number of countries	32	32	32	28	28	28
R^2	0.28	0.28	0.28	0.28	0.28	0.28

Source: IMF staff calculations.

Note: Robust standard errors clustered at the country level in parentheses, not reported for controls. Variables are in logarithmic scale. Constant included, but not reported. EPS = Environmental policy stringency; MA = moving average; PMR = product market regulation.

*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

Annex Table 3.2.2. Electricity Mix (1990–2014)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variables:	Δ(electricity share of renewables)	Δ(electricity share of renewables)	Δ(electricity share of coal)	Δ(electricity share of coal)	Δ(electricity share of natural gas)	Δ(electricity share of natural gas)	Δ(electricity generation per capita)	Δ(electricity generation per capita)
Solar wind and biomass share MA_{t-1}	0.0826*	0.0799+						
	(0.0365)	(0.0419)						
Coal electricity share MA_{t-1}			-0.0930***	-0.0821**				
			(0.0225)	(0.0293)				
Natural gas electricity share MA_{t-1}					-0.0878***	-0.0972***		
					(0.0172)	(0.0233)		
Electricity generation per capita MA_{t-1}							-0.281+	-0.319+
							(0.164)	(0.166)
Policy variables								
Market EPS taxes	0.0860	0.133	-0.0885	-0.0771	-0.298	-0.237	0.0407	0.0358
	(0.147)	(0.155)	(0.194)	(0.260)	(0.226)	(0.284)	(0.107)	(0.105)
Market EPS feed-in tariff	0.0625*	0.0666*	-0.0574	-0.0532	0.106	0.130	-0.00233	-0.00160
	(0.0290)	(0.0307)	(0.0764)	(0.0821)	(0.0940)	(0.108)	(0.0139)	(0.0138)
Market EPS trading green certificates	0.0918*	0.108**	0.00752	-0.0500	0.00692	-0.0101	-0.00158	-0.00843
	(0.0373)	(0.0322)	(0.0915)	(0.0838)	(0.119)	(0.135)	(0.0233)	(0.0228)
Market EPS trading CO_2	0.0392	0.0298	-0.153	-0.0391	-0.0560	-0.0214	-0.0297	-0.0411
	(0.0360)	(0.0388)	(0.0989)	(0.0911)	(0.0684)	(0.0698)	(0.0237)	(0.0264)
Market EPS trading white certificates	0.0561	0.0491	0.238	0.233	-0.376	-0.414	-0.0586	-0.0607
	(0.102)	(0.101)	(0.221)	(0.226)	(0.274)	(0.328)	(0.0367)	(0.0430)
Non-market EPS	-0.146	-0.138	-0.330	-0.350	0.173	0.321	0.0335	0.0671
	(0.113)	(0.130)	(0.195)	(0.234)	(0.213)	(0.221)	(0.0672)	(0.0854)
Log electricity PMR_{t-1}	-0.445**	-0.568**	0.389	0.503	0.617	0.117	0.0188	0.0114
	(0.141)	(0.174)	(0.359)	(0.530)	(0.633)	(0.735)	(0.0974)	(0.122)
Controls								
Log GDP per $capita_{t-1}$	0.113	-0.898+	0.518	2.106	2.545*	-0.325	0.423*	0.687
Short-term interest $rate_{t-1}$		0.00176		0.106*		-0.0969*		-0.0228+
Log crude oil $price_{t-1}$		-0.542		1.388*		-0.162		0.140
Proven oil reserves per $capita_{t-1}$		-47.24		-17.14		-92.29		-100.2
Proven natural gas reserves per $capita_{t-1}$		890.8		-6299.6		5473.0		388.5
Hydropower $share_{t-1}$		-0.0122		0.198**		0.143*		
Nuclear $share_{t-1}$		-0.00976		0.00656		-0.0256		
Number of observations	652	558	652	558	652	558	652	558
Number of countries	32	28	32	28	32	28	32	28
R^2	0.28	0.28	0.10	0.17	0.20	0.25	0.10	0.11

Source: IMF staff calculations.
Note: Robust standard errors clustered at the country level in parentheses, not reported for controls. Constant included, but not reported. EPS = Environmental policy stringency; MA = moving average; PMR = product market regulation.
*** p<0.001, ** p<0.01, * p<0.05, + p<0.1

Annex 3.3. Employment Effects of Environmental and Green Supply Policies

A. Environmental Policies and Labor Demand at the Firm Level

Introduction

The impact of environmental policies on employment has become an important issue particularly in view of the growing call for a "green" recovery, amid widespread labor market stresses due to the pandemic. While there is relatively widespread support for the view that renewable energy and energy efficiency can be more job-intensive than fossil fuels,[9] there is more ambiguity about the impact of other environmental policies, for instance regarding the impact of carbon taxation.[10] For example, using sectoral data, Yamazaki (2017) finds that carbon taxation implemented in the British Columbia province of Canada led to a fall in employment in carbon-intensive and trade-intensive sectors, offset by an increase in employment in low-carbon service industries, yielding a small overall positive effect. Examining the same policy change but using household data, Yip (2018) comes to the opposite conclusion: carbon taxation resulted in a small increase in the unemployment rate, with the effects concentrated on low- and medium-skilled workers. Using a sample of EU countries Stock and Metcalf (2020) do not find evidence of significant negative employment effects in aggregate data; indeed, their results also suggest a modest positive impact. Relatively few papers appear to look at labor demand in micro data; one example is Kahn (1997) who examines the effect of particulate matter regulation in the United States and finds that employment growth was weaker in plants located in "non-attainment" areas (i.e., areas that did not meet the national air quality standard) in certain sectors. Similarly, Greenstone (2002) found that in a large sample of U.S. plants, carbon monoxide and ozone regulations had strong depressing effects on labor demand in non-attainment counties, especially among industries that emitted multiple pollutants (e.g., pulp and paper, and petroleum refining industries). Finally, Liu and others (2017) use plant-level data from China to show that firms impacted by more stringent waste-water regulations in the Jiangsu region of China reduced their labor demand quite significantly.

Estimation Methodology

The basic approach is to estimate an augmented labor demand equation, controlling for standard determinants in the literature (e.g., Van Reenen 1997), and introducing the EPS indicator, interacted with an indicator variable to capture the intensity of a firm's CO2 emissions. The estimating equation is

$$n_{i,t} = \sum_{k=1}^{T} a_k \, n_{i,t-k} + \boldsymbol{bX}_{i,j,t} + c_1[EPS_{j,t} \text{ x } d_C] + d_C + d_i + d_j + d_t + \varepsilon_{i,t}; \text{ where}$$

$$d_C = 1 \; if \; CO2 \; emissions = \text{"high"}, \; 0 \; otherwise$$

[9] See Wei, Patadia, and Kammen (2010) for evidence on the U.S., and Stavropoulos and Burger (2020) for an extensive review of the literature. IEA (2020a) looks at the global job-creation potential of a green investment push as part of an economic recovery plan in the wake of the pandemic.

[10] See Deschenes (2018) for a brief and useful summary of research on environmental regulation and employment.

All variables are expressed in logs, except the EPS indicator which enters in levels. Firm-level employment $n_{i,t}$ is regressed on its own lags, a vector of controls, and firm, country, and year fixed effects. The vector of controls $\boldsymbol{X}_{i,j,t}$ includes firm-level average annual employee wages; real capital stock (sum of building and machinery capital stock deflated by the building and machinery price indices from Penn World Tables); the rental rate of capital (proxied by the price of capital services, taken from Penn World Tables); and the output gap.[11] $EPS_{j,t}$ x d_C is the interaction of interest, where EPS refers to the value of the selected environmental policy indicator in country j and time t. This specification is referred to below as Specification 1.

In an alternative Specification 2, the CO2 emission intensity is proxied by the sector of the firm in order to expand coverage of the sample, given the relatively low count of firms reporting actual CO2 emissions. In the interaction term, the CO2 dummy is replaced with a sector dummy. Following Van Reenen (1997), the estimation methodology is panel GMM.

Data

The firm-level data are from the Worldscope database. From the original Worldscope sample of more than 30,000 firms, only firms reporting unbroken spells of data on employment, staff costs, and capital stock are selected. For the specification interacting EPS with the CO2 emissions indicator, an additional restriction for inclusion in the sample is imposed, namely that the firm must report at least 3 instances of CO2 emissions. For each firm, only the longest spell including all the required variables is selected.[12] The samples consist of 670 firms when the availability of CO2 emissions data is taken into account; and 5305 firms when using sectoral dummies

Annex Table 3.3.1. Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
Sample 1: Interaction with high/low CO_2				
Aggregate EPS	2.5	0.9	0.4	4.1
Market EPS	1.9	1.0	0.0	4.0
EPS: CO_2 tax	0.1	0.9	0.0	6.0
Non-market EPS	3.1	1.2	0.6	5.5
Log employees	9.6	1.5	2.8	13.4
Log capital stock	14.5	1.8	8.3	19.6
Log wage	3.9	0.8	-3.4	11.5
Log r	0.0	0.1	-0.8	0.6
Output gap	0.0	2.2	-15.4	8.9
Log CO_2 emissions	8.9	10.0	-1.3	12.3
Sample 2: Interaction with sector dummies				
Aggregate EPS	2.2	0.9	0.4	4.1
Market EPS	1.7	0.9	0.0	4.0
EPS: CO_2 tax	0.1	0.8	0.0	6.0
Non-market EPS	2.7	1.3	0.6	5.5
Log employees	7.8	1.9	0.0	13.4
Log capital stock	12.2	2.2	3.4	19.5
Log wage	3.2	1.2	-3.8	11.5
Log r	0.0	0.1	-0.8	0.6
Output gap	-0.2	2.0	-15.4	8.9

Source: IMF staff calculations.

Note: Estimation sample 1 includes 670 firms, from 30 countries over 2000–15. Sample 2 consists of 5,305 firms, covering 31 countries over 2000–15. Capital stock is calculated as sum of machinery and building stock (in thousand US dollars), deflated by corresponding capital goods price deflators from Penn World Tables. Wages are calculated as total staff costs (in thousand US dollars) divided by total employees. Rental rate *r* is log of the price of capital services at the country level, from Penn World Tables. CO_2 emissions are measured in thousand tons. EPS = environmental policy stringency.

[11] Assuming a standard CES production function, Van Reenen (1997) derives labor demand as a function of real output and real wage, or, substituting for real output with capital, as a function of nominal factor prices and the real capital stock. The specifications implemented here follow the latter approach. However, we note that the results are robust to substituting nominal wages with real wages (defined as the nominal wage deflated by the aggregate CPI price index). Note also that all firms in a country are assumed to have the same rental rate of capital which is a simplifying assumption. This is similar to Van Reenen (1997) who proxies the rental rate with year fixed effects for a panel of UK firms.

[12] Few firms report unbroken spells of CO2 emissions. To make use of the available information in the best possible manner, a firm is coded as high-emission if its emissions-to-employees ratio exceeds the median for the country-year in any year that it reports this data. Thus, this is a time-invariant property of the firm in this framework. On average, a high-emission intensity firm emits more than 10 times more CO2 than a

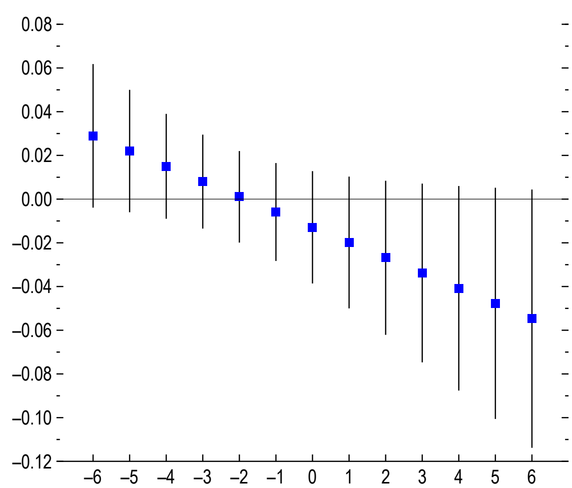
instead. The data span 31 countries over 2000-2015. Additionally, data on rental rate of capital is taken from Penn World Tables (using the price of capital services index as a proxy). The EPS variables are from OECD, measured as indices on a scale from 0 to 6. These include cross-country data for 32 OECD and emerging market countries between 1990-2015 for various policy indicators, including aggregate, market-based, and non-market-based policies, and sub-indices that further disaggregate these policies for instance into tax, trading, regulatory limits, subsidies, etc. Finally, controls for the output gap are from the IMF *WEO* database. Annex Table 3.3.1 presents summary statistics of the variables for the two samples used.

