CHAPTER 1

CLIMATE CROSSROADS: FISCAL POLICIES IN A WARMING WORLD

Introduction

The world is warming. The year 2023 is turning out to become the warmest one on record. According to the World Meteorological Organization, temperatures are likely to increase by more than 1.5 degrees Celsius (°C) above preindustrial levels within the coming five years. The Intergovernmental Panel on Climate Change predicts that under current trends, temperatures could increase by 3°C or more, relative to preindustrial levels, by 2100.[1] Such increases will have detrimental effects on lives and livelihoods through increased morbidity and mortality due to more prevalent infectious diseases and natural disasters; lower productivity in agriculture, fishing, and work exposed to extreme temperature conditions; and more frequent disruptions from extreme weather events and rising sea levels. The likelihood of climatic "tipping points"—such as the melting of glaciers and ice caps—increases with greater warming, bringing potential catastrophic consequences for life on the planet (IPCC 2021; Georgieva 2022; McKay and others 2022; Ditlevsen and Ditlevsen 2023).

Countries have recognized the need for urgent action to address global warming. In the 2015 Paris Agreement, they agreed to "hold the increase in the global average temperature to well below 2°C above preindustrial levels" and ideally to 1.5°C to avert catastrophic outcomes. Countries have also committed to longer-term targets for net zero emissions—cutting greenhouse gas emissions released into the atmosphere to as close to zero as possible, with the remaining emissions captured and stored—by about midcentury. Despite progress, large gaps in ambition and implementation exist (Figure 1.1).

Achieving temperature goals will require a fundamental transformation of consumption, production, and investment by households, firms, and governments over the coming years. Investment and innovation in green sectors, processes, and products, along with behavioral changes, should decrease emissions but will come at the expense of existing brown activities (Aghion and Howitt 2005; Stern and Valero 2021), creating new opportunities and risks (Mercure and others 2018; Gourinchas, Schwerhoff, and Spilimbergo 2023).

Fiscal policies will play a central role in such a transformation, including by creating a larger role for private sector financing (October 2023 *Global Financial Stability Report*, Chapter 3). A key question is how governments can encourage firms and households to decarbonize, through spending, taxation, or regulation or a combination of the three (Figure 1.2). The impact on public finances hinges critically on the decarbonization actions by firms and households as well as their responses to policies. A push for energy security is prompting countries to pursue a faster, but likely more bumpy, green transition (that is, a transition to low carbon energy and building resilience against climate risks), raising concerns that firms may not be ready to face the resulting higher energy costs. At the same time, fiscal policies will play a key role in mitigating the cost of transition for households and firms and guiding private sector decisions. Many countries—notably low-income countries and small developing states—have multiple competing development needs alongside the imperative to adapt to climate change, suggesting scope for global cooperation. Fiscal interventions in all these areas will need to respect government budget constraints. Assessing the fiscal implications of policies to achieve climate objectives is particularly pertinent at this juncture, as many countries are facing elevated debt levels, high inflation, and weak growth prospects. Rising geopolitical fragmentation also poses risks to cross-border climate technology diffusion (October 2023 *World Economic Outlook*, Chapter 3).

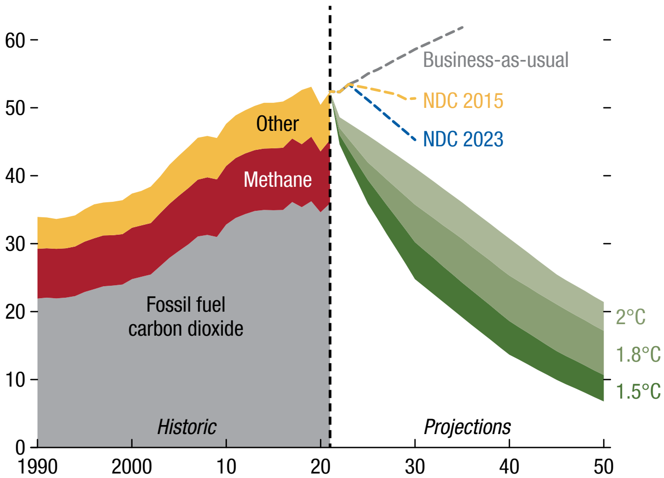
Against this background, this chapter addresses the following questions:

- *Can countries rely mostly on spending-based climate policies to achieve net zero emissions?*
- *How can policymakers design politically acceptable climate policies in a cost-effective and fiscally sustainable way?*
- *How can governments facilitate the green transition among firms?*

[1]The panel's central estimates under the "SSP2-4.5" scenario have a range for the increase as 2.1–3.5°C.

Figure 1.1. Annual Global Greenhouse Gas Emissions, 1990–2050

(Billions of tons of carbon dioxide emissions equivalence)



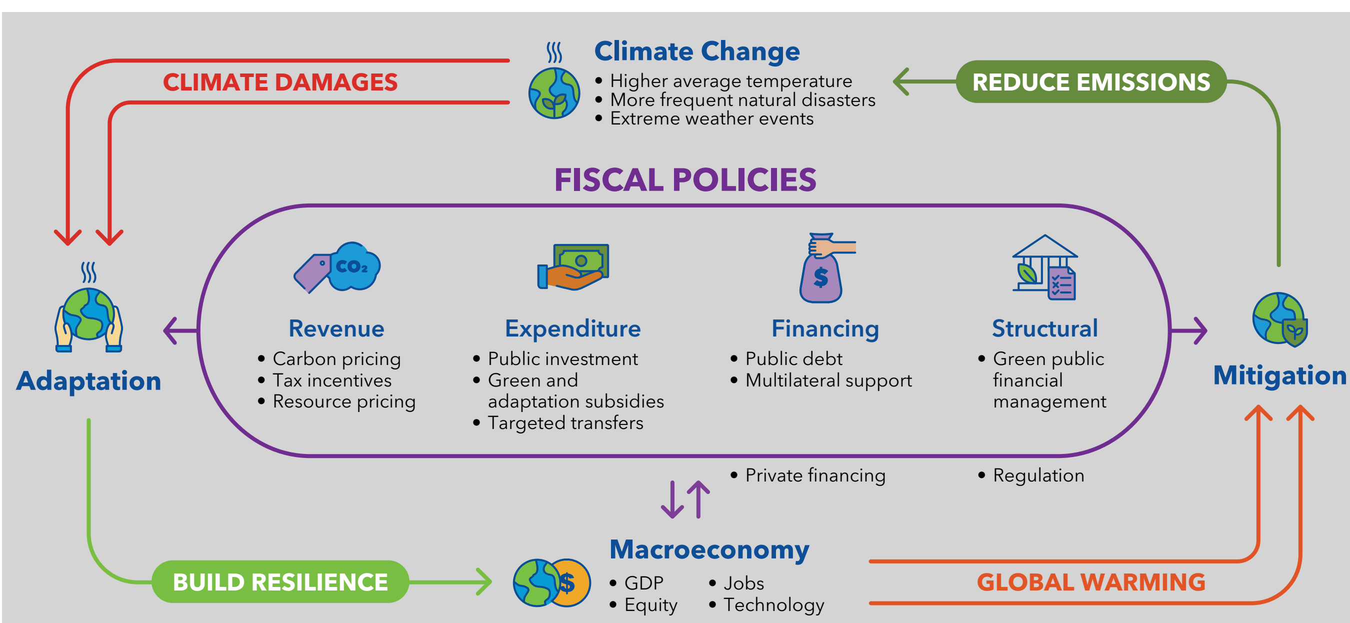
Sources: Intergovernmental Panel on Climate Change; Black, Parry, and Zhunussova 2023; and IMF staff estimates.
Note: The figure shows estimates from projection using the IMF–World Bank Climate Policy Assessment Tool. °C = degrees Celsius; NDC = nationally determined contribution.

The main contributions of the chapter include (1) conducting granular analyses to illustrate and quantify the fiscal impact and public debt implications across country groups during the green transition; (2) assessing the evolving optimal mix of climate instruments from a macrofiscal perspective in light of their cost-effectiveness, political acceptability, and other attributes; and (3) examining interactions among public incentives, green investment, and adoption of technologies by firms based on microlevel analyses, strengthening the case for using a mix of fiscal instruments. While the chapter focuses on domestic policies, it also highlights the role of international coordination in mitigation policies.

Are Current Policies Scalable on the Road to Net Zero?

Despite country efforts to meet their national climate goals, estimates using the IMF–World Bank Climate Policy Assessment Tool put the combined reduction in emissions as a result of existing and planned mitigation policies, relative to a baseline for 2030 without such policies, at 13 percent across the

Figure 1.2. The Green Transition Brings Close Interactions among Fiscal Policies, Climate, and Macroeconomy

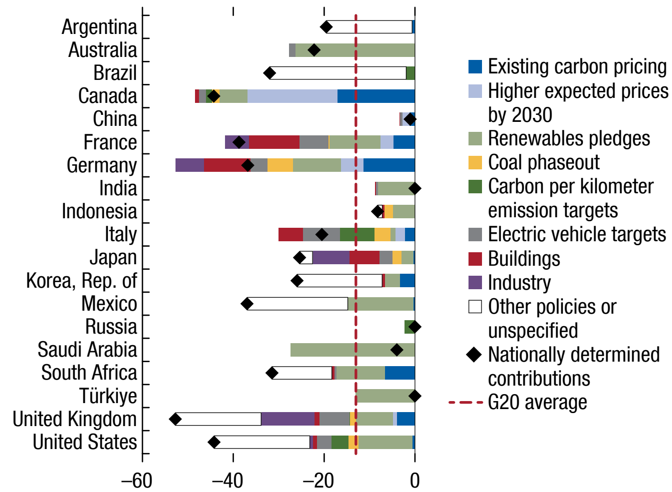


Source: IMF staff compilations.
Note: The green transition involves reducing greenhouse gas emissions and building resilience against climate risks. Economic activity emits greenhouse gases, leading to environmental damages, which could pose adverse economic impact. Mitigation policies aim to reduce emissions, while adaptation policies enhance resilience for countries to limit the disruptions to the economy. These point to intertwined linkages between fiscal policies, the macroeconomy, and climate outcomes.