Results

Annex Table 3.3.2 shows the results of Specification 1. Column 1 shows the results of a standard labor demand equation, incorporating 2 lags of employment, and controlling for wages, rental rate of capital, and capital stock. The coefficient estimates of the standard determinants of labor demand are all highly statistically significant and have the expected sign with respect to factor prices, capital stock, as well as lags of employment. In column 2, the interaction term of aggregate EPS with the CO2 emissions dummy is included. The interaction is significant, indicating that high-emission firms experience negative employment effects in response to tightening EPS, whereas low-emission firms experience an increase in employment (although the effect is not significant for low-emission firms). The estimated semi-elasticities suggest that a 1-standard deviation tightening in the EPS indicator would lower employment in high-carbon firms by 5 percent, but raise employment in low-carbon firms by 2.6 percent. Column 3 shows the results for market EPS. The coefficients again suggest that employment would decline in high emission-intensity firms and increase in low emission-intensity ones. The results are qualitatively similar for carbon taxation (though again not significant; column 4). In the case of non-market EPS (column 5), the

Annex Figure 3.3.1. Impact of Market EPS on Employment Conditional on Output Gap

(Effects on fitted values on y-axis, output gap percent of potential on x-axis)



Sources: Worldscope database; and IMF staff calculations.
Note: Figure shows point estimates and 95 percent confidence intervals. EPS = environmental policy stringency.

low-emission firm. The relatively sparse reporting on CO2 emissions raises questions about selection issues if reporting emissions is an endogenous choice by firms. It is possible that high-emission firms do not report CO2 emissions to avoid market consequences, for instance. Looking across sectors, however, a higher proportion of firms in high-emission sectors—fossil fuel industries (26%), transport industries (24%), and utilities (34%)—report at least one year of CO2 emissions relative to the average rate of at least one CO2 emission report across all firms in all the sectors (21%). The exception is high-emission manufacturing (15%). This pattern is also observed when considering firms that report at least 3 instances of CO2 emissions (a condition imposed to be included in the regression sample). Across countries, the share of firms reporting at least on year of CO2 emissions in China, India and Indonesia is relatively much lower than in other OECD countries (3%, 4%, and 5% respectively of sample firms compared to the sample average of 32%). However, the frequency of "high-emission" firms from these countries (among the firms that do report emissions), is very similar to the sample average. These factors would suggest that a selection bias is unlikely to be present in this case.

coefficients on both non-market EPS and its interaction with the emission intensity indicator are significant, suggesting that a 1-standard deviation tightening in the non-market EPS would lower employment in high-emission firms by 5 percent, and raise it in low-emission firms by 4.4 percent. [13]

To examine the sensitivity of the employment-EPS relationship to cyclical conditions, in columns 6 through 9, we also include an interaction of the output gap with the EPS indicator. The output gap term has the expected sign, though it is only significant in the regression considering market EPS. Column 7 also shows that the market EPS indicator can have a positive employment effect when the output gap is negative. Indeed, the average marginal effects of market EPS on employment are modestly positive under severe contractionary conditions, and turn negative during normal/expansionary periods (see also Annex Figure 3.3.1)**.** An explanation for this pattern may lie in the inflationary impact of tighter EPS, which under severe contractionary conditions may help to lower the real rate of interest (for instance if policy rates are at the zero-lower bound), thus stimulating demand.[14]

Turning to Specification 2, Annex Table 3.3.3 provides additional detail on the sectoral classification and sample characteristics. This specification helps to increase the sample size substantially. There are more firms in the sample from among low-emission industries, services, and high-emission industries, and fewer firms from the other sectors, with the utilities sector having the fewest. However, it does not appear that there are too few firms in any one sector.

Annex Table 3.3.4 shows results from replacing the CO2 dummy with sector dummies to proxy for emission intensity. The interactions span the entire sample of firms included in the regressions. Six sectors are included in the baseline: fossil fuel industries, high-emission manufacturing industries (food, metals and minerals, chemicals, paper and packaging)[15], services, construction, transport, and other (low-emission) manufacturing industries.

Column 2 shows the results for aggregate EPS. Each of the interactions has the expected sign (individually significant in the case of construction industries), and the set of interactions are jointly significant. The construction sector here includes not only residential but also commercial and industrial construction. The sector uses high-emission inputs such as cement, and thus the negative effect from tighter EPS may reflect both the impact on the cost of high-emission inputs, and a negative effect due to lower activity in high-emission sectors. For market EPS (column 3), the positive impact on services is also statistically significant at the 10 percent level. However, the sign on fossil fuel industries is positive.[16] In the case of non-market EPS, the

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[13] These results are robust to setting the high/low emission intensity threshold at a different level, for example at the 75th percentile of the distribution within a country-year, in place of the median. The results are also broadly robust to excluding all firms with fiscal year ending before December of the given year in terms of the sign of the coefficients, but they lose statistical significance as the sample size is significantly reduced. Results available upon request.

[14] Evidence for expansionary effects of negative supply shocks that are otherwise thought to be output-reducing can be found in Eggertsson (2012). For evidence that disputes such negative effects, see Garin and others (2019), and Weiland (2019).

[15] These are among the most emission-intensive industries in Europe for example (see "Sectoral Policies for Climate Change Mitigation in the EU", IMF 2020c. Oil refineries which are also a high-emission industry are included among fossil fuel industries.

[16] The aggregate market EPS reflects the combined effect of different types of market-based policies. Examining the sub-components of market EPS reveals that the interaction with fossil fuels is negative in the case of tax policies, but positive in the case of trading schemes. This likely reflects that trading policies allow firms to maintain output (and employment) by being able to buy pollution permits, whereas increased

pattern is similar to that of market EPS, except that the interaction with the fossil fuel sector is negative (column 5).

In columns 6 and 7, the output gap is included as an additional regressor, to capture country-specific macroeconomic conditions. The sign on the output gap is positive and significant, as expected. Upon introducing this control, the coefficient on high-emission manufacturing industries also becomes significant (and remains negative).[17]

These specifications exclude the fossil fuel utilities sector, although it is likely to be significantly impacted by EPS, given the very small number of fossil fuel utilities in the sample. However, a broader utility category is included in a robustness exercise that includes not just fossil fuel utilities, but also multiline utilities whose activities include electricity generation, and also distribution. These regressions are shown in the columns 9 and 10. The sign on the utilities coefficient is negative, as expected, and the interactions remain jointly significant at the 10 percent level.[18]

Based on the preferred specifications that include controls for the output gap, we can also infer the net impact on total employment in the sample. Based on the estimates in columns 6 and column 9, there is a net loss of between 500-600 thousand jobs (about 1 percent of the total employment in the sample) in the case of aggregate EPS tightening by 1 standard deviation. In contrast, tightening market EPS by 1 standard deviation results in a small net job increase between 13-34 thousand jobs, based on the estimates in columns 7 and 10 (Annex Figure 3.3.2).

Finally, we implement a set of regressions to examine the medium-term effects of EPS, embedding an estimating equation similar to the specifications above, except that they exclude interactions with CO2 emissions.[19] Thus, we are looking at the average effect over time across all firms from a given change in EPS. Over the medium-term, the short-term effects of aggregate EPS, market EPS, and non-market EPS tend to reverse and fade away (Annex Figure 3.3.3).

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stringency of tax policies may cause firms to reduce output including by outsourcing polluting activities, or shifting the location of pollutive activities production to jurisdictions with weaker enforcement (see Ben-David and others, 2020, for evidence of multinational firms shifting emissions to other locations). Even for the high-emission industries sector, for instance, although the effect of more stringent trading policies is negative, the effect is insignificant and much smaller than the effect of more stringent tax policy.

[17] The t-statistic rises from 1.2 in the regression excluding the output gap (Column 1), to 1.9.

[18] The results are also broadly robust to excluding all firms with fiscal year ending before December of the year. Results available upon request.

[19] Results available upon request.

Annex Table 3.3.2. Regression Results (Specification 1)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
EPS Indicator:		Agg EPS	Mkt EPS	CO_2 Tax	Non-Mkt	Agg EPS	Mkt EPS	CO2 Tax	Non-Mkt
Dependent variable:	Log N	Log N	Log N	Log N	Log N	Log N	Log N	Log N	Log N
Log N_{t-1}	0.573***	0.560***	0.566***	0.565***	0.555***	0.556***	0.561***	0.562***	0.552***
Log N_{t-2}	-0.142***	-0.144***	-0.144***	-0.143***	-0.144***	-0.141***	-0.142***	-0.141***	-0.140***
Log capital stock	0.276**	0.266**	0.268**	0.275**	0.263**	0.266**	0.272**	0.273**	0.262**
Log wages	-0.260**	-0.252**	-0.252**	-0.254**	-0.238*	-0.256**	-0.255**	-0.259**	-0.256**
Log r	0.308**	0.292***	0.301**	0.308**	0.300***	0.256**	0.275**	0.284**	0.247**
EPS		0.0270	0.0224	0.0408	0.0355*	0.0243	0.0194	0.0364	0.0282
EPS x (High CO_2 = 1)		-0.0785*	-0.0561	-0.0948	-0.0760**	-0.0799*	-0.0560	-0.0981	-0.0773**
Output gap						0.0151	0.0147**	0.00367	0.0128
Output gap x EPS						-0.00489	-0.00697**	-0.00995	-0.00286
Observations	6,899	5,991	5,991	5,991	5,991	5,991	5,991	5,992	5,993
Number of firms	773	670	670	670	670	670	670	671	672

Source: IMF staff calculations.

Note: "EPS" in the list of explanatory variables refers to Aggregate EPS in column 2 and 6; Market EPS in column 3 and 7; Carbon taxes in column 4 and 8; and Non-market EPS in column 5 and 9. All regressions include panel and year fixed effects. In columns 2-9, wages, capital, and rental rate are GMM-instrumented with lags. The Hansen J-test cannot reject instrument validity at 1% in column 1, at 10% in columns 2-9. EPS = environmental policy stringency; N = employment.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Annex Table 3.3.3. Descriptive Statistics of Firms by Sector

	Labor			Capital stock			Number of firms
Sector	Median	LQR	UQR	Median	LQR	UQR	
Fossil fuel industries	2,740	763	12,032	544	76	3,369	122
High emission industries	2,299	974	5,907	272	102	848	779
Other industries	2,193	976	5,570	131	50	330	1,160
Services	1,972	811	5,368	98	32	306	955
Construction	2,040	808	6,453	75	38	341	124
Transport	4,500	1,541	12,299	292	77	945	147
Utilities	6,111	1,442	10,944	2,444	1,334	6,072	47

Source: IMF staff calculations.

Note: Labor and capital stock figures are for 2015. Labor is measured in total number of employees, and real capital stock in million US dollars, calculated as deflated sum of building and machinery stock, using appropriate price deflators from Penn World Tables. Sector details: (a) Fossil fuel industries include coal, and oil and gas production, and equipment and services; (b) High emission manufacturing includes metals and mining (excluding fossil fuel mining), construction materials, paper and forest products, containers and packaging, and food and beverages; (c) Other industries include manufacturing industries not in (b); (d) Services include industrial, commercial (professional and business support), consumer services, finance, insurance, real-estate, healthcare, and technology; (e) Construction includes residential, commercial, and industrial/engineering construction; (f) Transport includes freight and passenger transport by land, sea, and air; and (g) Utilities includes fossil-fuel based and multiline utilities. LQR = lower quartile; UQR = upper quartile.

Annex Table 3.3.4. Regression Results (Specification 2)

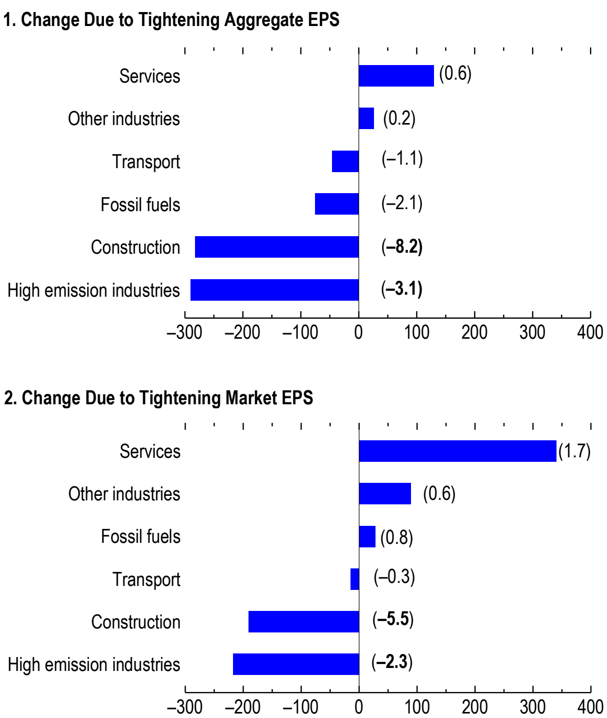
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
EPS Indicator:		Agg EPS	Mkt EPS	CO2 Tax	Non-Mkt EPS	Agg EPS	Mkt EPS	Non-Mkt EPS	Agg EPS	Mkt EPS
Dependent variable:	Log N	Log N	Log N	Log N	Log N	Log N	Log N	Log N	Log N	Log N
Log N_{t-1}	0.543***	0.555***	0.550***	0.541***	0.551***	0.554***	0.545***	0.549***	0.554***	0.546***
Log N_{t-2}	0.0189	0.0148	0.0157	0.0171	0.0154	0.0157	0.0172	0.0170	0.0172	0.0184
Log capital stock	0.186***	0.189***	0.190***	0.203***	0.191***	0.178***	0.178***	0.179***	0.171***	0.171***
Log wages	-0.218***	-0.218***	-0.216***	-0.226***	-0.218***	-0.215***	-0.214***	-0.218***	-0.214***	-0.213***
Log r	0.241***	0.234***	0.234***	0.242***	0.224***	0.150***	0.148***	0.134***	0.141***	0.139***
Output gap						0.00806***	0.00920***	0.00838***	0.00857***	0.00967***
Fossil fuels X EPS		-0.0181	0.00821	-0.723	-0.0345	-0.0234	0.00980	-0.0380	-0.0243	0.0104
High CO_2 industries X EPS		-0.0228	-0.0257	-0.00432	-0.0212	-0.0346*	-0.0295*	-0.0293**	-0.0361*	-0.0292*
Other industries X EPS		0.0155	0.0131	-0.00534	0.00565	0.00189	0.00726	-0.00436	0.000557	0.00673
Services X EPS		0.0174	0.0225*	-0.00792	0.00517	0.00697	0.0208	-0.00344	0.00545	0.0201
Construction X EPS		-0.0836***	-0.0693**	-0.140	-0.0717***	-0.0906***	-0.0695**	-0.0766***	-0.0919***	-0.0706**
Transport X EPS		-0.00319	-0.00696	-0.0188	-0.00631	-0.0118	-0.00417	-0.0148	-0.0115	-0.000983
Utilities X EPS									-0.0226	-0.0266
Joint significant (p-value)		0.05	0.06	0.65	0.05	0.05	0.07	0.03	0.07	0.10
Observations	28,122	25,631	25,631	25,637	25,637	25,631	25,631	25,631	26,072	26,072
Number of firms	5,579	5,305	5,305	5,305	5,305	5,305	5,305	5,305	5,384	5,384

Source: IMF staff calculations.

Note: "EPS" in the list of explanatory variables refers to Aggregate EPS in column 2; Market EPS in column 3; Carbon taxes in column 4; and Non-market EPS in column 5 and 8; Aggregate EPS in column 6 and 9; and Market EPS in column 7 and 10. All regressions include panel and year fixed effects. Wages, capital, and rental rate are GMM-instrumented with lags. EPS = environmental policy stringency; N = employment.

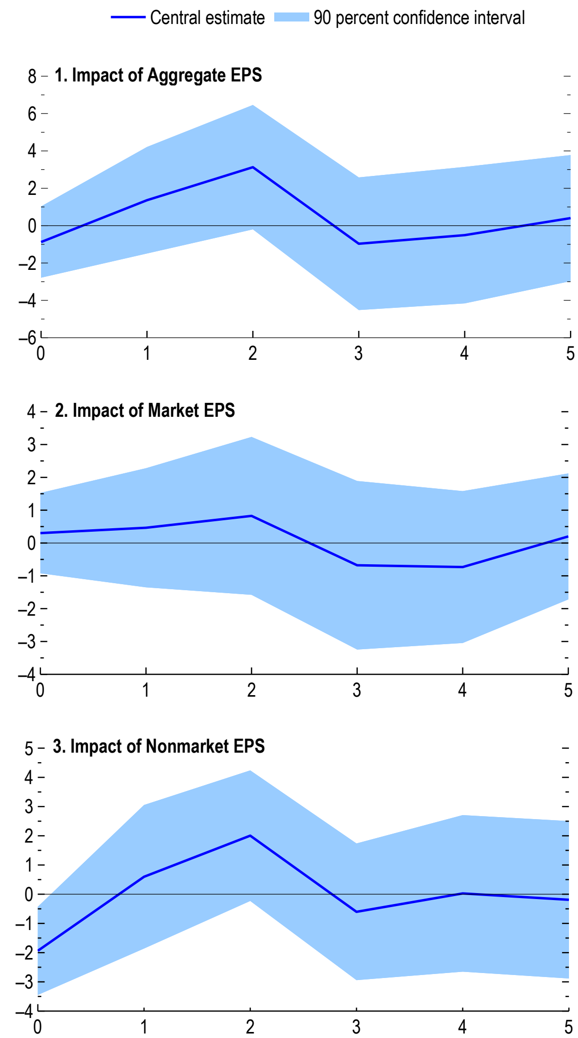
*** p<0.01, ** p<0.05, * p<0.1.

Annex Figure 3.3.2. Job Reallocation Effects of Tightening EPS
(Change in employees, thousands)



Sources: Penn World Tables; Worldscope database; and IMF staff calculations.
Note: Bars show change in employment in thousands, and the figures in parentheses are semi-elasticities computed from the interaction between the sector dummy and the EPS indicator, for a one standard deviation tightening of the EPS indicator. For both Aggregate EPS and Market EPS, the interactions are jointly significant at 10 percent (bold numbers in parentheses are semi-elasticities significant at conventional levels). EPS = environmental policy stringency.

Annex Figure 3.3.3. Medium Term Effects of EPS on Jobs
(Percent change; years on x-axis)



Sources: Penn World Tables; Worldscope database; and IMF staff calculations.
Note: Each panel shows the estimated percent change in employment with respect to a unit change in the EPS indicator, and the 90 percent confidence interval, over a five-year horizon. The estimation sample includes 2,148 firms that have at least 10 continuous years of data. The estimation is via local projection using a GMM estimator. The regression includes the level of the EPS variable, and (logs of) two lags of employment, capital stock, factor prices; as well as firm, country, and year fixed effects. EPS = environmental policy stringency.

Conclusions

Based on this exercise, we are able to conclude that at least in the short term, tightening of environmental policies is associated with a reallocation of jobs, with employment rising in low-CO2 emissions firms, and falling in high-CO2 emissions firms. When emissions are proxied by the sector of the firm, the effects suggest a reallocation of labor from high carbon-intensive sectors to low carbon-intensive ones in general. While the evidence generally supports reallocation effects, the overall impact remains somewhat uncertain as it depends on the particular set of policies. Past policy changes suggest that short-term effects are negative with respect to overall EPS, likely driven by negative effects of non-market policies. However, to the extent that future policy changes will rely more on market-based policies, the overall effects may be positive going by these findings. In the case of the carbon taxation, however, it is unclear from the wider literature what the overall effects would be. Regardless, the short-term effects whether net positive or net negative appear to be quite modest. Moreover, the effects tend to fade away over the medium term. Finally, the evidence also suggests that the impact of tightening market-based policies depends on the state of the business cycle. Under highly contractionary conditions, the impact may be positive (other things equal), whereas as under more normal or expansionary periods, the effect is negative.

Annex 3.4. G-Cubed Simulations

The model used for this project follows the approach in the G-Cubed model (McKibbin and Wilcoxen 1999, 2013). A number of changes were implemented specifically for this project compared to the most recent published model in Liu et al (2020). The key changes to the model for this project are:

- The database was significantly updated to include data from GTAP10 and the latest data from the IMF, the World Bank, OECD, UN, and US Energy Information Administration.
- The gas extraction and gas utilities sectors were merged into one gas sector.
- A new sector for construction was added to the model.
- A capacity for implementing government infrastructure investment following Calderon and others (2015) was implemented. Green infrastructure projects were incorporated.

A. Regions and Sectors

There are 10 regions and 20 sectors in the version of the model (version GGG20v154) used in this report.

Annex Table 3.4.1. Regions in the G-Cubed Model

Region code	Region description
AUS	Australia
CHN	China
EUW	Europe
IND	India
JPN	Japan
OPC	Oil-Exporting developing countries
OEC	Rest of the OECD
ROW	Rest of the World
RUS	Russian Federation
USA	United States

The coverage of each region in the above table is presented below:

- Europe: Germany, France, Italy, Spain, Netherlands, Belgium, Bulgaria, Croatia, Czech Republic, Estonia, Cyprus, Lithuania, Latvia, Hungary, Malta, Poland, Romania, Slovenia, Slovakia, Luxemburg, Ireland, Greece, Austria, Portugal, Finland, United Kingdom, Norway, Sweden, Switzerland, Denmark
- Rest of Advanced Economies: Canada, New Zealand, Iceland, Liechtenstein
- Oil-Exporting and the Middle East: Ecuador, Nigeria, Angola, Congo, Iran, Venezuela, Algeria, Libya, Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen

- Rest of World: All countries not included in other groups.

The sectors in the model are set out in table 3.4.2.

Annex Table 3.4.2. Sectors in the G-Cubed Model

Number	Sector name	Notes
1	Electricity delivery	Energy sectors other than generation
2	Gas extraction and utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Construction	Goods and services
7	Other mining	
8	Agriculture and forestry	
9	Durable goods	
10	Nondurable goods	
11	Transportation	
12	Services	
13	Coal generation	Electricity generation sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

The G-Cubed sectors 1-12 are aggregated from 65 sectors of GTAP 10. We then further disaggregate the electricity sector into the electricity delivery sector (sector 1) and 8 electricity generation sectors (sectors 13-20).

B. Model Structures and Features

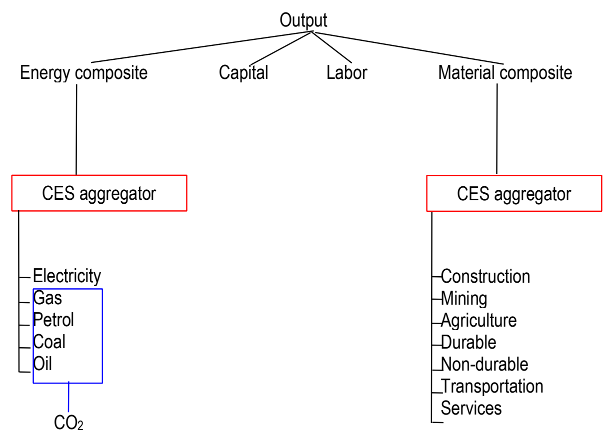
The structure in the model is set out in McKibbin and Wilcoxen (2009, 2013). An illustration of the production structure is contained in Figure 3.4.1. CO2 emissions are measured through the burning of fossil fuels in energy generation.

Several key features of the standard G-Cubed model are worth highlighting here.

- The model completely accounts for stocks and flows of physical and financial assets. For example, budget deficits accumulate into government debt, and current account deficits accumulate into foreign debt. The model imposes an intertemporal budget constraint on all households, firms, government, and countries. Thus, a long-run stock equilibrium obtains through the adjustment of asset prices, such as the interest rate for government fiscal positions or real exchange rates for the balance of payments. However, the adjustment towards the long-run equilibrium of each economy can be slow, occurring over much of a century.

- Agents in G-Cubed must use money issued by central banks for all transactions. Thus, central banks in the model set short term nominal interest rates to target macroeconomic outcomes (such as inflation, unemployment, exchange rates, etc.) based on Henderson-McKibbin-Taylor monetary rules. These rules approximate actual monetary regimes in each country or region in the model. These monetary rules tie down the long-run inflation rates in each country as well as allowing short term adjustment of policy to smooth fluctuations in the real economy.

Annex Figure 3.4.1. Production Structure in the G-Cubed Model



Source: McKibbin and Wilcoxen (1999, 2013).

- Nominal wages are sticky and adjust over time based on country-specific labor contracting assumptions. Firms hire labor in each sector up to the point that the marginal product of labor equals the real wage defined in terms of the output price level of that sector. Any excess labor enters the unemployed pool of workers. Unemployment or the presence of excess demand for labor causes the nominal wage to adjust to clear the labor market in the long run. In the short-run unemployment can arise due to structural supply shocks or changes in aggregate demand in the economy.

- Rigidities prevent the economy from moving quickly from one equilibrium to another. These rigidities include nominal stickiness caused by wage rigidities, lack of complete foresight in the formation of expectations, cost of adjustment in investment by firms with physical capital being sector-specific in the short run, monetary and fiscal authorities following particular monetary and fiscal rules. Short term adjustment to economic shocks can be very different from the long-run equilibrium outcomes. The focus on short-run rigidities is important for assessing the impact over the initial decades of demographic change.

- The model incorporates heterogeneous households and firms. Firms are modelled separately within each sector. There is a mixture of two types of consumers and two types of firms within each sector, within each country: one group bases their decisions on forward-looking expectations and the other group follows simpler rules of thumb which are optimal in the long run, but not necessarily in the short run.

- The fiscal rule in the model varies across model versions. In the version of the model in this report we assumed an exogeneous budget deficit (it changes according to the revenue generated by carbon taxes or lost through various subsidies or changes in infrastructure spending) with lump sum taxes on households adjusted to ensure fiscal sustainability. In the long run the changes in interest servicing costs from any changes in revenue or expenditure that is exogenously imposed is offset through a lump sum tax on households. Thus, the level of government debt can permanently change in the long run with the change in the debt-to-GDP ratio equal to the ratio of the long run fiscal deficit to the long run real growth rate of the economy.

C. Baseline Inputs and Assumptions

The key inputs into the baseline are the initial dynamics from 2018 to 2019 and subsequent projections from 2019 onwards for sectoral productivity growth rates by sector and by country. Sectoral productivity growth is driven by labor force growth and labor productivity growth.

- Labor force: We use the working-age population projections from the UN Population Prospects 2019 to calculate our economy-wide labor growth rates.

- Labor productivity: We use a catch-up model to generate labor productivity growth rates (labor-augmenting technological progress). The sectoral productivity projections follow the Barro approach estimating that the average catchup rate of individual countries to the worldwide productivity frontier is 2% per year. We use the Groningen Growth and Development database to estimate the initial productivity level in each sector of each region in the model, and then take the ratio of the initial productivity to the equivalent sector in the US (the frontier). Given this initial gap, we use the Barro catchup model to generate long-term projections of the productivity growth rate of each sector within each country. Where we expect that regions will catch up more quickly to the frontier due to economic reforms or more slowly to the frontier due to institutional rigidities, we vary the catchup rate over time. The calibration of the catchup rate attempts to replicate recent growth experiences of each country and region in the model.