Group of Twenty (Figure 1.3).[2] This falls significantly short of the 25–50 percent reduction by 2030 needed to achieve the Paris Agreement's temperature goals (Black, Parry, and Zhunussova 2023). The largest emitters, including *China,* the *European Union, India*, and the *United States,* together account for more than 60 percent of global emissions by 2030. The share of emerging market economies is expected to reach almost 70 percent by 2035, signifying their importance for global mitigation efforts.

Countries have pursued different policy mixes to curb emissions to date. An increasing number of countries have put an explicit carbon price on greenhouse gas emissions, but their carbon-pricing schemes cover only one-quarter of global emissions, and the average price is $20 a ton—well below the level of coverage and price needed to achieve net zero goals (IEA 2021; Black and others 2022a). Instead of raising prices on carbon emissions, some large economies have adopted policy packages that largely rely on spending-based measures such as investments in green infrastructure, public funding for investments in clean energy, and green subsidies (or tax expenditures) to provide incentives for private investment and adoption of low-carbon technologies. For example, the Inflation Reduction Act of 2022 represents the largest federal policy to date in the *United States* (costing nearly $400 billion over 10 years) to tackle climate change and envisages higher investment in clean energy and electric vehicles (Bistline, Mehrotra, and Wolfram 2023). Rapid deployment of clean energy-generating capacity and achieving the full potential of the Inflation Reduction Act will hinge on overcoming real-world challenges, such as delays in permitting and electricity transmission siting. The *European Union* has supplemented its carbon-pricing approach by proposing a Green Deal Industrial Plan comprising tax breaks and relaxation of state aid (subsidy) rules in the coming years to boost renewable investment by the private sector. *China* has scaled up green public investment and subsidized the deployment of solar energy over the last decade under its Made in China 2025 initiative. Some countries also have targets to reduce energy use in buildings (*France*, *Germany*, *Italy*, *Japan*), while others have set regulations for new buildings to have net zero emissions by 2030 (*Canada*, *Korea*, *South Africa*, *United States*) (Online Annex 1.1).

Figure 1.3. Impacts of Current Policies, Relative to No Climate Policies, on Carbon Dioxide Levels in 2030
(Percent reduction relative to no climate policies)



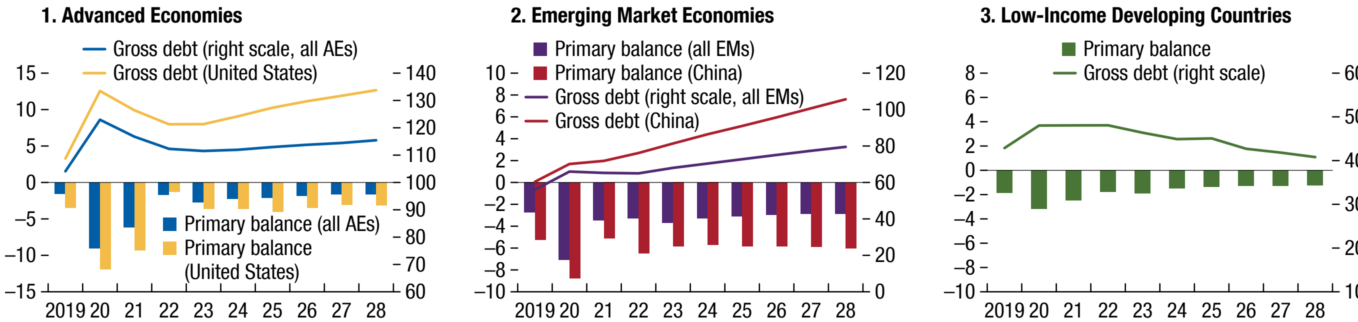
Source: IMF staff estimates using the IMF–World Bank Climate Policy Assessment Tool (see Online Annex 1.1).
Note: "Other policies or unspecified" includes policies not quantified here or not yet specified by national authorities. The no-climate-policy counterfactual implies that countries would stop any existing carbon pricing. The figure includes estimates of emission reductions from the power and industry sectors under the US Inflation Reduction Act. G20 = Group of Twenty.

These policies contribute toward reducing emissions and some are necessary to achieve specific targets, although they are not always cost-effective. For example, the carbon price equivalent for the sectoral policies shown in Figure 1.3 varies significantly, implying countries could have achieved the same mitigation goal at lower cost (Black and others 2022b).

Estimates by the International Energy Agency suggest that achieving net zero emissions by 2050 will require an additional global investment in mitigation of $2 trillion to $2.5 trillion over the next decade. Partly because of the substantial government budget constraints (discussed in the remainder of the chapter), private investment in low-carbon technologies—working in tandem with governments through fiscal incentives and regulatory measures—will need to account for the lion's share of this investment.

[2]The IMF–World Bank Climate Policy Assessment Tool is a spreadsheet-based model that helps policymakers assess, design, and implement climate mitigation policies, allowing them to estimate the effects of such policies for more than 200 countries. It includes impacts on energy demand and prices, emissions of carbon dioxide and other greenhouse gases, fiscal revenues, GDP, and welfare, as well as distributional impacts on households and industries and development co-benefits like health benefits from reductions in local air pollution and road accidents. See Black and others (2023b) for details.

Figure 1.4. Historic and Projected Public Debt and Primary Balance, 2019–28
(Percent of GDP)



Source: IMF, World Economic Outlook database.
Note: AEs = advanced economies; EMs = emerging markets.

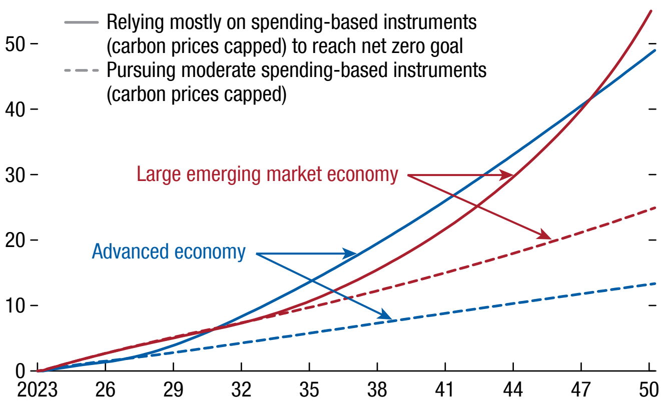
Elevated public debt levels across most countries are complicating climate challenges at the current juncture. Following a decline in 2021–22, global public debt ratios are projected to rise again in 2023 and to continue to increase by 1 percentage point a year over the medium term, growing faster than foreseen before the pandemic (Figure 1.4). Fiscal adjustments are necessary over the medium term to rebuild fiscal buffers. However, this leaves limited resources to achieve climate goals in many instances.

Relying largely on expenditure-based measures to achieve net zero emissions by midcentury would raise public debt-to-GDP ratios sharply and put debt sustainability at risk, as shown in an illustrative simulation (Online Annex 1.2).[3] For a representative advanced economy, the simulation considers a policy package that combines a carbon price of $75 a ton by 2030, maintained at that level until 2050, with spending-based mitigation policies that scale up public investment and subsidies. Private sector investment responds to government policies, and accounts for the lion's share of the total green investment needed for decarbonization in the model. The simulation considers two scenarios with regard to spending policies: a substantial scaling up of green investment and subsidies to reach the net zero goal (solid blue line in Figure 1.5), and a moderate increase in such spending to contain the rise in debt (dashed blue line in Figure 1.5). The former scenario entails a much larger fiscal cost, a significant rise in the debt-to-GDP ratio (by 45 percentage points by 2050), and an associated pickup in government borrowing costs. Rising debt levels of the magnitude projected in the scenario are likely unsustainable. A gradual erosion of existing fuel tax bases as the economy decarbonizes could exacerbate these risks.[4] In the scenario with a more moderate increase in expenditures, however, emissions would only fall by about 40 percent by 2050 from the current levels, insufficient to meet targets. Relying solely on carbon pricing to reach net zero would require a higher carbon price—at $280 per ton by 2050 according to simulations in Online Annex 1.2—that might be politically unpalatable in many countries, despite carbon pricing's effectiveness in reducing emissions and generating revenues. It could adversely affect output and lead to uneven transition costs among households, making carbon taxes—similar to other revenue measures—less popular to enact or expand (Känzig 2023; Metcalf 2023).

[3]The simulation employs a New Keynesian dynamic general equilibrium model with an energy input and a rich set of fiscal policies based on Traum and Yang (2015). In the model, energy is used in the production of final goods and generated from both green and brown sources. Each energy source employs private capital and labor, as well as public capital in the case of green energy (for example, electricity grids) and private investment subject to adjustment costs. Heterogeneity among households allows the distributional effects of climate policies to be analyzed. Fiscal policies include carbon pricing, green subsidies, public investment, and targeted transfers, as well as standard taxes on consumption, labor, and capital income. See details in Online Annex 1.2. Similar studies have been conducted for *France* (Pisani-Ferry and Mahfouz 2023) and the *United Kingdom* (Office of Budget Responsibility 2021), using country-specific assumptions. The October 2020 *World Economic Outlook* considers the impact of a near-term investment push on climate transition and the macroeconomy.

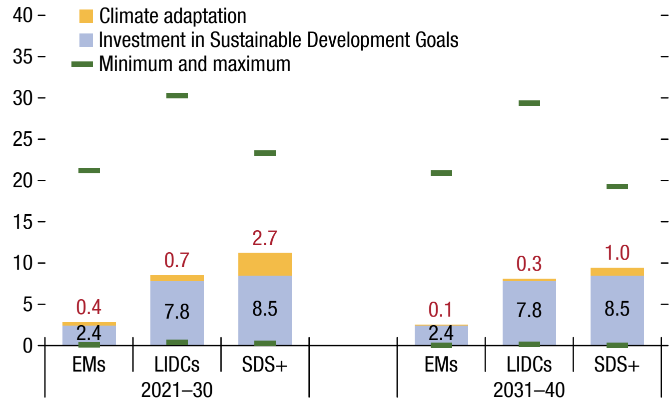
[4]If countries find alternative ways to finance the spending-based measures (other than through carbon taxes or deficit financing), the rise in debt levels will be smaller.

Figure 1.5. Illustrative Debt Dynamics When Expenditure-Based Climate Policies Are Expanded
(Percent of GDP)



Source: IMF staff simulations.
Note: The figure shows cumulative change in debt-to-GDP relative to a "business-as-usual" scenario based on simulations from a dynamic general equilibrium model (see Online Annex 1.2 for details). The lines for the advanced economy (large emerging market economy) cap the carbon price at $75 ($45) a ton. The solid lines scale up green public investment and subsidies (at 2 percent of GDP a year on average) to meet the net-zero-emissions target by 2050 (2060 for the emerging market economy), while the dashed lines have the same profile on carbon prices and a moderate rise in investment and subsidies, in line with International Energy Agency estimates.

Figure 1.6. Annual Investment Needs for Climate Adaptation and Sustainable Development Goals, 2021–40
(Percent of GDP)



Sources: Aligishiev, Bellon, and Massetti 2022; and IMF staff estimates based on IMF's SDG Financing Tool.
Note: The figure shows the investment needs across country groups related to additional climate adaptation needs and, for countries that have not done so, achieving the Sustainable Development Goals (SDGs). Lines indicate the minimum and maximum total investment needs. SDGs are assumed to be met by 2040 by spending a constant fraction of GDP each year. Additional climate adaptation needs refer to needs to build resilience. "SDS+" consists of developing small states as well as countries that have adaptation needs larger than 2.5 percent of GDP for 2021–30. EMs = emerging markets; LIDCs = low-income developing countries.

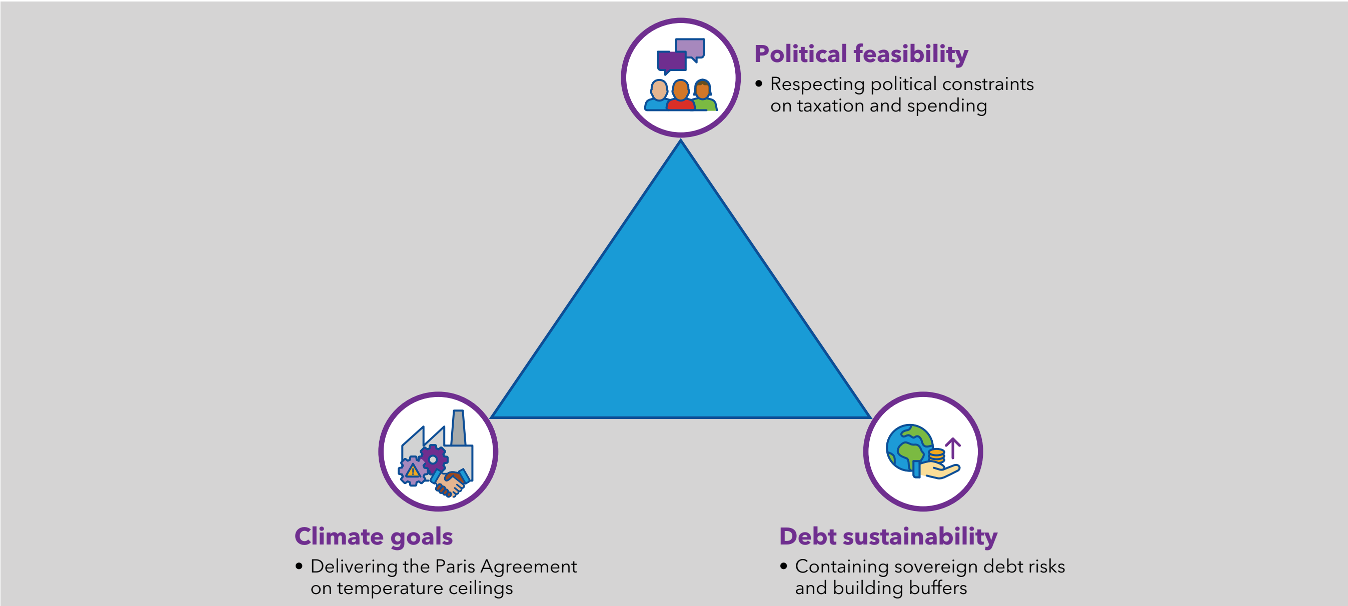
The key priority for emerging market and developing economies is growth and development. This already entails significant challenges with respect to public finances regarding raising tax capacity and enhancing the spending efficiency (Benitez and others 2023; Budina and others 2023). The green transition would entail additional fiscal costs, especially if they rely on expenditure-based measures. A comparable simulation for a representative large emerging market economy considers a cap on carbon prices at $45 a ton during 2030–50, together with a substantial increase in green investment and subsidies to reach net zero goals by 2060. Results of the simulation show that such a package would lead to an unsustainable surge in the debt-to-GDP ratio of more than 50 percentage points by 2050 (solid red line in Figure 1.5), with an associated sharp rise in borrowing costs. In the scenario with a more moderate increase in spending, emissions will only fall by 10 percent from current levels and will not be sufficient to achieve the net zero target (dashed red line in Figure 1.5).

Beyond investment in mitigation, many emerging market and developing economies need to build resilience and adapt to climate change. This is particularly the case for small developing states, which have the largest needs for climate adaptation, at an average 2.7 percent of GDP a year until 2030, in addition to their already-sizable needs for investment to meet other Sustainable Development Goals (Figure 1.6). Many low-income countries have no fiscal space, despite large needs in adaptation and relatively low-cost opportunities for abatement.

Fossil fuel-producing countries face a distinct fiscal challenge, as commodity revenues will decline markedly if the global economy pursues a path toward net zero emissions. Mesa Puyo and others (2023) estimate that for a group of 27 fossil fuel producers, fiscal revenue will decline by 5.5 percent of GDP on average between 2019 and 2040. These countries also need to reduce domestic emissions including from extractive industries, possibly adding to fiscal costs. However, the scope for using extractive revenues to finance economic development is highly sensitive to the pace of global decarbonization efforts (Box 1.2).[5]

[5]The impact on fossil fuel revenues depends on the scenarios of global transition, which affect the demand and production of fossil fuels. A given path for global fossil fuel production could be consistent with different price paths, implying a wide range of possible revenue and economic outcomes for fossil fuel-producing countries.

Figure 1.7. Climate Crossroads—Tackling the Climate Change Trilemma



Source: IMF staff compilations.

These issues point to a fundamental trilemma for policymakers between achieving (1) climate goals, (2) fiscal sustainability, and (3) political feasibility (Figure 1.7). If governments rely mostly on expenditure measures, this approach can be politically feasible, but debt will rise substantially. But if they instead continue on the current emission paths with only moderate measures, they cannot achieve their climate goals. Carbon pricing can relax fiscal pressures but—similar to other revenue measures—can be politically unpopular despite its efficacy in reducing emissions and revenue-generating potential (Klennert and others 2018; Douenne and Fabre 2022). The only way to jointly achieve these three goals is through a carefully calibrated mix of policies that varies across countries and involves carbon pricing alongside other measures to address distributional concerns and cost-of-living impacts, elaborated in the following sections.

Designing Efficient and Fiscally Responsible Policies

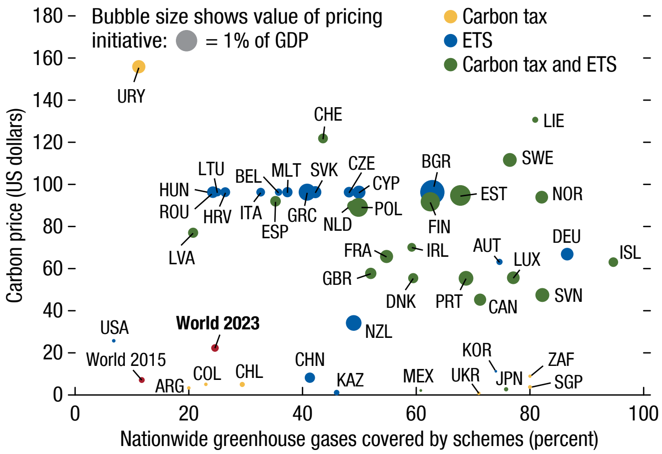
Governments need to design mitigation policy packages that effectively combine different instruments. This entails encouraging private sector behavioral shifts primarily through pricing mechanisms while accounting for (1) climate goals: choosing low-cost, efficient instruments for abatement to achieve emission reductions; (2) fiscal sustainability: exploiting scope for revenue mobilization; and (3) political feasibility. At the same time, the policy mix should include complementary measures to address market failures, for example, to facilitate investment, innovation, and technology deployment, as well as to address social, distributional, and political acceptability concerns. These instruments are elaborated in the following.

Economywide Mitigation Policies

Carbon pricing is necessary but not sufficient to reduce emissions (Nordhaus 2021). It is the principal economywide mitigation instrument and can take the form of a carbon tax or an emission trading system.[6]

[6]See the October 2019 *Fiscal Monitor* and Parry, Black, and Zhunussova (2022) for details on carbon taxes and emission trading systems. An example is the EU Emissions Trading System, which limits, via permits, emissions of specified pollutants from sectors such as power generation, energy-intensive manufacturing, and air transportation and allows firms to trade their emission permits (a "cap-and-trade scheme"). The cap for total EU-wide emissions tightens every year. Some firms are still receiving free allowances for certain emissions, but those allowances will be phased out by 2030. Emission trading systems typically require more involved administration and may not be practical in countries with small numbers of firms that do not have liquid trading in the market (Dechezleprêtre, Nachtigall, and Venmans 2018).

Figure 1.8. Explicit National, Subnational, and Regional Carbon-Pricing Schemes, 2022
(Carbon prices, US dollars)



Sources: National sources; World Bank, Carbon Pricing Dashboard; and IMF staff calculations.
Note: EU ETS includes *Iceland*, *Liechtenstein*, and *Norway*. Prices are weighted averages across schemes in a country. Country-specific values are calculated using sold auctions and average prices. *Mexico*'s subnational schemes and ETSs for *Indonesia* and *Montenegro* and are not included in the figure owing to lack of data. Data labels in the figure use International Organization for Standardization (ISO) country codes. ETS = emission trading system.