D. Scenarios

Carbon tax

Net Zero Emissions in 2050

In the G-Cubed model, there are fossil fuels and renewable sectors, but no carbon removal technologies. To achieve net zero emissions by 2050 in the real world, carbon removal technologies also play an important role. IPCC (2018b) provides a review on carbon removal technologies, of which one main reference is Fuss (2018).

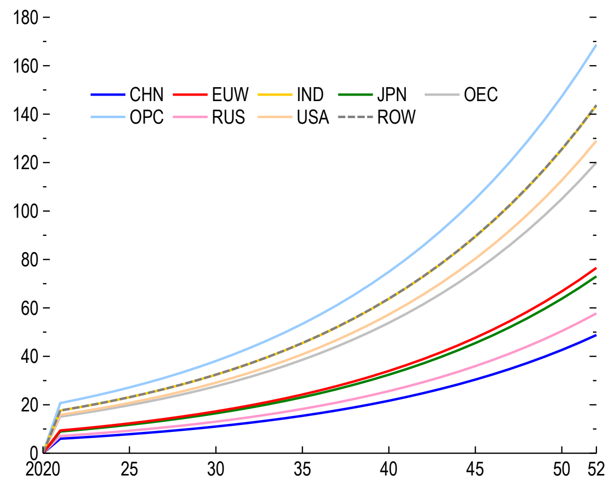
We draw on the estimates of carbon removal potentials from Fuss (2018). The estimates of global carbon removal technologies by 2050 by Fuss (2018) are as follows:

Annex Table 3.4.3. Global Carbon Removal Potentials in 2050
(Gigaton CO_2)

Carbon removal technologies	Potentials
Afforestation and reforestation	0.5–3.6
BECCS	0.5–5
Biochar	0.5–2
Enhanced weathering	2–4
DACCS	0.5–5
Soil carbon sequestration	Up to 5

We take the average of the range for each technology and sum them up (13.8Gt CO2). We make a conservative assumption that about 75% of 13.8 Gt can be achieved by 2050, i.e., about 10Gt CO2 per year. This is about 20% of global CO2 emissions in the baseline in 2050. We assume that all regions in our model reduce their emissions by 80% by 2050 relative to 2018 except OPC remains at the same level of 2018 by 2050.

Annex Figure 3.4.2. Carbon Tax
(US dollars per ton of CO_2, deviation from baseline)



Source: IMF staff calculations.
Note: Data labels use International Organization for Standardization (ISO) country codes. EUW = European Union, Norway, Switzerland, United Kingdom; OEC = Australia, Canada, Iceland, Liechtenstein, and New Zealand; OPC = oil-exporting countries and the Middle East; ROW = rest of the world.

In the main results, we assume a constant growth rate of 7 percent for carbon taxes over the period of 2019-2050, and then solve the tax rates to achieve the emissions targets by 2050 in the policy package—after accounting for emissions reductions from other layers of the policy package (Figure 3.4.2). For comparison, we also use a growth rate of 5 percent for carbon taxes and solve the tax rates to achieve the same targets by 2050.

Green Public Investment

We base our analysis on the results from Calderon, Moral-Benito and Serven (2015) who find that for every 10 percent increase in the aggregate stock of infrastructure capital, productivity in private sector output rises by 0.8%. We assume this new infrastructure once in place is sustained by spending by the government of 0.2% of GDP to offset depreciation. This locks in the productivity gains of the sectors that benefit from the green infrastructure. Rather than applying the improvement in productivity uniformly across all sectors in the economy, we assume that some sectors gain a productivity boost relative to others because of the strategic allocation of the infrastructure spending. We allocate the gains in productivity to these individual sectors. Once we assume which sectors receive the productivity boost, we scale the size of the productivity boost to those sectors in such a way that the aggregate productivity gains for the economy as a whole correspond to the results of Calderon and others (2015). For example, suppose the infrastructure is focused mainly on the renewable energy sectors, then the productivity gains would be scaled up in these sectors so that when the shocks are weighted by the share of each sector in the economy, the aggregate productivity shocks match Calderon and others (2015). This implies that a small sector will have a very large productivity gain if all infrastructure is allocated to that sector. Because of capital adjustment costs, which are sector specific in the model, the economy-wide output gains will be lower than if the productivity was allocated across all sectors because rapid productivity growth increases the cost of accumulation private capital in the sector growing quickly.

Green Subsidy

We subsidize solar and wind output at a rate of 80% for all regions since 2019.

Avoided Damages from Climate Change

We introduce economy-wide productivity improvements driven by avoided damages from climate change due to all other policies in the package, and impose the productivity improvements equally on all sectors except electricity generation. The economy-wide improvements reflecting avoided damages from climate change are calculated using the extension of the Hassler and other (2020) integrated assessment model performed for this chapter (see Annex 3.5).

Carbon Tax Revenue Transfer 25%

We transfer 25% of carbon tax revenues to households as compensatory transfers to offset their loss of purchasing power from the carbon tax. The fraction of revenues needed for compensation was set at 25% based on the analysis in the section How to build inclusion (and Annex 3.7).

Aggregate Policy Package

This is the policy package including carbon taxes, green investment, green subsidy, avoided damages, and the carbon tax revenue transfer.

Aggregate Policy Package for Top 5 Emitters

This scenario assumes that only the top 5 emitters (USA, EUW, CHN, IND, ROW) participate in the policy package. For comparison with the aggregate scenario, we do not re-solve carbon taxes to achieve 80% reduction in the scenario, but directly use all shocks for the five regions from the aggregate scenario.

Aggregate Policy Package for Advanced Economies Only

This scenario assumes that only advanced economies (USA, EUW, JPN, AUS, OEC) participate in the policy package. Similarly, we do not re-solve carbon taxes in the scenario.

Timing

Given that 2018 is the last year of observed data, the policy shocks are applied from 2019 onward. For presentational purposes, the simulation is presented as starting in 2021. This should not affect much the starting level of CO2 emissions, as CO2 emissions grew in 2019 but declined in 2020 due to the pandemic.

Annex 3.5. Climate Change Mitigation and the Direction of Technical Change

This annex outlines the model used to analyze the interaction between climate change mitigation policies and the direction (that is, the greenness) of technical change. This interaction is potentially important for two reasons. First, because the response of technological change to policy alters the effectiveness of mitigation policies, not only in the present but–because the direction of technical progress in the present affects the set of available technologies in future–also in future periods. Second, this channel expands the set of policies which can be analyzed, admitting a role for subsidies to research and development.

The model used here allows for the scale and direction of technical change to respond endogenously to policies, extending the model of Hassler and others (2020) in three important dimensions: adding a more general form of research and development (R&D) which allows for more flexible returns to scale; including non-unit price elasticity in final energy demand; and extending the range of fuel sources available to match IEA data. The resulting model framework is a useful laboratory for policy experiments, as it is rich enough to allow an analysis of the role of how the direction of technical change responds endogenously to policy but is tractable enough for the resulting outcomes to be comprehensible.

Conceptual Framework

We use a global integrated assessment model (IAM) in the spirit of Hassler and others (2020) (which itself follows in the tradition of earlier IAMS, such as Nordhaus 2010, and Golosov and others 2014). The global economy is modelled as several distinct regions, each producing a single energy good used as an input to aggregate domestic production. The energy good is made by combining fuels with a constant elasticity of substitution production technology. Fuel usage produces CO2 emissions, with different carbon intensities (the quantity of CO2 produced per unit of energy) for fuel in each region. Emissions in each region are therefore a function of both the total amount of energy used and its composition (green versus dirty). The sum of emissions across regions drives global temperatures via a climate model, which in turn reduces regional productivities, causing a climate externality.

Governments have two policy tools available to them to mitigate this climate externality: a tax on carbon, and a subsidy for research and development. Energy-producing firms conduct fuel-specific research and development (R&D), which lowers the input cost or the carbon intensity of fuel usage (or both). Firms therefore increase their R&D spending on a given fuel when the market for that fuel expands. Thus, policies which increase the market for a given fuel technology (say, renewable energy), spur further R&D in that technology, reducing costs and further amplifying the effect of the policy. There is also an inter-temporal spillover, as the cost of production is a function of research conducted in the past, as well as in the present. By stimulating research in the present, policies which lower the current cost of clean energy thus make clean energy more affordable in future.

The Energy Sector

Energy is produced by a CES technology using N fuels. Imported conventional oil is always indexed first. Energy production in region j in time t is therefore given by:

$$E_{jt} = \left(\sum_{i=1}^{N} \lambda_{i,j} e_{ijt}^{\rho}\right)^{1/\rho} \qquad (3.5.1)$$

where: g_{ijt} is usage of fuel *i* in region *j*; $\lambda_{i,j}$ is the production weight of fuel *i* in country *j*; and $\frac{1}{1-\rho}$ is the intra-fuel elasticity of substitution, common across all regions.

In each region, there is a fuel-specific technology for producing each fuel. At the start of each period *t* this technology is common knowledge.[20] The level of this technology is denoted $\bar{x}_{ijt}$, which represents the number of units of final good that are spent to produce one unit of input *i*. Firms can improve the technology they use via research, increasing this productivity to x_{ijt} at a cost:

$$r_i^x(x_{ijt}/\bar{x}_{ijt}) = \frac{\epsilon_{ij}(1-\chi_{ijt})}{\eta-1}\left(\frac{x_{ijt}}{\bar{x}_{ijt}}\right)^{\eta-1}$$

where ϵ_{ij} is a region-specific cost parameter, and χ_{ijt} is the subsidy to R&D in fuel *i*. Crucially, $\eta > 1$, implying that this cost function is convex, and $\frac{1}{\eta-1}$ is the returns to scale in R&D. So as η declines, the returns to scale in R&D improve.

Technology similarly governs the carbon intensity of production, i.e. the amount of carbon dioxide produced per unit of energy. This is also common knowledge at the start of the period, denoted $\bar{g}_{ijt}$ and also improvable (i.e., reducing carbon intensity) via research, at cost:

$$r_i^g(g_{ijt}/\bar{g}s_{ijt}) = \frac{\theta_i j(1-\chi_{ijt})}{\eta-1}\left(\frac{g_{ijt}}{\bar{g}_{ijt}}\right)^{1-\eta}$$

where θ_{ij} is also a region-specific parameter. Endogenous technical change therefore takes two forms: input-saving, and emissions-reducing. For simplicity we assume that the returns to scale and government subsidies across the two types are the same.

Letting $p_{ijt} = \frac{1}{x_{ijt}}$, the cost of production net of research is then:

$$c(e_1, \dots e_N, p_1, \dots p_N, g_1, \dots g_N) = \sum_{i=1}^{N}(\tau_{jt} g_{ijt} + p_{ijt}) e_{ijt} + \frac{\epsilon_i(1-\chi_{ijt})}{\eta-1}\left(\frac{p_{ijt}}{\bar{p}_{ijt}}\right)^{\eta-1} + \frac{\theta_i(1-\chi_{ijt})}{\eta-1}\left(\frac{g_{ijt}}{\bar{g}_{ijt}}\right)^{1-\eta}$$

where τ_{jt} is the carbon tax for country *j* in period *t*.

[20] Fried (2018) shows that within-sector energy technology spillovers often occur within five years. As we later calibrate the model using a ten-year time period, assuming that the previous decade's worth of innovations are freely available to all firms is not unreasonable.

The cost of production defined above produces a downward-sloping average cost curve, meaning that energy production is a natural monopoly. This arises because research is a fixed cost; with increased sales, this cost is defrayed over more units, creating a cost advantage for larger firms and eventually resulting in a monopoly. For simplicity, we assume that energy supply is regulated so that the monopoly energy supplier makes zero profits. This can be implemented by a price cap such that the energy price equals the average cost. This is a not unreasonable assumption given frequent regulation of real-world energy markets. It is also a standard method for determining equilibrium a monopoly, and one which delivers the (static) socially optimal outcome without subsidies to energy production.[21]

This setting differs from the Hassler and others (2020) approach in two important ways. First, the cost of research is more general, allowing for returns to scale governed by the parameter η. Second, this approach allows for an aggregate market size effect. In the Hassler and others (2020) setting, the relative composition of research responds to relative market shares. In contrast, here total research also increases with total energy demand increases. This is potentially an important amplification channel for policy, as the impact on aggregate energy prices (and hence demand for energy) is a crucial mechanism by which mitigation policies work.

The advantage of this framework over a richer approach, such as Acemoglu and others (2016), is its simplicity. Changes in the composition of the energy bundle are determined by the relationship between the elasticity of substitution and the returns to scale in R&D (via an R&D composition effect); changes in aggregate energy usage are determined by a similar relationship between the elasticity of energy demand and the returns to scale in R&D (via an aggregate R&D effect).

Domestic Economy

The energy sector is an input into aggregate production. As the focus of the analysis is on the role of R&D in energy, the aggregate economy is kept deliberately very simple. Aggregate production is given by a CES aggregate of energy with a Cobb-Douglas energy bundle:

$$Y_{jt} = \phi_j(T_{t-1})\left(\left(1-\nu_j\right)\left((A_{jt}L_{jt})^{1-\alpha_j}K_{jt}^{\alpha_j}\right)^{\sigma} + \nu_j E_{jt}^{\sigma}\right)^{1/\sigma}$$

where ν_j is the energy share parameter for region *j*, α_j is the capital share for region *j*, A_{jt} is labor productivity, L_{jt} the labor force, K_{jt} the capital stock, and $\frac{1}{1-\sigma}$ is the elasticity of substitution of energy in final production. This last feature is an important further extension over Hassler and others (2020), as the elasticity of energy demand determines the aggregate response of energy usage to changes in the price of energy, such as those caused by climate mitigation policies.