Economists find it to be the most efficient mitigation instrument, as it promotes the full range of behavioral responses to reduce energy use and shift to low-carbon fuels. It can also incentivize the private sector to innovate in and adopt new, low-carbon technologies, especially if a clear and credible rising price path is specified. Over the short to medium term, carbon pricing can raise substantial revenue, which can be used to finance other mitigation instruments and achieve broader economic and distributional objectives and thereby gain public support (Dabla-Norris and others 2023a; Dabla-Norris and others, forthcoming; Box 1.1). Carbon taxes are relatively easy to administer and can be integrated into existing procedures for collection of fuel taxes and extended to fossil fuels.

An increasing number of countries have adopted carbon pricing, suggesting that limited public support for carbon pricing is not a given. Carbon-pricing initiatives currently span 49 advanced and emerging market economies at various government levels, more than double the total one decade ago (Figure 1.8); at least 23 additional countries are planning to introduce carbon-pricing schemes, including *Kenya* as part of its efforts to achieve national emissions reduction targets (IMF 2023a). For example, *Sweden* successfully introduced a carbon tax in 1991 as part of a broader set of fiscal reforms that included cuts in corporate and personal taxes, alongside extensive social discussion to reinforce political trust and transparency. *Chile* introduced green taxes in 2014 as part of a broader tax reform package that also included increasing education and health care spending. The process included public consultations and commitment to present results periodically. *Singapore* introduced a carbon tax in 2019 and reduced policy uncertainty by announcing the scheduled tax path through 2030, with carbon revenues used to support decarbonization efforts and help businesses and households cope with the green transition.

That said, overcoming political hurdles is challenging, making it difficult to raise carbon prices significantly or expand coverage to broader economic activity. Even if governments can overcome the negative perceptions, carbon-pricing schemes alone will be insufficient to enable countries to achieve their climate goals. For instance, carbon pricing alone will not suffice in reducing emissions in hard-to-abate sectors such as buildings, which require stronger incentives to retrofit old structures (for example, with electric heat pumps) to cut consumption of fossil fuel-based energy.[7] Hence, carbon pricing is a necessary part of the policy mix but requires additional sectoral and other complementary policies.

In many countries, fuel excises provide an important source of fiscal revenues, generating between ½ and 1½ percent of GDP a year (de Mooij and others 2023). Over the medium to long term, however, those excises will decline as the carbon footprint of economies shrinks, requiring governments to collect alternative revenues to offset the loss, such as charges on vehicles per kilometer traveled (Online Annex 1.3). Elsewhere, countries still subsidize fossil fuels, sometimes at a high cost to government. Phasing them out provides opportunities to mitigate climate externalities and reduce fiscal costs.[8]

[7]Providing incentives for insulation and other retrofitting and for adopting energy-efficient appliances may require public support and could entail sizeable fiscal costs (UK Office of Budget Responsibility 2021; UNCTAD 2022a; Pisani-Ferry and Mahfouz 2023).

[8]According to Black and others (2023a), explicit fossil fuel price subsidies were $1.3 trillion (1.3 percent of global GDP) in 2022. However, the absence of a price for the environmental damages from global warming, local air pollution, and traffic congestion adds another implicit subsidy on fossil fuels. Including all those social costs yields a staggering $7 trillion (7.1 percent of global GDP) of total subsidies on fossil fuels.

Table 1.1. Comparison of Mitigation Instruments

Mitigation Instruments		Desirability and Feasibility				Environmental Effectiveness by Sector						
Coverage	Instrument	Economic Efficiency	Revenue Mobilization	Administrative Practicality	Political Acceptability	Power	Industry	Transport	Buildings	Forestry/ Land Use	Extractives (CH_4)	Livestock (CH_4, NO_x)
Economywide policies	Carbon taxes	dark green	dark green	dark green	red	✓✓✓	✓✓✓	✓✓	✓✓	✓	✓✓✓	✓✓✓
	Emission trading systems	dark green	light green	red	yellow	✓✓✓	✓✓✓	✓✓	✓✓	✓	✓✓	✓✓
Sectoral policies	Feebates (fees/rebates for dirty/clean firms/ products/activities)	light green	yellow	yellow	light green	✓✓	✓✓	✓✓✓	✓✓	✓✓	✓✓	✓✓
	Tradable performance standards	light green	yellow	red	light green	✓✓	✓✓	✓✓			✓	✓
	Green subsidies	light green	red	yellow	dark green	✓✓	✓✓	✓✓	✓	✓	✓	✓
	Requirements for green technologies/ activities	red	yellow	yellow	yellow	✓	✓	✓✓	✓✓	✓	✓	✓

Complementary policies					
	Issue	Network externalities for clean technologies	Innovation market failures	Burdens on households	Burdens on firms
	Instruments	Public investments	R&D incentives, timebound technology subsidies	Targeted assistance, equitable revenue use	Output-based rebates, tax relief, border adjustments

Color scale (dark green → light green → yellow → red): Declining efficiency/revenues/practicality/acceptability

✓ = Somewhat environmentally effective
✓✓ = Effective
✓✓✓ = Very effective

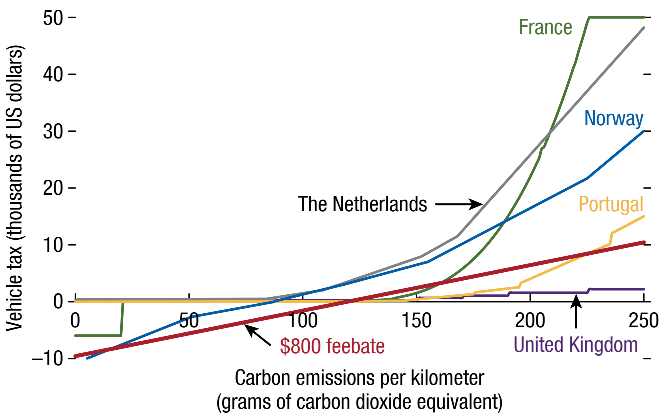
Source: IMF staff compilation.
Note: Environmental effectiveness reflects the extent to which policies exploit various potential behavioral responses for reducing emissions within a sector (based on economic theory and model simulations). CH_4 = methane; NO_x = nitrogen oxides; R&D = research and development.

Sectoral Mitigation Policies

Sectoral mitigation instruments complement carbon pricing in important ways. Depending on their design, they are generally politically acceptable, can promote a broad range of behavioral responses from households and firms for cutting emissions, and address certain market failures or externalities. Common sectoral mitigation instruments include the following (also see Table 1.1).

- *Feebates* involve a sliding scale of fees associated with (and rebates on) products or activities with emission rates above (below) a specified pivot point whereby energy efficient practices are rewarded. They encourage a decline in emission intensity in a particular sector, although they do not promote full behavioral responses. For example, feebates encourage people to buy electric or fuel-efficient vehicles, but they do not encourage people to drive less. They are revenue neutral if the pivot point is aligned with average emission rates and updated over time. European countries have increasingly integrated them into vehicle taxation—often with very high implicit carbon prices—promoting a rapid shift to electric vehicles in countries like *The Netherlands* and *Norway* (Figure 1.9). Feebates can also be applied to other sectors, although new administrative and technical capacity to monitor emissions is needed (Online Annex 1.4). Feebates usually have greater public support than carbon pricing, as they do not impose additional costs on the average household or firm.
- *Tradable performance standards* also provide broad incentives to reduce emission intensity. For example, firms are often required to meet a standard for average carbon emissions per kilowatt-hour across power generation plants or per ton of steel. Those that fall short of the standard can purchase credits from other firms that exceed the standard. Although such standards are usually politically acceptable, they do not raise significant fiscal revenue and require fluid markets for trading credits; thus, they are less practical for some sectors, such as forestry and residential buildings. *Canada* has a federal backstop program that includes an output-based pricing system for its industrial sector that concentrates taxation on large emitters to minimize

Figure 1.9. Effects of Feebates for New Vehicles, 2021



Sources: European Automobile Manufacturers' Association; and IMF staff estimates.

competitiveness and carbon leakage risks.[9] *China*'s tradable performance standard for the power sector, or intensity-based emission trading system, includes a benchmark on the maximum emissions per electricity generated.

- *Green subsidies* aim to overcome market failures and externalities related to the development, deployment, and adoption of low-carbon technologies.[10] Although subsidies are generally considered undesirable from an economic standpoint because of potential distortions, the urgent need for rapid global decarbonization, including through technological innovations, can justify their use to address market failures and other externalities common in climate change. For example, subsidies for research and development can overcome underinvestment by private firms in critical technologies. Deployment subsidies can help firms exploit economies of scale to speed up the use of established low-carbon technologies. For instance, as part of reforms enacted in 2014–16, *Egypt* provided incentives to invest in and operate renewable power projects and sell electricity via long-term power purchase agreements to stabilize electricity prices (known as a "feed-in subsidy"). Under its Contracts for Difference scheme, the *United Kingdom* offers subsidies for large-scale renewable energy projects, which gives private electricity generators greater certainty and reduces exposures to volatile wholesale prices. However, subsidies promote only limited mitigation responses. For example, subsidies for wind and solar generation only favor their use; they do not encourage a broad shift toward sources of less-polluting energy, such as from coal to gas or to other renewables. While subsidies often have strong domestic political appeal, they entail large fiscal costs and can generate negative spillovers, raising cross-border competitiveness concerns if not carefully designed or coordinated (Kammer 2023).[11]
- *Regulation or minimum standards.* Another type of sectoral policy involves regulations or requirements such as minimum shares of renewable use for power generators or minimum shares of electric vehicles in vehicle sales fleets. For instance, since 2023, *Colombia* has required power utilities to procure at least 10 percent of the electricity sold to end users from renewable energy sources. Regulations promote only narrow behavioral shifts, however. For example, requirements regarding shares of electric vehicles in vehicle sales do not promote shifts to more efficient internal combustion engine vehicles. Regulations are also unlikely to generate fiscal revenue and can be costly for firms to comply with, particularly small and medium-sized enterprises. Regulations can be made more flexible and cost-effective by allowing firms to pay a fee or purchase credits that exceed their requirements. While the public usually supports these measures, they can often be difficult to administer, as multiple entities are involved.

Complementary Policies

Complementary policies to address market failures, support private sector efforts, and ease burdens on households and firms can play a role in improving the public perception and political feasibility of mitigation policies. These policies are not substitutes for economywide and sectoral mitigation policies but can improve their effectiveness.