The function $\phi_j(T_{t-1})$ is the region-specific damages from global temperature, assumed to be a function of temperature at the end of the preceding period, T_{t-1}. This determines the size

[21] The efficient outcome here requires a subsidy, the size of which is dependent on the slope of the demand curve.

of the climate externality and is allowed to vary by region given evidence that warmer countries typically have higher costs of climate change (see Nordhaus 2010, Dell, Jones and Olken 2014, Burke, Hsiang, and Miguel 2015).

Labor and capital are supplied in competitive markets. Labor is assumed to in fixed supply and grow exogenously over time. For simplicity, the capital stock is assumed to depreciate fully each period and to be owned by domestic households who have an inter-temporal elasticity of substitution equal to one. This means that saving is a fixed fraction of output, greatly simplifying the analysis.

International Economy

Following Hassler and others (2020), conventional oil is assumed to be produced at zero cost by an oil-producing region, which manages a fixed stock of oil reserves to maximize their monopoly rents. Unconventional (fracked) oil can be produced domestically. In equilibrium, the international price of oil moves to equate global oil demand with supply from the oil-producing region. The oil price is therefore the main international price linkage; there is no trade in other goods.

We allow for an international diffusion of ideas, modelled as a constant rate of catch-up by each region to the frontier level of technology.

$$\bar{x}_{ij,t+1} = \omega_j \bar{x}_{ijt} + (1-\omega_j)\max_j \bar{x}_{ijt}$$

$$\bar{g}_{ij,t+1} = \omega_j \bar{g}_{ijt} + (1-\omega_j)\min_j \bar{g}_{ijt}$$

Pollution and Climate Externality

Emissions in region *j* are

$$m_{jt} = \sum_{i=1}^{N} g_{ijt} e_{ijt}$$

and global emissions are

$$M_t = \sum_{j=1}^{M} m_{jt}$$

Past emissions contribute to the stock of global CO2 as in Golosov and others (2014), with:

$$S_t = \sum_{s=o}^{\infty} (1-d_s) M_{t-s}$$

where the decay of absorption of emissions is parameterized by:

$$1 - d_s = \psi_L + (1-\psi_L)\psi_0(1-\psi)^s$$

The interpretation of this formulation is that for each unit of emissions, a fraction ψ_L remains in the atmosphere permanently, with the rest decaying at rate ψ. The evolution of emissions can therefore be expressed recursively using a separate variable for the permanent share of emissions.

Atmospheric and ocean temperatures, T_t and $\hat{T}_t$ respectively follow an energy budget model, derived from RICE/DICE (Nordhaus 2010). This is a linear coupled system with the stock of atmospheric CO2 acting as a forcing variable.

$$\begin{bmatrix} T_t \\ \hat{T}_t \end{bmatrix} = \begin{bmatrix} T_{t-1} \\ \hat{T}_{t-1} \end{bmatrix} + \begin{bmatrix} -\sigma_1(\hat{\eta}/\hat{\lambda} + \sigma_2) & \sigma_1\sigma_2 \\ \sigma_3 & -\sigma_3 \end{bmatrix} \begin{bmatrix} T_{t-1} \\ \hat{T}_{t-1} \end{bmatrix} + \begin{bmatrix} \sigma_1\hat{\eta} \\ 0 \end{bmatrix} 2^{\left(\frac{S_t}{S_{pre}}\right)}$$

where S_{pre} is the pre-industrial emissions stock, $\hat{\lambda}$ is the long-run climate sensitivity (the temperature increase due to a doubling of the atmospheric carbon stock), $\hat{\eta}$ determines the rate of convergence of temperature to the long-run level, σ_1 governs the auto-regressivity of atmospheric temperatures, and σ_2 and σ_3 capture the directed temperature exchange between the atmosphere and the oceans.

Productivity is a region-specific quadratic function of global temperature:

$$\phi_i(T_t) = 1 - \phi_i^0 + \phi_i^1 T_t + \phi_i^2 T_t^2$$

This cost function nests the specifications of Nordhaus (2010) and Burke, Hsiang and Miguel (2015), just with different specific parameter choices.

Model Solution

The state of the model is defined by the value of the region-specific labor productivity, capital, and fuel-specific technologies $\bar{x}_{ijt}$ and $\bar{g}_{ijt}$, as well as global stock of emissions and their permanent share. With nine productive regions and six improvable fuels this gives 128 state variables, justifying the strong simplifying assumptions on the structure of the macroeconomy.

Calibration

In order to match the G-cubed model (see Annex 3.4), there are ten regions, all of which have the production structure discussed above except for OPEC, which produces only oil for international trade. There are seven fuel types: international oil; domestic oil, natural gas, coal, hydroelectric, nuclear, and renewables. International and domestic oil are respectively identified with production via conventional and unconventional (e.g., fracking) methods of production.

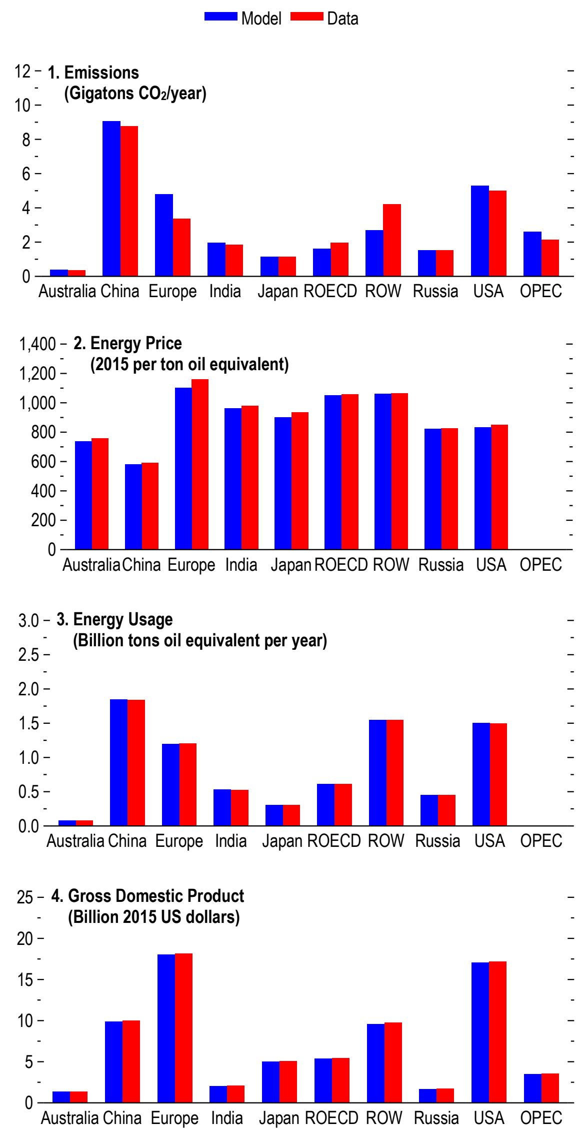
Annex Table 3.5.1. Calibrated Production Parameters

Parameter	Description	Type	Value	Target
$\lambda_{i,j}$	CES fuel weight	Regional		IEA fuel shares
ϵ_{ij}	Efficiency R&D cost shift	Regional		Regional fuel prices
θ_{ij}	Carbon intensity R&D cost shift	Regional		IEA carbon intensities
ρ	Intra-fuel CES parameter	Common	0.67	Papageorgiou et al. (2013)
η	R&D returns	Common	10	Fried (2018) dynamics
ν_j	Energy output share parameter	Regional		IEA energy shares
α_j	Capital share	Regional		WEO capital shares
σ	Aggregate CES parameter	Common	-3	Consistent with Annex 3.6

The parameters of the aggregate and energy production functions are chosen to match data from the IEA on the usage, price, and carbon intensities of the different fuels (see Annex Table 3.5.1). The intra-fuel elasticity of substitution is set to three, consistent with Papageorgiou and others (2013), and the elasticity of substitution of energy and the capital-labor bundle is 0.25, in line with the assumptions of Annex 3.6. Returns to R&D are chosen to match aggregate responses of other models in the literature. Fried (2018) estimates that the innovation response in a model of endogenous technical change in the energy sector reduces by 20 percent the carbon tax required to meet a given reduction in emissions in 20 years. After accounting for key model differences, this implies returns to scale in R&D of around 0.11, or η of 10.

Aggregate production parameters are chosen to match the expenditure shares of energy, labor and capital. Initial values for capital and labor productivity are set to match average regional weights in global GDP and emissions during 2010-2019. Labor force growth is taken from ILO forecasts until 2030, and to converge smoothly to an annual growth rate of 0.2% by 2070, consistent with UN population projections. The long-run growth rate of labor productivity is assumed to be 1.3% per year, with catch-up growth in productivity in three regions (India, China, and RoW) during the short term. To capture trends in energy efficiency, the energy share parameter ν_j is assumed to decrease at around 0.7 percent annually, in line with recent trends.

Annex Figure 3.5.1. Results of Model Calibration, 2010–19 Average



Source: IMF staff calculations.
Note: OPEC is modeled as having only an extractive sector, so the usage and price of the composite energy is omitted. OPEC = Organization of the Petroleum Exporting Countries; ROECD = rest of Organization for Economic Co-operation and Development countries; ROW = rest of the world.

Annex Figure 3.5.1 compares the results of the calibrated model to the data, averaged across 2010-2019. Overall, the model matches the level and distribution of output, emissions, energy usage, and prices across the various regions.

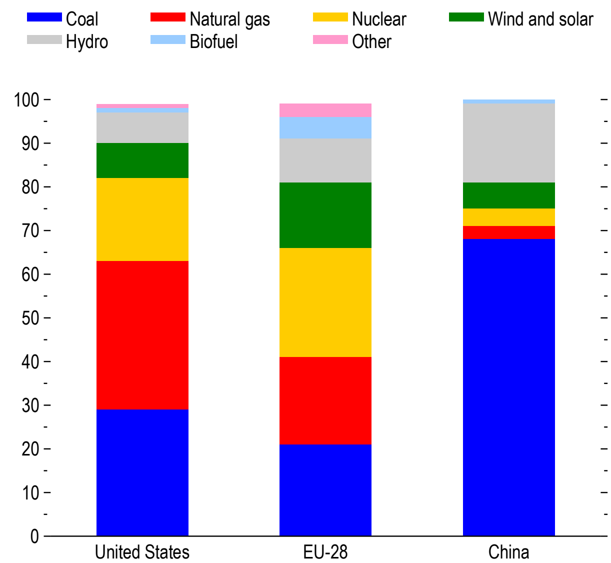
The calibration of the climate module takes standard parameter values from Nordhaus (2010), Golosov and others (2014), and Hassler and others (2020). Baseline climate damages of higher temperatures are taken from Nordhaus (2010) with an alternative specification using Burke, Hsiang, and Miguel (2015).

Annex 3.6. The Macroeconomic Impact of Decarbonizing Electricity Generation

Carbon Emissions in the Electricity Sector

Emissions from electricity generation and heating amounted to roughly 40 percent of total global carbon dioxide (CO2) emissions in 2018 and are expected to grow further. Energy efficiency improvements will not be enough to offset the world's rising electricity needs due to projected economic growth and rising incomes in developing economies. Given current emissions trajectories and the electricity sector's role as key emitter, an immediate low-carbon transition is indispensable to avoid irreversible global warming. However, not only are currently adopted policies greatly insufficient to meet emissions reductions' targets from the Paris agreement, but policymakers' commitments for further electricity sector reforms in the future are generally estimated to fall short of what is needed to avoid irreversible climate damage. According to the International Energy Agency, the growth of low-carbon electricity sources up to 2040 under stated policies is estimated to be half as large as what is needed to meet the UN's Sustainable Development Goals and to cut emissions in line with the objectives of the Paris Agreement.

Annex Figure 3.6.1. Electricity Mix in 2018
(Share of total electricity production)



Sources: International Energy Agency; and IMF staff calculations.

Electricity generation from coal dates to the 1880s and emits about one kg of CO2 per kWh, making it the heaviest-polluting electricity source that, by itself, causes roughly 30 percent of global CO2 emissions. The share of natural gas in the electricity mix has been rising in many countries, facilitated by an increase in supply from the fracking boom in the United States. With about 400 grams of CO2 per kWh, it is less polluting than coal–and so-called gas-for-coal switching lowered emissions in many countries–but emissions are still too high for gas to play a significant role in a low-carbon economy, aside from providing flexibility for backing up intermittent renewables.

Annex Figure 3.6.1 shows the electricity mix in the European Union, the United States and China. In all regions, the share of coal and natural gas is unsustainably high in the sense that absent a dramatic rebalancing, electricity generation will be a key driver of irreversible climate damage. The mix in the European Union is the least emitting, which is reflected in comparably low annual per-capita CO2 emissions from electricity and heating of 2,176 kg (as of 2017). However, coal still has a share of over 20 percent and is in many places backed by subsidies that delay the required transition. Per-capita emissions in the United States are about 2.5 times higher than in the EU (5,592 kg in 2017), which results from a per-capita electricity consumption about twice as large, combined with a more polluting electricity mix in which coal and gas together make up over 60 percent of the generation. Electricity consumption in China is about 2/3 as large as in the EU, but the extremely high share of coal–almost 70 percent–elevates annual per-capita emissions to 3,312 kg.

Transition in the Electricity Sector

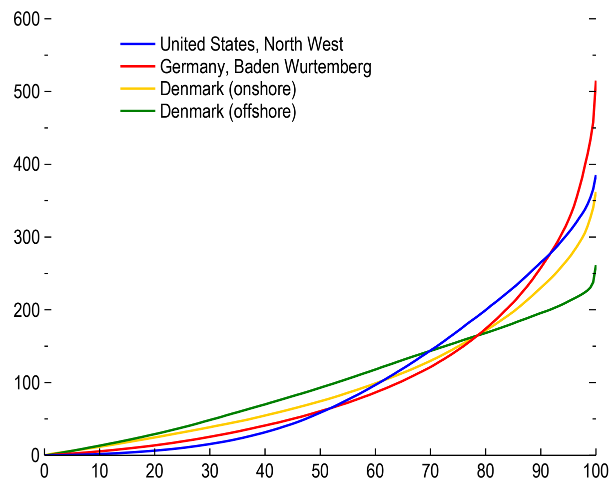
The need for an immediate transition towards low-carbon electricity raises questions about its technical feasibility, its costs, and the role governments can play in its facilitation. Feasibility has improved dramatically over the last decade, with prices for key renewable technologies having undergone a rapid decline that is expected to continue. This made them economically viable and gave them the potential to replace coal-fired electricity on a large scale. The improved competitiveness of renewables means that the balance between low and high-carbon technologies can be more easily tipped in favor of the sustainable kind, and thereby creates the conditions for mitigation policies to be especially effective. This is crucially different from a decade ago when limited technology readiness constrained the effectiveness of the green stimulus provided after the Global Financial Crisis in decarbonizing electricity generation (IEA, 2020c), suggesting that that episode may offer little guidance on the likely impact of green policies at the current juncture. The following analysis shows that in the current technological environment mitigation policies can lead to substantial reductions in emissions. The associated macroeconomic costs are modest and, under any reasonable probability distribution, dwarfed by the costs of global warming. Governments thus must seize the opportunity and play a key role in accelerating the transition that, left to market forces alone, will come too late. This holds especially at the current juncture with low interest rates and the need for economic stimulus to stabilize demand during the Covid-19 crisis.

There are various low-carbon technologies to produce electricity. Each has its specific advantages and drawbacks, and it is difficult to predict how technology will evolve in the future. Hydraulic power generation has geographic requirements that limit the availability of sites and causes broader environmental damages. Biomass can be used to generate electricity, but its production could compete with other uses of land. Nuclear power is a carbon-neutral technology with a scalability that would allow to replace coal and gas but has a generally low popularity. The latter results from a combination of recent nuclear disasters, the prominent discussion of nuclear waste management, and an underappreciation of its potential to curb global warming when it replaces high-carbon technologies. In actuarial terms however the costs of nuclear power–a low probability of devastating but geographically limited damage–will likely be dwarfed by the certain, global and irreversible damages from climate change. The most promising and politically acceptable carbon-neutral technology is renewable electricity generation from wind and solar photovoltaic (PV). The key drawback of this technology, discussed in detail below, is that electricity from renewables is intermittent, i.e. that it is only generated when there is wind or sun. Carbon capture and storage (CSS) technologies have the potential to reduce emissions from coal power plants, but a significant deployment of this technology is prevented by high costs that are not predicted to fall substantially in the near term. In this analysis we focus on renewables as the technology to bring about an electricity transition, as it is in principle scalable and, in contrast to nuclear power, politically less controversial.

Intermittency of Wind and Solar

Annex Figure 3.6.2. Generation Duration Curve for Electricity from Wind

(Percent of average production over a year; percent of generation duration on x-axis)



Sources: Bonneville Power Administration; EnergyNet; TransnetBW; and IMF staff calculations.

Our focus on renewables merits a closer inspection of its intermittency problem. Annex Figure 3.6.2 shows so-called generation duration curves for different illustrative regions, i.e. the cumulative distribution function of electricity output from wind. The data is normalized by average electricity output over time so that, for example, the curve for the US Northwest tells us that output during the top 20 percent of the time exceeds twice the average output. We observe that there are substantial periods in which wind generates close to no output. The load factor (i.e. the ratio between average generation and peak generation) of the shown data is between 35 percent for onshore wind and 45 percent for offshore wind. For solar PV, it amounts to about 25 percent.

Thus, to ensure that electricity supply can always meet demand, either demand must be managed to decline in line with supply when renewable output is low, or total electricity supply must be stabilized in the face of output fluctuations from renewables. Demand management on the part of private households and industrial production has potential but is still insufficient to solve the problem of intermittency. Electricity storage could smooth out output fluctuations and is developing rapidly but is not yet ready to be deployed at a sufficiency large scale. The most prominent example for utility-scale electricity storage are hydro-pumps, whose global power capacity the International Hydropower Association estimates at 158 GW. In the United States, the European Union and China (IHA, 2020), this would represent about 30 minutes of power consumption, while managing solar (wind) intermittency would require about 18 hours (72 hours) of electricity storage. Chemical storage (batteries or hydrogen) are still too expensive for large deployment and other technologies based on heat or gravity are not mature yet. With electricity storage still not being economically viable at a large scale, the intermittency of renewables must be compensated by other flexible electricity sources in the grid. Natural gas and hydro are the most commonly used for this purpose. The International Energy Agency points to flexibility retrofits that can potentially allow coal power plants to serve as a backup for renewables (IEA, 2019). While this can give existing power plants a role in an electricity transition, it would entail a slower decline in emissions relative to the use of other backups.

The constraints that intermittency poses for the expansion of renewables are captured by a dedicated module of our macroeconomic model introduced below. Under the assumption that demand flexibility and electricity storage are not yet sufficiently mature to manage intermittency, the model requires that any intermittent generation capacity is paired with a dispatchable back-up capacity that is idle for most of time but can cover power shortfalls of intermittent technologies (see Morris and others, 2010). More precisely, the backup covers, at any point in time, the difference between intermittent power generation and the desired output. Pairing renewables with a backup increases costs relative to stand-alone renewables, but fully compensates for their drawback of being intermittent. The framework allows for so-called overcapacity, i.e. the installation of renewable capacity that, at peak output, produces electricity above demand that must be curtailed.

The Optimal Renewables-Backup Mix

Generation duration curves as show in Annex Figure 3.6.2 can be well approximated by the power function

$$E = p^{\gamma}$$

where γ is a parameter measuring the degree of intermittency (the corresponding load factor is given by $1/(1+\gamma)$). Offshore wind is generally more stable than onshore wind, reflecting in an intermittency parameter of between 1 and 1.5, compared to values between 2 and 3 for onshore wind. Solar intermittency has a different intermittency profile—it does not produce at night—but has a similar pattern as wind during the day.

Variable costs of the backup, fixed costs of renewables, and fixed costs of the backup are denoted by C^{v}, C^{fr}, and C^{fb} respectively. We assume that a utility using renewables paired with a backup aims to produce a constant output L. The size of the backup capacity relative to renewable capacity is endogenously determined by cost-minimization based on γ (as the degree of intermittency influences the need for a backup) and the costs structures of both technologies. To build intuition for the choice a utility faces, we first consider the illustrative case in which there is a given backup capacity but no renewables. Deploying renewables—operating at zero variable costs—lowers the utility's overall variable costs, as costly generation from the backup can be substituted for. Under our assumptions on the cost structure after taxes and subsidies, variable cost savings from expanding renewables exceed their installation costs, so the utility chooses to increase renewable capacities at least up to the point where peak renewable output equals L. Expanding renewables above this point still lowers variable costs by reducing the share of output from the backup, but the variable cost savings are declining in size because of curtailment: since peak renewable output now exceeds L, a positive share of renewable output has to be curtailed. Because of the shape of the generation duration curve, this share rises at an increasing pace when additional renewable capacity is installed. At the cost-minimizing ratio between renewable and back-up capacities, curtailment reduces the variable cost savings from additional renewables such that they equal the fixed costs. Optimality implies that the following output B is produced from the backup (and the remainder $L - B$ from renewables):

$$B = \frac{\gamma}{1+\gamma}\left(\frac{C^{v}}{C^{fr}}\right)^{\frac{-1}{1+\gamma}}$$

Model Description and Calibration

The analysis uses GIMF-E, a Dynamic Structural General Equilibrium (DSGE) model tailored for analyzing how governments can trigger an electricity transition and its macroeconomic implications. Such analysis implies two key modelling requirements. First, a detailed description of the government and the macroeconomy is necessary to capture the fiscal dimension of policies and their general-equilibrium effects. GIMF-E meets this requirement as it largely builds on the IMF's workhorse model GIMF and inherits a detailed description of the interaction between households, firms, a detailed fiscal sector and monetary policy, as well as a menu of real and nominal rigidities. GIMF-E is currently a closed-economy model. The second modelling requirement is that the electricity sector should be sufficiently granular to capture technology-specific practical constraints to an electricity transition. GIMF-E's electricity sector encompasses four technologies: coal, natural gas, renewables, and nuclear power plus hydro. The fuel required for coal and natural gas generation is mined in two specific mining sectors. Nuclear and hydropower have negligible carbon emissions and close to zero marginal cost. Hydro and nuclear capacities are exogenous, reflecting limited availability of hydropower sites and the crucial role of political considerations, rather than market-based ones, in the development of nuclear power. When nuclear power expands, building additional capacities is subjected to a time-to-build constraint. Due to intermittency, renewables are paired with a backup capacity in a cost-efficient manner as outlined above. The most common backups are hydropower and natural gas, while coal (assuming appropriate flexibly retrofits) comes third according to a merit-order model. Different electricity generations compete on a commodity market for electricity where output from the different sources are treated as very close substitutes (they are equally dispatchable, as intermittency from renewables is compensated by the backup). For the US model, natural gas is assumed to be the only backup, whereas both natural gas and coal are used as backup in China and the European Union (to take into account the shortage of natural gas in both regions). Electricity is used as an intermediate input in the production of manufacturing goods and services, and also directly enters the final consumption good.

The structure of GDP by sector (electricity, manufactured goods and services), by expenditure (private consumption and investment as well as public consumption and investment), and by income (total compensation, gross operating surplus and taxes and subsidies) reproduces national accounts in 2018 and the most recent input-output tables. The share of the different electricity-generation technologies and their emissions (abstracting from those associated with the installation and dismantlement of capacity) reproduce data from the IEA. Flexible generation from hydropower and the development of offshore wind can to some extent alleviate the intermittency problem, which we do not explicitly model but proxy for by using an intermittency parameter γ lower than observed. Annex Table 3.6.1 shows for the three regions the share of electricity generation in output, and the breakdown of electricity use between final consumption and as input in manufacturing and services.

Annex Table 3.6.1. Electricity Generation and Use
(Percent of GDP)

	United States	European Union	China
Electricity	1.9	3.0	2.3
Manufacturing	0.4	0.9	1.2
Services	0.5	0.7	0.6
Consumption	1.0	1.4	0.5

Impact of the Introduction of a Carbon Price

Before turning to the simulation results, we highlight key aspects of the transmission of a carbon price into the electricity price, and of the electricity price into macroeconomic variables.

Transmission of a Carbon Price into the Electricity Price

When a carbon price is introduced, the mining sector absorbs some of the carbon price burden, which cushions the rise in fuel costs experienced by coal-based (and to a lesser extent gas-based) electricity producers. A carbon price reduces fuel demand and thereby the price of coal and gas, at least in the short run, so that electricity producers do not face a one-for-one increase in fuel cost. The impact of a given rise in fuel costs on the electricity price is further dampened by the competition in the market. The carbon price increases fuel costs of electricity generation from coal (and gas) but has no impact on marginal costs of other technologies. Given the high degree of competition, coal and gas producers are not able to significantly increase prices despite rising fuel costs. Some of the required room for absorbing higher costs results from a decline in investment, which, in turn, follows from expected permanently reduced profitability. A further factor mitigating the adjustment of the electricity price is the rebalancing of the electricity mix. A carbon price tilts relative prices to the disadvantage of carbon-intensive technologies and thereby triggers a gradual transition towards low-carbon technologies. The associated decline in the average carbon intensity of the electricity mix means that a given carbon price leads to a smaller increase in the electricity price. The strength of this effect depends on the availability of natural gas as a backup: If gas is scarce and a more carbon-intensive technology has to be used as backup, a given surge in renewables implies a weaker decline in emissions and thereby in the carbon price burden.