[9]The federal backstop does not apply in all provinces as some have opted for their own carbon pricing policy design.

[10]Subsidies are sometimes part of government efforts to promote low-carbon technologies through measures targeted toward specific domestic firms, industries, sectors, or regions to promote domestic innovation, adoption, and production, generally referred to as "green industrial policies."

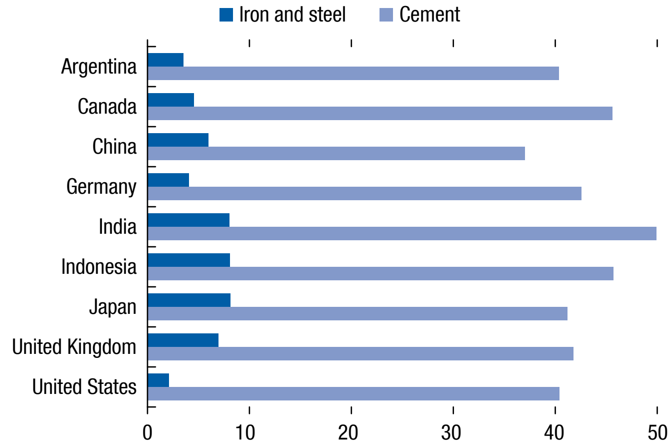
[11]Subsidies tend to be generally politically acceptable because, while their benefits are typically well understood, their costs in terms of higher taxes or lower spending elsewhere tend to be less salient to the public (Dabla-Norris and others 2023b).

Public investment. With the right mix of policies, the private sector will fund most clean investments for decarbonization. However, some large-scale investments—such as pipelines for clean hydrogen and carbon capture and storage, high-voltage transmission lines to link different plants using renewables to generate electricity, or charging stations for electric vehicles—could be undersupplied if left entirely to the market. At the global level, the required additional public investment (new green investment on clean technologies of 0.4 percent of GDP net of the decline in fossil fuel investment of 0.1 percent of GDP) is estimated at about 0.3 percent of GDP a year, on average, with the upfront capital costs concentrated over the next 20 years and declining thereafter (IEA 2021; IMF 2021). Governments can undertake green public investment to complement private capital. For example, the *United States* National Electric Vehicle Infrastructure Program provides $5 billion over five years to expand infrastructure for charging electric vehicles and establishing an interconnected national network. *India* has launched several initiatives regarding such infrastructure, notably the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles scheme.

Transfers. Climate measures such as phasing out fossil fuel subsidies and higher carbon prices will raise energy prices and, indirectly, the prices of other goods that use energy as an input. Governments can compensate households for the resulting impact by using a portion of the revenue from carbon-pricing schemes for targeted transfers to households, social safety nets, or lowering other taxes. Unemployment insurance coupled with active labor market policies could support workers in regions severely affected (Coady, Parry, and Shang 2018; October 2019 *Fiscal Monitor*). *Oman*, for example, started to phase out electricity subsidies in 2021 while protecting low-income households. *Indonesia*'s fuel reform in 2016 included targeted support for poor households, which was linked to its social assistance program.

Competitiveness. Unilateral pursuit of climate policies can raise cross-border competitiveness concerns. For example, production costs for energy-intensive, trade-exposed industries covered by carbon-pricing schemes would increase because of the associated costs to adopt emission reduction measures as well as from higher electricity costs. To avoid these costs, industries could relocate to other countries with less stringent emission standards or carbon pricing.

Figure 1.10. Change in Domestic Iron and Steel and Cement Production Costs from Baseline, 2030
(Percent)



Source: IMF staff estimates using the IMF–World Bank Climate Policy Assessment Tool.
Note: The pricing policy depicted in the figure imposes charges of $50 a ton of carbon dioxide. Production cost increases include mitigation costs and charges on unabated emissions.

Using the IMF–World Bank Climate Policy Assessment Tool, Figure 1.10 illustrates direct production cost increases, relative to baseline production costs, for iron and steel and cement under a unilaterally imposed carbon tax of $50 a ton in 2030. Production costs increase by about 5–10 percent for iron and steel but by a more substantial 35–50 percent for cement. Changes in sectoral emissions arising from moving production to countries with laxer emission standards (carbon leakage) are estimated at 10–30 percent, under plausible assumptions regarding production cost increases, pass-through into domestic consumer prices, and the cost of relocation (Parry and others 2023). These effects are small, however, relative to the economywide reductions in emissions that the tax achieves. Border carbon adjustments, in which a fee is charged on carbon embodied in imported products, possibly matched by rebates for exports to restore a level playing field for domestic and foreign firms, can mitigate these competitiveness concerns.[12]

[12]The *European Union* is phasing in a border carbon adjustment mechanism involving charges on imported aluminum, cement, steel, fertilizers, and electricity. It is also phasing out free allowance allocations under its Emission Trading System for domestic producers in the industries that produce these products. See Parry and others (2021) and Keen, Parry, and Roaf (2021) for a discussion of the economic and legal aspects of border carbon adjustments.

However, such adjustments need to account for carbon pricing in trading partners, limit administrative burdens, and avoid violating World Trade Organization rules.

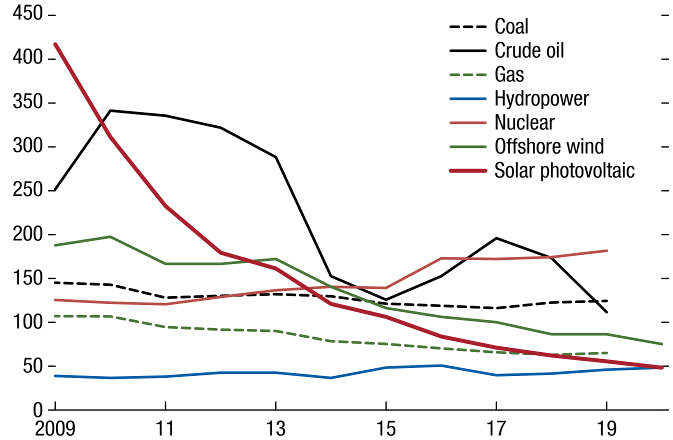
Promoting Technology Diffusion and Innovation

Technological innovation and deployment of low-carbon technologies will play a key role in achieving global climate mitigation goals. Overcoming obstacles to diffusion is crucial, as many technologies for emission reductions already exist. According to the International Energy Agency (2020, 2022a), use of known and commercially proven technologies can achieve about 90 percent of the emission reductions necessary to achieve climate goals by 2030. The cost of many of these technologies has already decreased significantly during recent years (Figure 1.11). Solar power has become the most affordable renewable source of electricity—even cheaper than fossil fuels—thanks to modular production, installation efficiency, economies of scale, learning-by-doing effects, and government support from various countries (IEA 2020b; see Online Annex 1.5). However, financing and capacity limitations hinder the adoption of clean frontier technologies in emerging market and developing economies (UNCTAD 2022b; Capelle, Pierri, and Bauer 2023). Moreover, government policies and network infrastructure can play a vital role in the adoption and deployment of low-carbon technologies. For instance, renewables require electricity markets with low regulatory barriers to encourage private sector participation, while the electrification of energy end use in transportation, industry, and buildings requires upgraded grid technologies.

In the medium to long term, new technologies will be necessary, including those that are currently in the early stages and not yet commercially available. For instance, carbon capture and storage is still in its infancy—even though efforts to accelerate adoption have been ongoing for decades. A key challenge for technology adoption is that firms pioneering the technology may not fully capture the spillover benefits that other firms imitating the technology could gain by leveraging the knowledge or benefiting from the learning-by-doing experiences. Fiscal interventions are thus likely needed, including through public research and development, as well as incentives for private research and development through patents, research subsidies, tax incentives, prizes, or some combination

Figure 1.11. Learning Curves for Power Generation, by Technologies

(US dollars per megawatt-hour)



Sources: IRENA 2022; Way and others 2022; and Ziegler and Trancik 2021a, 2021b.
Note: The figure shows the levelized cost of electricity: The average net present cost of electricity generation over the lifetime of the generator.

of these.[13] However, these incentives need to be carefully designed.

An increasing number of countries are adopting policies to promote domestic innovation, adoption, and production of low-carbon technologies, such as subsidies and tax incentives for specific domestic firms, industries, sectors, or regions. Such policies will need to be time bound, transparently presented in budgets under a strong governance framework, and complemented with carbon pricing. They should not violate the legal obligations imposed by trade agreements; international coordination is required to minimize adverse spillovers. When implemented in accordance with these principles, such policies could accelerate decarbonization. However, uncoordinated actions pose significant risks by distorting trade and investment flows and could give rise to competitiveness concerns and a "subsidy race" that harms developing countries (Cherif and others 2022; IMF, forthcoming). Other instruments such as government credit guarantees and public-private partnerships, often

[13]In principle, with a robust and efficient price for carbon emissions, additional incentives for development of clean technology should be similar to those for general research and development. Additional treatment can be warranted if the appropriability problem is more severe for clean technologies than for other technologies. This may be plausible in regard to technologies that are currently far from the market (for example, green hydrogen–based energy).

carry fiscal risks and need to be monitored closely under strong institutional frameworks (Battersby and others 2022).

Technology transfer and stronger institutions are conducive to technology absorption. They require robust legal and regulatory frameworks, transparent governance, property rights enforcement, and fair competition (Kiessling 2007; Manca 2009; Budina and others 2023). Moreover, enhancing development of human capital and investment in information and communications technology and other infrastructure can effectively harness the benefits.

Debt Impact of Climate Policy Packages

This section considers a policy package that achieves net zero emissions by midcentury. The package combines revenue and expenditure measures, including carbon pricing (to reduce emissions efficiently and generate fiscal revenues), green public investment (to complement green private capital), green subsidies (to encourage innovation and deployment of clean energy), and targeted transfers (to mitigate adverse impacts on households during the green transition). In this scenario, the private sector is expected to fund the majority of investment for decarbonization. The analysis operationalizes the net-zero-emissions target as an 80 percent reduction in 2023 emission levels by 2050 for advanced economies and by 2060 for emerging market economies, with the assumption that carbon capture and storage will offset the remaining emissions (IMF 2021; Black and others 2022a).