Transmission of a Higher Electricity Price into the Macroeconomy

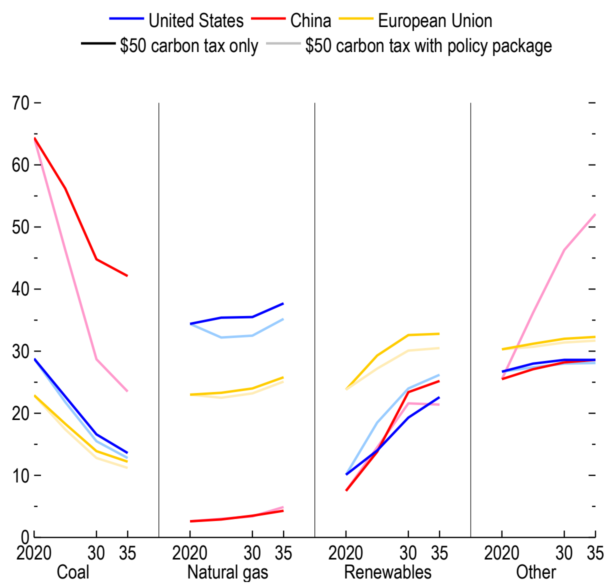
Electricity is used to operate machines (or buildings) that increase labor productivity. A higher electricity price does not significantly alter technical coefficients, so firms have limited means to substitute capital and labor for electricity when the latter becomes more costly, but instead reduce demand for capital and labor. Due to the high price elasticity of capital supply and the low price elasticity for labor in general equilibrium, the decline in demand translates into a reduction of investment and capital accumulation (implying that a higher investment share increases the impact of a carbon price on output), as well as into lower real wages. This causes the impact of a carbon price to affect sectors beyond electricity production. The strength of these spillovers is determined by the elasticity of substitution between electricity and other factors, which we set to 0.3, and by the share of electricity in the respective sector.

In a nutshell, the macroeconomic impact of a carbon price in the electricity sector depends on four factors: the initial share of coal in the electricity mix, the portion of the carbon burden that is absorbed by the mining sector, the availability of low-carbon backup technologies, and the investment share in the economy.

Carbon Price of 50USD in the United States, the European Union and China

We first study the gradual introduction of a carbon price, phased-in over 10 years, in the United States, China and the Euro Area, under the assumption that carbon tax revenues are given back to households as transfers. Lines in darker colors in Annex Figure 3.6.3 show the adjustment of the electricity mixes in this scenario. Annex Figure 3.6.4 shows in the same fashion the adjustment of output, investment, consumption and electricity-related CO2 emissions. In the interpretation of output costs, we need to consider that the model does not account for climate damages and therefore does not capture benefits from cutting emissions.

Annex Figure 3.6.3. Decarbonization of the Electricity Sector: Adjustment of Electricity Mixes
(Percent)



Source: IMF staff estimates.
Note: 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, front-loaded 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.

The carbon price discriminates by the carbon-intensity of the different technologies and thereby tilts relative prices to the disadvantage of coal and, to a lesser extent, natural gas. This results in a decline in the share of coal generation in all regions. In the United States, the share falls below 10 percent as natural gas is abundant enough to provide the grid sufficient flexibility to accommodate the rising share of renewables. Our assumption of an average 40-year lifetime of a coal power plant slows down the transition, as the immediate collapse of investment in that sector only translates into a gradual depreciation of the capital stock. In the European Union and China, the use of coal alongside gas as a backup for renewables mitigates to some extent the decline of the share of coal. As a result of introducing the carbon price, the electricity price rises gradually to reach a cumulative increase after ten years of 10 percent in the European Union, 20 percent in the United-states and 30 percent in China where the share of coal is the highest.

The carbon price reduces investment, as a result of shrinking coal sectors, as well as lower economy-wide investment due to the limited extent to which manufacturing goods and services producers can substitute away from more costly electricity. After an initial uptick caused by higher dividend pay-outs associated with less spending on investment, consumption declines. GDP declines gradually over ten years (relative to baseline), implying an average annual growth reduction of about 0.1 percentage point in the United-States and European Union, and 0.3 percentage point in China. The larger decline in China has two main explanations. First, the larger share of coal in the electricity mix amplifies the rise in the electricity price; and second, the high share of investment in the economy means that a given decline in investment translates into a greater drop in aggregate demand and output. Given its dampening impact on investment, the carbon price works towards rebalancing the economy towards a larger consumption share.

After ten years, carbon emissions in the electricity sector have declined relative to baseline by about 30 percent in the European Union, 35 percent in the United States, and 38 percent in China. Electricity-related emissions in China and in the United States decline by roughly the same proportion after ten years, but different initial emission levels cause the declines to differ in absolute size (745 megatons in the United States, 390 megatons in the EU, and 1919 megatons in China).

Carbon Tax with a Macro Package in the United States and the European Union

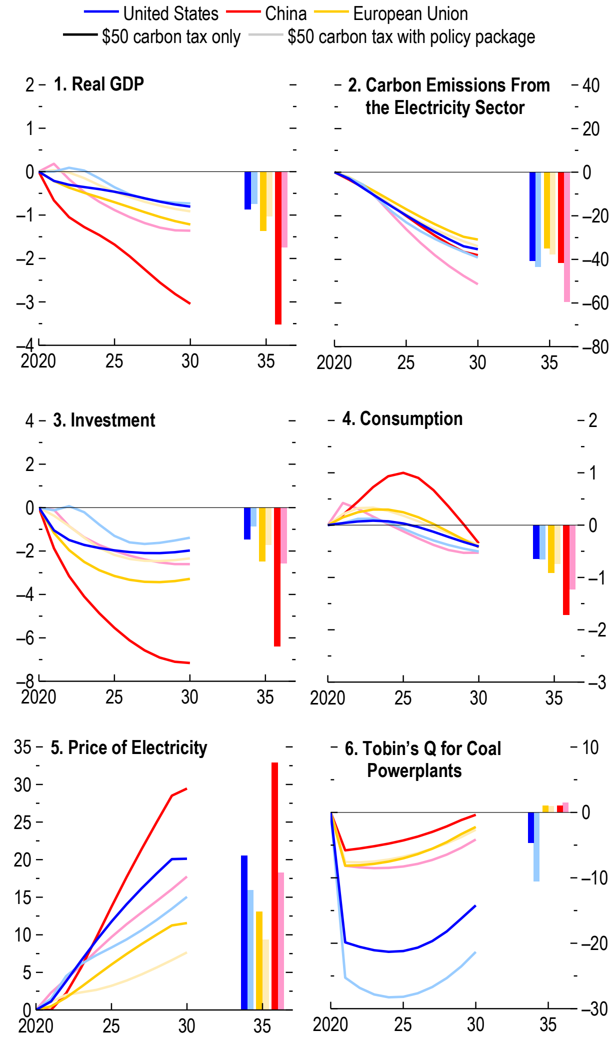
The additional government revenues generated by the carbon price offer the chance to foster the further development of renewables. For the United States and Europe, we consider a macro package that complements the carbon price with (i) frontloaded subsidies for investment in renewables, financed by public debt in the first five years, and (ii) accommodative monetary policy in the short run. In the United States, initial subsidies amount to 60 percent of the investment costs in renewables, and then decline to 30 percent after five years. In the European Union, the rate starts at 40 percent and declines to 20 percent after five years, reflecting lower carbon price revenues compared to the United States. The subsidies boost investment in the short term and thereby accelerate the electricity transition, which, by lowering the average carbon intensity, dampens the impact of the carbon price on the electricity price and GDP. Note that renewables investment subsidies come in addition to existing renewables production subsidies, which are incorporated in the initial calibration.

Lighter lines in Annex Figure 3.6.4 denote the adjustment when the macro package complements the introduction of the carbon price. The macro package compensates the output decline the short run and mitigates the decline of output in the long run, while it also amplifies the reduction in emissions. The effectiveness of the macro package is greater when it is paired with a carbon price. The reason is that the prospect of a higher long-run market share of renewables (brought about by the carbon price) amplifies the impact of a given subsidy.

Carbon Tax with a Macro Package and Additional Nuclear Power in China

China's strong reliance on coal amplifies the macroeconomic costs of introducing a carbon price. To investigate to what extent these costs can be mitigated by additional policies, we study a broader policy mix which, next to the gradual introduction of a 50 USD carbon tax, also features an expansion of nuclear power and an improved availability of natural gas (which can be used as backup for renewables). Annex Figure 3.6.4 compares the impact of this policy mix to the impact of the isolated 50 USD carbon price (from the previous exercise). The additional measures cut output costs by roughly a half and amplify the decline in emissions by about 50 percent. The deployment of additional nuclear power capacity immediately contributes to the decline in emissions, as additional supply leads to a crowding-out of other producers in the grid, which are mostly coal-based. The subsidy for natural gas generation leads to deployment of new capacities that can serve as backup for renewable generation. As a result, the surging need for a flexible backup capacity–brought about by the rising share of renewables triggered by the carbon price–is split between coal and gas. This further amplifies the decline in the coal share. A key reason for the mitigation of the output decline is that the additional measures partially offset the increase in electricity costs caused by the carbon price. There is a direct channel by which nuclear power immediately increases supply of electricity and lowers the price, as well as an indirect channel based to the rebalancing of the electricity mix: the reduction in the share of coal caused by the additional nuclear and natural gas capacity lowers the average carbon intensity of electricity generation, which in turn dampens the price increase caused by the carbon price.

Annex Figure 3.6.4. Decarbonization of the Electricity Sector: Macroeconomic Impact
(Percent deviation from baseline)



Source: IMF staff estimates.
Note: 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, front-loaded 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.

Policy Implications Beyond the Model Analysis

The large number of existing coal power plants and their young average age (60 percent are

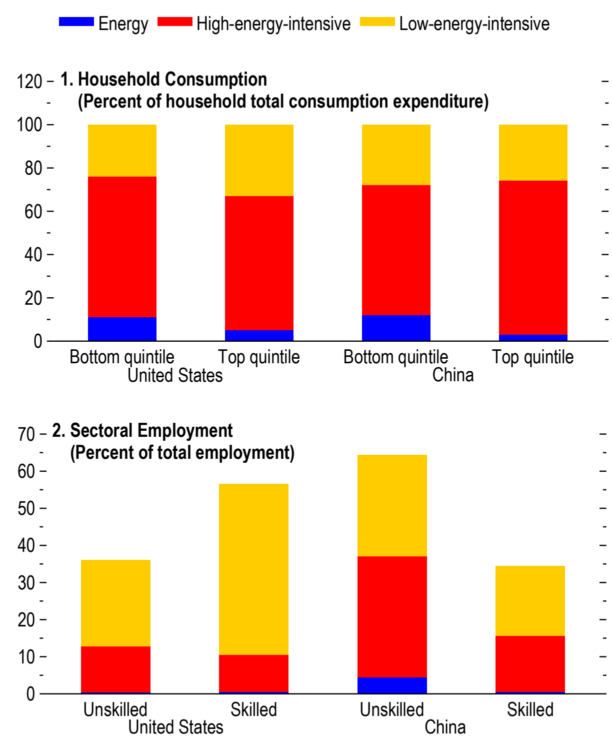
20 years or younger) are a key concern for the practical implementation of an electricity transition. Continued operation of the existing fleet would generate enough emissions to potentially put sustainable development targets out of reach (International Energy Agency 2019), but a rapid retirement of that capacity could impose financial losses to their owners, who often include governments. The IEA estimates that existing coal power plants represent globally more than $1 trillion unrecovered capital investment. In the model simulations, this aspect surfaces in a dramatic decline in the value of coal power plants–summarized by Tobin's Q of the respective capital stock. This raises the question of how an electricity transition can be designed to minimize financial damages. The International Energy Agency points to the possibility of retrofitting and repurposing a significant share of existing plants, especially younger and more efficient ones, to make their continued operation compatible with climate targets. Possible retrofitting options include installing equipment for CCUS (Carbon Capture, Utilization, and Storage) or biomass co-firing, while repurposed plants can continue their operation at lower utilization levels to provide flexibility and thereby facilitate an expansion of intermittent renewable sources.

Annex 3.7. How to Avoid A Further Widening in Income Disparities and Build Inclusion?

Understanding the impact of carbon taxes on income inequality is critical to galvanizing support to fight climate change. Achieving inclusive climate change mitigation policies requires a thorough understanding of the channels through which carbon taxes affect the income distribution and the magnitudes in question.

Carbon taxes can worsen income inequality because low-income households spend a proportionately larger fraction of their income on high-energy intensive goods, a fact that has been explored extensively in the literature (see Grainger and Kolstad 2010, Fremstad and Paul 2019, and IMF 2019 for examples).[22] However, another important fact that is less known is that carbon taxes can also worsen income inequality by affecting proportionately more the wages and job opportunities of unskilled low-income workers. Unskilled workers are more likely to work in the high-energy intensive sector that is impacted more by a carbon tax (Annex Figure 3.7.1).[23,24]

Annex Figure 3.7.1. The Distribution of Consumption and Employment



Sources: American Community Survey; China Family Panel Survey; Consumption Expenditure Survey; National Bureau of Statistics of China; and IMF staff calculations.
Note: 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. Unskilled workers are workers with a high-school education or less, while skilled workers have more than a high-school education.

In this section, a model that captures both the consumption and employment impacts of a carbon tax is developed. The model is used to quantitatively analyze the effect of a 50 USD per ton of CO2 tax on income inequality, considering different uses of the carbon tax revenue. Four different revenue recycling cases are examined in the analysis: (i) the carbon tax revenue is used to finance spending on the low-energy intensive good; (ii) the carbon tax revenue is used

[22] There are examples where carbon taxes can improve income inequality, in these cases high-income households spend a relative larger share of income on energy-intensive goods. This is sometimes the case in EMs and LIDCs, where poor households do not have access to electricity. In these cases, carbon taxes can be progressive instead of regressive, but they may also reduce future access to electricity for poor households. IMF (2019) finds that this is the case for India.

[23] Chateau and others (2019) analyzes the impact of a carbon tax across occupations in a Computational General Equilibrium model (CGE) and find that low-skilled occupations are more likely to be negatively affected by carbon taxes. Marin and Vona (2019) use a shift-share instrumental variable approach applied to 14 European countries and shows that climate policies have been skill-biased against manual workers and have favored technicians.

[24] An important limitation of this data is the inability to account for the share of employment in clean energy production. This is an issue that has been documented extensively in the literature (see for instance US Department of Energy 2017).

finance a universal cash-transfers program; (iii) the carbon tax revenue is used to finance a targeted cash-transfers program for the bottom two quintiles of the income distribution; and (iv) the carbon tax revenue is used to fund a subsidy to clean energy consumption "feebates".

Model

This analysis uses a multi-sector heterogeneous agent model to simulate the impact of the various policies on income inequality. More details about the model and calibration can be found in Tavares (2020). The model is a small open economy with four goods (high-energy intensive good, low-energy intensive good, dirty energy, and clean energy) and two household types (skilled and unskilled). The high-energy intensive good and the low-energy intensive good are produced using capital, high-skilled labor, low-skilled labor, dirty and clean energy. The use of inputs differs across sectors: the high-energy intensive sector is more energy and low-skilled labor intensive than the low-energy intensive sector. Dirty and clean energy are produced using low-skilled labor and capital, and clean energy is more labor-intensive than dirty energy.[25]

There are two types of households: skilled and unskilled. Skilled and unskilled households differ in their average productivity and the sectors in which they can find employment. Skilled and unskilled households have the same preferences over the consumption of the high-energy intensive good, the low-energy intensive good, dirty energy, clean energy, and leisure. They face idiosyncratic productivity shocks that they can partially insure against by investing in a risk-free asset.

The two key features of the model are that: (i) household preferences are non-homothetic; and (ii) the skilled and unskilled labor-intensity varies across sectors.

Preferences

Non-homothetic preferences imply that low-skilled and low-income households consume a larger share of energy and energy-intensive goods in their consumption basket because their income is lower. Households in the model maximize expected lifetime utility over the consumption of the low-energy intensive good c^l, the consumption of the high-energy intensive good c^h, energy e, and hours worked l, subject to the borrowing constraints.

Households' utility function is given by

$$u(c^l, c^h, e, l) = \psi_l \log(c^l + \bar{c}^l) + \psi_h \log(c^h) + (1 - \psi_l - \psi_h) \log(e - \bar{e}) - \chi \frac{l^{1+\frac{1}{\gamma}}}{1+\frac{1}{\gamma}}$$

where e is the consumption of energy. The latter is a composite of clean e^c and dirty e^d energy given by

[25] Despite its richness, this model abstracts from some channels that have been explored in literature. These include for example, the impact of carbon taxes on capital income (Metcalf 2019), informality (Bento and others (2018), and differences across ages and cohorts (Fried and others 2018).

$$e = \left(\mu^e (e^c)^{\rho^e} + (1-\mu^e)(e^d)^{\rho^e}\right)^{1/\rho^e},$$

where ρ^e determines the elasticity of substitution between clean and dirty energy. The term $\bar{e}$ captures that the energy is a "subsistence" good that is consumed disproportionally more by low-income households while $\bar{c}^l$ is a "luxury" good that is consumed disproportionally more by high-income households.

The household budget constraint is given by

$$p^h c^h + p^l c^l + p^c e^c + (1+\tau)p^d e^d + \ b' \leq w \quad l \quad z \quad + (1+r)b + T(w^k l^k s^k),$$

where p^h is the price of the high-energy intensive good, p^l is the price of the low-energy intensive good, p^c is the price of clean energy, and p^d is the price of dirty energy. b is the risk-free asset, r is the risk-free interest rates w is the workers' wage that depends on skill level, z denotes the current idiosyncratic productivity shock, and $T(\cdot)$ is the government transfers.

Production

Differences in the labor intensity across sectors imply that unskilled households are more likely to find employment in the high-energy intensive sector. High and low-energy intensive goods are produced using constant elasticity of substitution (CES) production functions given by

$$f^j\left(K^j, L^{s,j}, L^{u,j}, E^{c,j}, E^{d,j}\right) = A^j \left(\mu_k^j \left(K^{\alpha^j} L^{1-\alpha^j}\right)^{\rho_k^j} + (1-\mu_k^j)\left(E^j\right)^{\rho_k^j}\right)^{\frac{1}{\rho_k^j}}$$

where K^j is the capital; L^j is the aggregate effective labor input, which is a combination of effective skilled $L^{s,j}$ and unskilled labor $L^{u,j}$; and E^j is a combination of clean energy $E^{c,j}$ and dirty energy $E^{d,j}$. These are given by

$$L^j = \left(\mu_l^j \left(L^{s,j}\right)^{\rho_l^j} + (1-\mu_l^j)\left(L^{u,j}\right)^{\rho_l^j}\right)^{\frac{1}{\rho_l^j}} \text{ and } E^j = \left(\mu_e^j \left(E^{d,j}\right)^{\rho_e^j} + (1-\mu_e^j)\left(E^{c,j}\right)^{\rho_e^j}\right)^{\frac{1}{\rho_e^j}}$$

where $j \in \{h, l\}$. The key assumptions in the model based on data analysis is that the high-energy intensive sector is more energy-intensive than the low-energy intensive sector (e.g. $\mu_k^h < \mu_k^l$) and the high-energy intensive sector is more intensive in unskilled labor than the low-energy intensive sector (e.g. $\mu_l^h < \mu_l^l$).

Equilibrium

The household state variables, *x*, are asset holdings, *b*, and idiosyncratic labor productivity, *z*. Given the distribution of skilled and unskilled workers μ, carbon tax τ, interest rates *r*, a utility function $U : R_+ \times R_+ \times R_+ \times R_+ \rightarrow R$, factor prices $\{w^s, w^u, r, p^h, p^l, p^c, p^d\}$ and capital depreciation rate δ, a stationary competitive equilibrium consists of workers' decision rules $\{c^{j,l}, c^{j,h}, e^{j,c}, e^{j,d}, l^j, b'^{,j}\}_{\{j\in\{u,s\}\}}$, goods firms' production plans $\{K^j, L^{j,s}, L^{j,u}, E^{j,d}, E^{j,c}\}_{\{j\in\{h,l\}\}}$, energy firms' production plans $\{K^j, L^{u,j}\}_{\{j\in\{c,d\}\}}$, and the distribution of agents, $\Gamma(x)$, such that the following holds:

- Given prices and policies, a household with skill level *j* maximizes lifetime expected utility subject to the borrowing constraints.
- Goods producer *j* demands for $K^j, L^{j,s}, L^{j,u}, E^{j,d},$ and $E^{j,c}$ satisfy the firm optimization problem.
- Energy producer *j* demands for K^j and $L^{j,u}$ satisfy the firm optimization problem.
- The government budget constraint is satisfied.
- Skilled and unskilled labor markets clear.
- The low-energy intensive good market clears.
- The distribution $\Gamma(x)$ is stationary.

Calibration

The model is calibrated to the data by matching the households' consumption composition by income level to sectoral energy-intensity. The calibration uses the Consumption Expenditure Survey (CEX) to match consumption in the United States and the China Family Panel Survey (CFPS) for China. Using these two data sets, consumption goods are divided into three main categories: Energy (primarily utilities and gas), high-energy intensive goods (industrial goods and transportation), and low-energy intensive goods (services less transportation). To match the three sectors to workers, the calibration uses data from the American Community Survey (ACS) for the United States and data from the National Bureau of Statistics of China (NBS) for China in order to measure the skill intensity of the different sectors of the economy. Finally, each sector's energy intensity is calibrated using data from the International Energy Agency (IEA). All the elasticities of substitution are taken from the literature and are assumed to be the same in the United States and China.[26]

Results

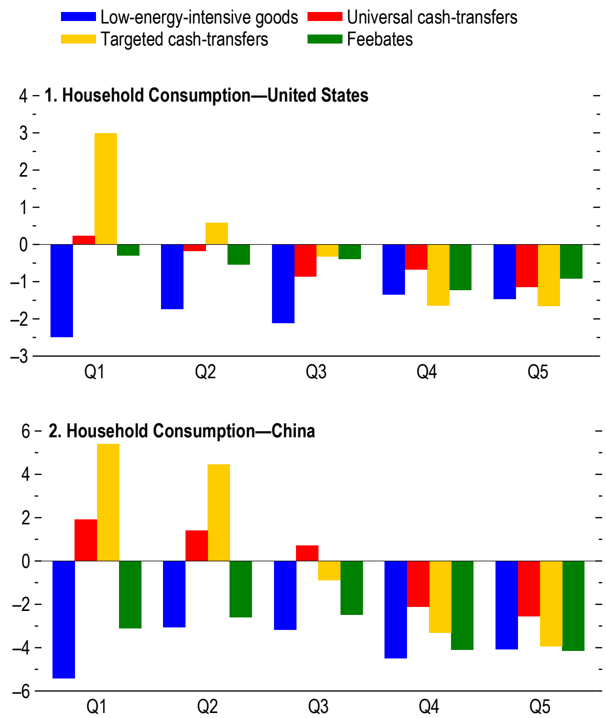
To examine the distributional impact of a carbon tax, this section simulates the baseline economy with no carbon tax and then conducts a series of counterfactual experiments in which a constant carbon tax set at 50 USD per ton of CO_2 is imposed. In particular, three different policies that differ in how the government recycles the carbon tax revenue are considered. In the

[26] There are three critical elasticities of substitution in the model. The elasticity of substitution between clean and dirty energy is selected to be equal to 3 in the range estimated by Papageorgiou and others (2013). The elasticity of substitution between energy and the capital-labor composite is selected to be equal to 0.25 in the range estimated by Van Der Werf (2008). The elasticity of substitution between skilled and unskilled labor is selected to be equal to 2, in the range estimated in the literature and discussed in Acemoglu and Autor (2011).

first case, the government uses the revenue to finance government spending on low-energy intensive goods. In the next two cases, the government uses the revenue to finance, respectively, a universal cash-transfer program, and a cash-transfer program targeted to the bottom two quintiles of the income distribution.

This section's main result is that without compensatory measures, carbon taxes lead to an increase in income inequality measured by the Gini coefficient (Annex Table 3.7.1). Income inequality increases because households at the bottom of the income distribution are impacted more by the carbon tax (Annex Figure 3.7.2). These households are affected by both the increase in energy prices and a reduction in wages. Unskilled workers' wages fall more than the wages of skilled workers. The skill premium increases because the carbon tax reduces the high-energy intensive goods' demand and unskilled workers work disproportionately more in this sector.

Annex Figure 3.7.2. Distributional Impact of Carbon Taxes
(Percent of household total consumption expenditure)



Source: IMF staff calculations.
Note: Panels 1 and 2 show the result of the multisector heterogeneous agent model simulation of a $50 tax per ton of carbon dioxide, 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, and (4) a subsidy to the consumption of clean energy. In panels 1 and 2, each bar shows the percentage change in consumption with respect to the baseline, in a model calibrated to the United States (Panel 1), and in a model calibrated to China (Panel 2). Q = quintile, where Q1 = bottom quintile and Q5 = top quintile.

When the revenue is used to finance a cash-transfer program instead of government spending, consumption of unskilled households goes up (Annex Figure 3.7.2), reducing income inequality to levels below the baseline, and this reduction is more considerable when the transfers are targeted to the bottom two quintiles of the income distribution.

Feebates are another tool that governments use to fight climate change. Feebates can be targeted to specific markets, and their impact on emissions depends on the size of the market and its energy intensity. This section considers a feebate scheme under which the revenue from the carbon tax is used to subsidize clean energy consumption. The feebate impacts the price of energy and high-energy intensive goods relative to low-energy intensive-good less than in the case of a pure carbon tax scheme because of the subsidy to clean energy. This mitigates the effects on the consumption of households at the bottom of the income distribution. In addition, because the revenue is used to subsidize clean energy consumption, and the production of clean energy is more intensive in unskilled labor than the production of dirty energy, feebates boost labor demand for unskilled workers. This boost in demand mitigates the carbon tax impact on the skill premium, reducing income inequality (Annex Table 3.7.1).

Annex Table 3.7.1. The Distributional Impact of Carbon Tax and Mitigation Measures
(Percent change)

	Low-energy government spending	Universal cash-transfers	Targeted cash-transfers	Feebates
United States				
Gini coefficient	0.35	-1.35	-2.24	-0.28
Skill premium	1.72	1.1	0.14	-0.41
China				
Gini coefficient	0.12	-3.81	-4.52	-0.27
Skill premium	2.52	1.53	0.24	-1.51

Source: IMF staff calculations.
Note: The Table shows the result of the multi-sector heterogeneous agent model simulation of a 50 US dollar per tCO_2 tax on carbon where the revenue is used to finance government spending on (1) low-energy intensive goods, (2) universal cash-transfers, (3) targeted cash-transfers to the bottom two quintiles of the income distribution, and (4) a subsidy to the consumption of clean energy. The table shows the percentage change with respect to the baseline of the Gini coefficient and the skill premium, measured as the ratio of wages of workers with more than high school education (skilled) over the wages of workers with at most high school education (unskilled).