Using the same dynamic general equilibrium model as in "Are Current Policies Scalable on the Road to Net Zero?" this section simulates the effects of this policy package on debt dynamics for a representative advanced economy and emerging market economy. The effects of the policy package also depend on how fiscal instruments affect growth and interest rates. For instance, carbon pricing will increase government revenues but reduce near-term output. Expenditure measures will support output in the short term, while higher public capital will add to the economies' productive capacity, boosting long-term output. However, higher expenditures raise budget deficits and add to the pressures on interest rates and government borrowing costs by raising the demand for capital (macroeconomic channel) and increasing the supply of government debt (fiscal channel). The balance between carbon-pricing and expenditure measures in the overall package, as well as the endogenous effects on output and interest rates, determine the debt dynamics between today and 2050.

Advanced Economies

For a representative advanced economy calibrated to the average of data for Group of Seven economies, the simulated policy package requires an ambitious increase in carbon pricing, with the price reaching \$130 a ton by 2030 and \$235 a ton by 2050.[14] Despite rising carbon prices, revenues from carbon sources are projected to peak in about 2030, as decarbonization gradually erodes the carbon tax base. Hence, despite increasing carbon prices, carbon revenues as a share of GDP decline during 2030–50. On the expenditure side, the simulations assume a combination of an increase in green public investment and front-loaded green subsidies equivalent to about ½ percent of GDP, and transfers equivalent to 30 percent of carbon revenue (Känzig 2023).

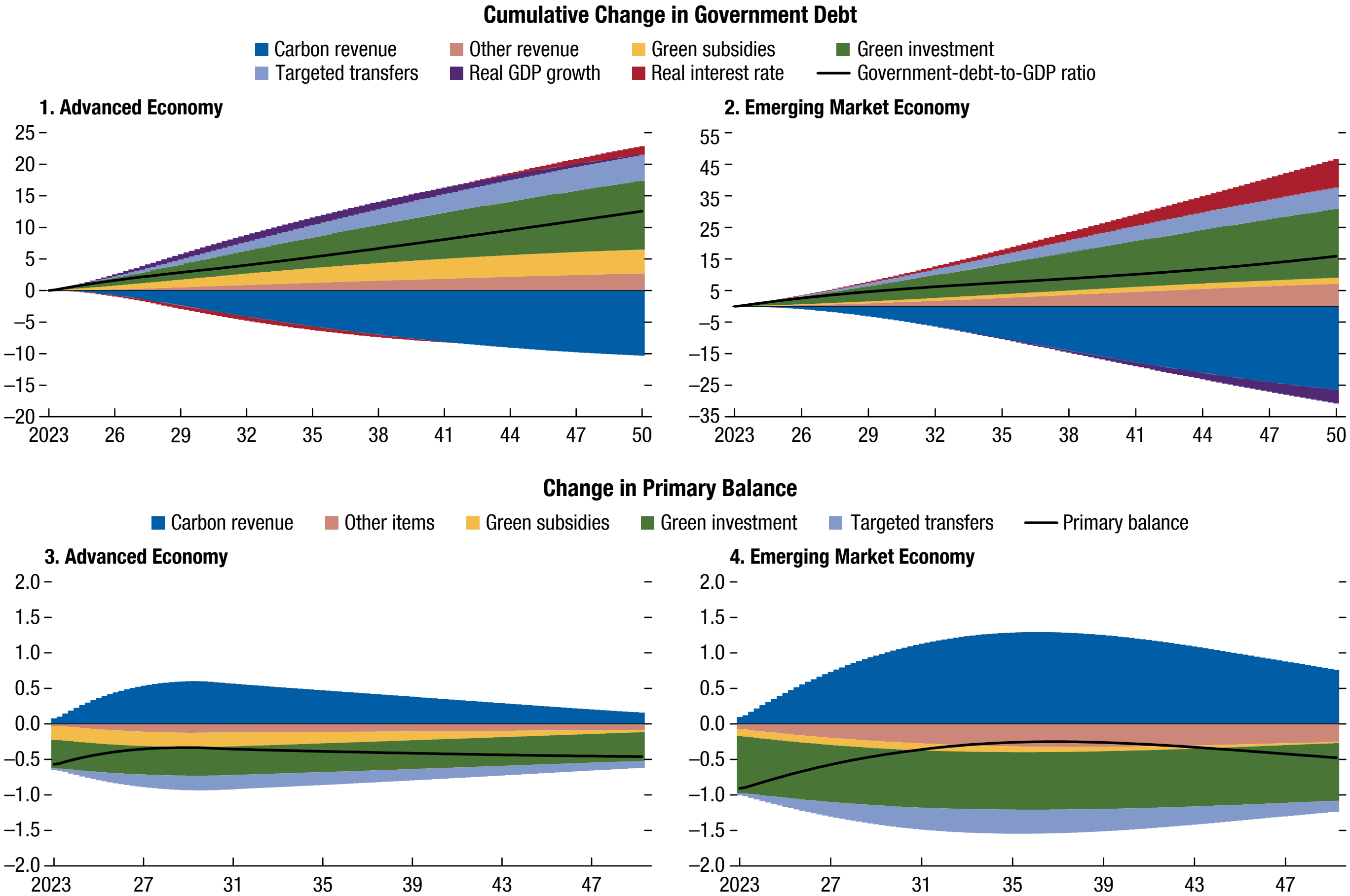
On balance, the debt-to-GDP ratio in this representative advanced economy increases by 10–15 percentage points by 2050, with the primary deficit rising moderately, by 0.4 percent of GDP a year, relative to the "business-as-usual" baseline in this scenario (Figure 1.12, panels 1 and 3) (Online Annex 1.2). Interest rate effects would be relatively muted because government debt would rise moderately, and lower demand for capital in brown sectors would partly offset the higher demand for capital in the green sector. Some advanced economies may have fiscal space to pursue such a combination of fiscal policies to meet the net-zero-emissions goal while maintaining debt sustainability. Countries can also raise revenues from other taxes or reduce other spending to contain the rise in debt.

Emerging Market and Developing Economies

A similar simulation is conducted for a representative large emerging market economy but with several differences compared to the representative advanced economy. First, most emerging markets currently have a lower share of

[14]The carbon prices are in line with the net-zero-emission scenario in IEA (2021). A price of \$235 a ton by 2050 is lower than the \$280 a ton by 2050 that would be necessary to achieve net zero emissions if carbon pricing were the only instrument used.

Figure 1.12. Implications of Net-Zero-Policy Packages on Debt and Primary Balance, Relative to "Business-as-Usual" Baseline, by Fiscal Component
(Percent of GDP)



Source: IMF staff simulations.
Note: For advanced economies, parameters and fiscal instruments are calibrated to a representative large advanced economy (that represents the average of data for Group of Seven economies). The policy package is designed to achieve net zero emissions in 2050. The value for public investment is consistent with the upper range of estimates by the International Energy Agency (2022b). Green subsidies are assumed to be front loaded and phased out after 2030, and targeted transfers are assumed to be proportional (at 30 percent) to carbon revenues. Given later emission peaks in emerging market economies, the policy package for those economies is designed to achieve net zero emissions by 2060. "Other revenue" includes taxes from capital, labor, and consumption, which vary owing to endogenous effects from macroeconomic variables even though tax rates are held the same. Parameters and fiscal instruments are calibrated to a representative emerging market economy that is assumed to reflect the weighted average of data for *Argentina*, *Brazil*, *China*, *India*, *Indonesia*, *Mexico*, *South Africa*, and *Türkiye*. The value for public investment is consistent with the upper range of International Energy Agency estimates for emerging market economies. For details, see Online Annex 1.2.

green energy than advanced economies and will have a lower carbon price during the initial phase of decarbonization—assumed in the simulation to reach $45 a ton by 2030, gradually rising to $150 a ton by 2050. Yet this lower carbon price yields greater carbon revenue than the case in an advanced economy for a longer period and leads to a later peak in emissions and carbon revenue (Figure 1.12, panels 2 and 4).[15] Second, green investment needs in emerging market economies are larger (at ¾ percent of GDP per year), owing to different ownership structures and less private investment in mitigation, consistent with International Energy Agency (2022b) estimates. Third, emerging market economies also face a higher risk premium—that is, greater sensitivity of borrowing costs to rising debt levels. Transfers to vulnerable households are assumed to be 30 percent of carbon revenue, the same as the scenario for advanced economies.

Incorporating these distinctive features and specific assumptions, the model simulation of this

[15]The simulations are based on *effective* carbon prices and so implicitly capture the effect of removing fossil fuel subsidies.

illustrative scenario suggests that public debt would increase by about 15 percent of GDP by 2050 in these economies relative to the "business-as-usual" baseline, equivalent to a rise in primary deficits by 0.4 percentage point of GDP a year on average (Figure 1.12, panel 4). The simulated rise in debt is subject to a wide range of 8–25 percent of GDP by 2050, depending on public investment, subsidies, and targeted transfers, as well as whether countries are fossil fuel producers (see alternative scenarios in Online Annex 1.2).[16] While the increase in debt-to-GDP ratio is comparable to advanced economies, the composition is different, with larger contributions from interest costs and higher public investment needs, while carbon revenues are higher.

Many emerging market economies would find the increases in debt and deficits challenging, especially those already experiencing high debt, as rising borrowing costs lead to higher interest payments and account for a sizable part of the deteriorating debt dynamics. As a result, they would be unable to afford a large redistribution of carbon revenues or meet their public investment needs. These call for improving spending efficiency and mobilizing alternative sources of finance, including other domestic tax revenues (Benitez and others 2023), and a greater role for private financing. A well-calibrated fiscal strategy could crowd-in private investment and financing to jumpstart growth, critical for emerging markets with limited fiscal space. Low-income developing countries should prioritize reducing energy intensity and adapting to climate change, given limited access to financing and modest contributions to global emissions. Reconciling climate challenges with growth and development needs in emerging market and developing economies therefore calls for efforts to mobilize domestic revenues and global financial support. For example, the IMF Resilience and Sustainability Trust provides long-term financing—which augments fiscal space and financial buffers—to strengthen economic resilience and support reforms that reduce risks associated with longer-term structural challenges, including climate change. The involvement of multilateral development banks plays a role to leverage private investment and provide risk-absorption capacity (October 2022 *Global Financial Stability Report*, Chapter 2). Moreover, knowledge transfers and deployment of established low-carbon technologies in these economies will be critical to raising productivity, crowding in private sector investment, and reducing overall fiscal costs (Online Annex 1.2).

[16]Fiscal costs will vary depending on the mix of revenue and spending policies. Sensitivity analysis shows that if government transfers are 50 percent of the revenue from carbon taxes, debt would rise by 25 percentage points of GDP by 2050, with an increase in primary deficits of 0.6 percentage point of GDP a year on average. If instead public mitigation investment and subsidy is reduced by about ¼ percent of GDP per year, debt would increase by 8 percentage points of GDP. Alternatively, if climate policies primarily rely on carbon pricing (higher than the baseline) with modest public investment of ¼ percent of GDP per year with no subsidy spending, the resulting carbon revenues can more than offset the investment spending and related transfers to households, leading to a small primary surplus, especially during the peak of carbon revenue (see Online Annex 1.2).

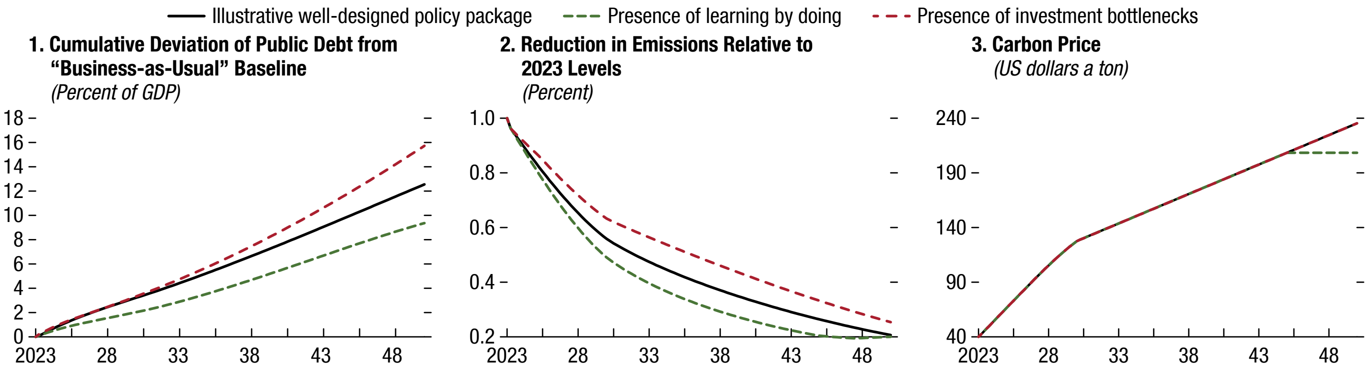
Technology Spillovers and Investment Bottlenecks

The effectiveness of green subsidies will depend on how firms respond to fiscal incentives and how easily they can shift to, or invest in, low-carbon technologies. Model simulations show that green subsidies will be more effective if learning-by-doing effects in clean technologies are present, allowing a faster reduction in emissions and limiting the associated output costs, while keeping public debt contained (dashed green line in Figure 1.13). However, bottlenecks to green investment, such as limited institutional capacities and disruptions in supply chains for critical minerals because of geoeconomic fragmentation (October 2023 *World Economic Outlook*, Chapter 3), could limit the potential for rapid uptake of green technology. Stranded assets in brown sectors—assets that need to be written down prior to the end of their economic life, such as old coal plants—could also be costly to divest or phase out. Such bottlenecks, if they take the form of adjustment costs imposed on investment, would slow the shift toward renewable energy, making green subsidies less effective and causing debt-to-GDP ratios to rise further (dashed red line in Figure 1.13). This also implies that emission targets may not be reached unless more forceful action through other measures, such as higher carbon prices, is taken.

The model is next used to explore different assumptions and policy packages. This exploration provides several key lessons in respect to policy design:

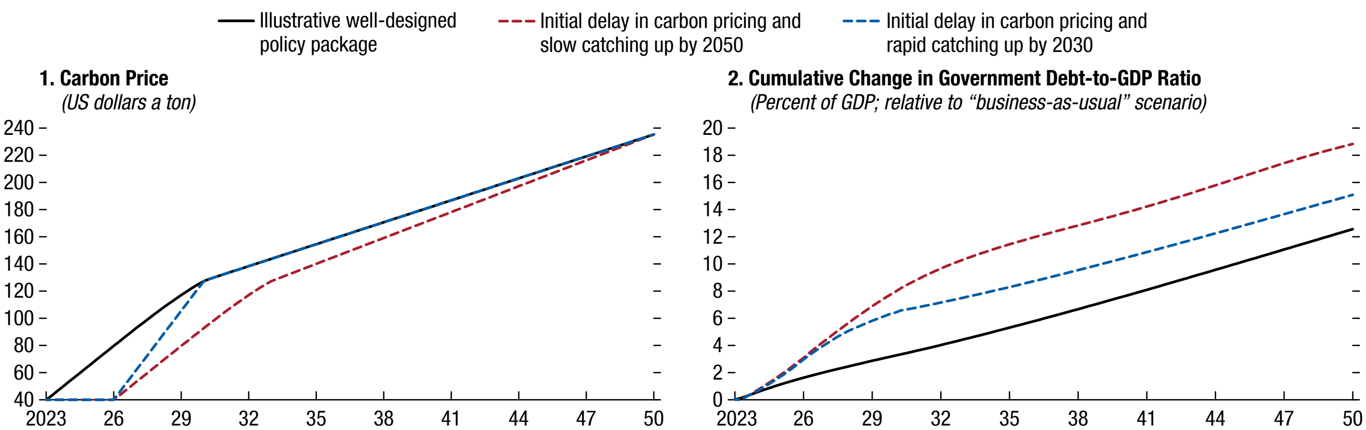
- *Delaying action on carbon pricing is costly.* Each year of delay in raising carbon prices is found to increase public debt by 0.8–2.0 percentage points of GDP in advanced economies, depending on how quickly carbon prices adjust after the initial delays and

Figure 1.13. Impact of Technology Spillovers and Investment Bottlenecks on Debt Dynamics



Source: IMF staff simulations.
Note: The figure assumes carbon prices are the same across scenarios before reaching net-zero-emission goals and is calibrated to a representative advanced economy (that reflects the average of the data for Group of Seven economies). When learning by doing is present, a 1 percent increase in energy capital is assumed to raise total factor productivity by 0.1 percent in the energy sector, in accordance with Chang, Gomes, and Schorfheide (2002) and Dietz and Stern (2015).

Figure 1.14. Costs of Delay in Raising Carbon Prices



Source: IMF staff estimates.
Note: The scenario depicted in the figure assumes a three-year delay (from 2023 to 2026) in raising carbon prices relative to the illustrative well-designed policy package for the representative advanced economy in the chapter text.

assuming that spending-based policies are scaled up to deliver the same level of emission reductions by 2050 (Figure 1.14; Online Annex 1.2). Although carbon revenues are projected to peak later for emerging market economies, delays would still increase debt in a notable way (about 0.9 percentage point of GDP), even when carbon prices catch up quickly following the initial delay. The longer countries wait to make the shift to a greener future, the costs will likely be larger (October 2022 *World Economic Outlook*, Chapter 3).

- *Policy sequencing matters.* Although public debt would likely increase during the green transition, combining fiscal instruments strategically can limit the rise in debt. For instance, the initial rise in carbon tax revenues could be timed to coincide with front-loaded expenditures on green subsidies, containing the impact on deficits. Delaying carbon revenues until after emissions have peaked will decrease the revenue base and widen fiscal deficits in the interim.
- *Accounting for technology spillovers and addressing investment bottlenecks is critical.* The presence of externalities or spillovers can increase the effectiveness of green subsidies, enabling lower decarbonization cost. At the same time, addressing bottlenecks, such as reducing trade frictions or diversifying supply chains, will allow firms to shift swiftly toward clean energy. At the international level, augmenting international climate finance

can facilitate trade in low-carbon technologies and their components and scaling up of technology transfer (IMF 2021).

- *Catalyzing private climate finance will help decarbonization.* Existing commercially proven technologies have potential to promote decarbonization. Policies that price carbon or otherwise incentivize these technologies help catalyze private climate finance and accelerate the shift toward clean energy and technologies. Catalyzing private climate finance can take many forms, including the use of subsidies, environmental regulations, and strengthening the climate information architecture (data, disclosure, and taxonomies), as well as public-private risk sharing through blended finance structures (October 2023 *Global Financial Stability Report*, Chapter 3). However, some instruments, such as government credit guarantees, can be associated with large fiscal risks.
- *Incorporating climate actions in debt sustainability analysis is essential.* Projected debt levels show considerable uncertainty, depending on the size of investment needs, assumptions about the elasticity of substitution between energy sources, the economic impact of fiscal policies, and the degree to which firms and households take up different tax credits and subsidies (Online Annex 1.2). In addition, the effects of global warming on economies are also subject to considerable uncertainty. Some mitigation policy packages for emerging market economies may turn out to be less affordable than others, which will require further mobilizing domestic tax revenues and incentivizing greater private financing. The uncertainty about the path that debt will take highlights the need to develop further tools to incorporate climate actions into debt sustainability analysis.[17]

[17]For example, the IMF Quantitative Climate Change Risk Assessment Fiscal Tool assesses the fiscal risks from long-term climate change by quantifying climate scenarios against a baseline (Harris and others 2022; Harris, Tim, and Rahman 2023). The IMF's Sustainable Development Goals–Climate tool integrates climate change and natural disaster risks into a dynamic growth model to assess the financing and debt trade-offs of policies in reaching Sustainable Development Goals (Bartolini and others 2023). Akanbi, Gbohoui, and Lam (2023) provide a tool in calibrating fiscal rules considering natural disaster risks. In addition, the IMF has made efforts to improve the availability of quality climate data to support decision making and foster public awareness, such as the IMF Climate Change Indicators Dashboard and related publication on *Data for a Greener World* (IMF 2023b) and IMF Data Standards Initiatives. The IMF continues to work toward enhancing the climate information architecture, collaborating with international standard setters and international financial institutions.

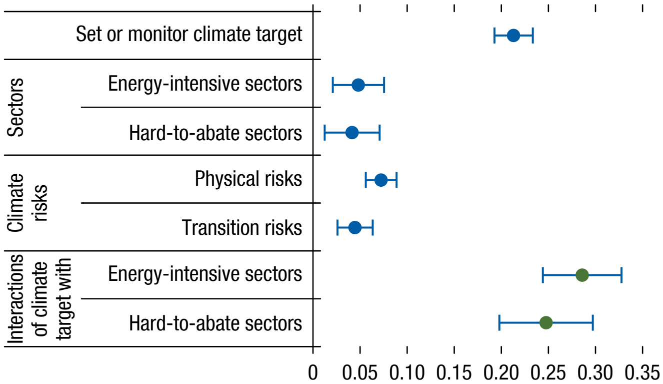
The effects of climate policies on debt dynamics also reflect the uneven impacts of such policies across age groups. Analysis based on an overlapping-generations model (Kotlikoff and others 2021) shows that mitigating the adverse impact of the green transition on current age cohorts through debt-financed transfers will impose higher taxes on future cohorts to finance future debt service (Online Annex 1.6). In contrast, if governments pursue a balanced-budget policy, each generation will bear the cost of contemporaneous climate change mitigation efforts. Current generations may be reluctant to advance climate mitigation, as they bear most of the costs, whereas future generations would suffer from worse climate outcomes arising from limited action today.

Rising public debt and scaled-up green public investment point to the need for strengthening fiscal frameworks and institutions to enhance spending efficiency and improving debt and investment management and practices (Online Annex 1.7). Green public financial management integrates climate considerations into existing budget processes. Existing frameworks can be adapted to prioritize and direct scarce resources to policies that respond to climate concerns. Public financial management should also promote transparency and accountability for the climate impact of fiscal policies. Moreover, governments need to ensure green public investment is routed through the usual budget channels. Alternative systems dedicated to green investments—such as extrabudgetary operations or provisions to exclude green investment in fiscal rules—run the risk of fragmenting the budget and fiscal decision making. While project-specific financing can attract private investors, earmarking public resources risks creating budget rigidities.

Facilitating Green Transition in Firms

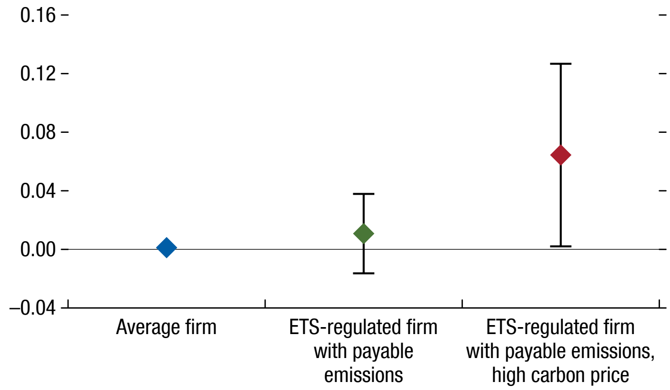
The green transition will require strong complementary actions on the part of public and private actors because—as discussed earlier in the chapter—firms will need to undertake the majority of decarbonization efforts, working in tandem with governments to shift toward clean energy and technologies. Regulatory measures and fiscal incentives can encourage firms to improve energy efficiency, reduce their energy use, or invest in or adopt low-carbon technologies. This section examines the impact of these policies on firms' climate investments and resilience to higher energy prices, strengthening the case for using a mix of

Figure 1.15. Likelihood of Investing in Mitigation: New, Less-Polluting Technology
(Coefficient estimates)



Sources: European Investment Bank Group Survey on Investment and Investment Finance 2022; and IMF staff estimates.
Note: The figure shows estimated coefficients obtained from a linear regression model that includes country fixed effects and robust standard errors (see Online Annex 1.8). The dependent variable is binary, based on firms' responses to a survey question on whether they are investing in new, less-polluting business areas and technologies to reduce their greenhouse gas emissions. Results are consistent with the findings of the 2023 *EIB Investment Report*. The whiskers indicate the 95 percent confidence interval for the estimated coefficients.

Figure 1.16. Environmental Policy Stringency and Changes in European Firms' Investment
(Coefficient estimates)



Sources: EU Emissions Trading System (ETS); European Investment Bank; IMF, World Economic Outlook database; Kalantzis and others, forthcoming; Orbis; and Organisation for Economic Co-operation and Development (OECD).
Note: The figure shows estimated coefficients obtained from a panel regression model for 12 European countries during 1995–2020 (see Online Annex 1.8). The dependent variable is changes in fixed assets (in logarithms) as a proxy for investment. Each coefficient estimate represents the impact of changes in the OECD's market-based Environmental Policy Stringency Index for the indicated sample of firms. "ETS-regulated firms" are those with regulated installations in the EU ETS. "Payable emissions" are the difference between verified emissions and free allowances. "High carbon price" refers to periods when EU carbon price exceeds 75th percentile. The whiskers indicate the 95 percent confidence interval for the estimated coefficients.

instruments, including carbon pricing, to facilitate decarbonization.

Regulations can enhance firm investment in low-carbon technologies. Analysis of a representative firm-level survey from the European Investment Bank[18] provides evidence that firms that set or monitor emissions, particularly those operating in energy-intensive or hard-to-abate sectors (which are often subject to government regulations or emission standards) are among the most likely to invest in new, less-polluting technologies or products (Figure 1.15; Online Annex 1.8).[19]

The stringency of regulatory policies associated with climate also affects the investment behavior of firms. To explore this, the analysis here examines firms regulated under the EU Emissions Trading System. It suggests that more stringent market-based policies that put a price on pollution, such as permit prices in carbon-trading schemes and taxes on greenhouse gas emissions, have a significant positive impact on the investment by firms regulated under the system, but only in periods of already-high carbon prices and when emissions exceed allowance levels (Figure 1.16). However, these regulations have no significant impact when emissions are within their free allowance levels. These findings suggest a reinforcing role between high carbon prices and market-based regulatory measures, in which stringent policies could provide incentives for investment by firms if they need to pay for emissions at high carbon prices (Online Annex 1.8).

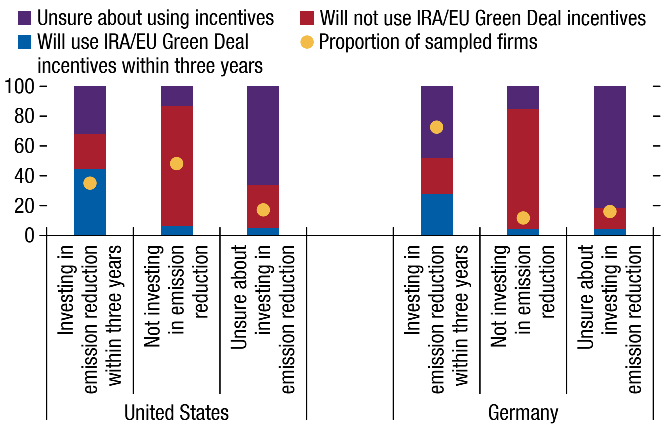
An important question is whether firms are sufficiently resilient to respond to a rise in the cost of carbon-based energy. To assess firm responses to shocks to energy cost, this section explores how firms have responded to the energy price hike of 2022. Two surveys of firms in *Germany* and the *United States* (Online Annex 1.9) show that firm balance sheets have

[18]The European Investment Bank Group Survey on Investment and Investment Finance is a survey, administered by the European Investment Bank, covering all *European Union* 27 countries, the *United Kingdom* (until 2021), and the *United States* (since 2019), comprising approximately 13,000 firms annually. The survey is designed to be representative at the country level as well as sector and firm-size levels for most countries. For technical details, please see Brutscher and others (2020).

[19]While firm-level data cannot distinguish between mandatory and voluntary climate targets, the empirical result corroborates findings in existing literature that firm-level climate targets are positively correlated with investment in renewable energy and emission reduction (Ioannou, Li, and Serafeim 2016; Wang and Sueyoshi 2018; Dahlmann, Branicki, and Brammer 2019; Colmer and others 2022), with stronger effects for firms in energy-intensive sectors or in sectors with high abatement costs. Several advanced economies, among them *France*, *Japan*, *New Zealand*, and the *United States*, have regulations mandating firms' disclosures of climate risks (Carattini and others 2022).

Figure 1.17. Firms' Plans for Utilizing Incentives of Recent Climate Policy Packages in United States and Germany, Spring 2023

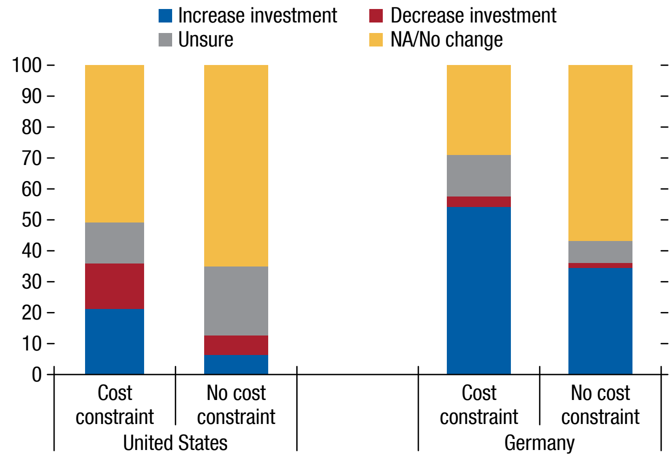
(Percent of firms surveyed)



Sources: Business Inflation Expectations Survey (Federal Reserve Bank of Atlanta); Bundesbank Online Panel—Firms; CFO Survey (Duke University, Federal Reserve Bank of Richmond, and Federal Reserve Bank of Atlanta); and IMF staff estimates.
Note: The stacked bars reflect the proportions of sampled firms that responded to surveys on their willingness to use incentives provided by the Inflation Reduction Act (firms in the *United States*) and Green Deal Industrial Plans (firms in *Germany*). The figure shows the share of firms that will use incentives in their country's policy packages. IRA = Inflation Reduction Act.

Figure 1.18. Firms' Responses to Financial Incentives to Invest in Emission Reduction, Spring 2023

(Percent of firms surveyed)



Sources: Business Inflation Expectations Survey (Federal Reserve Bank of Atlanta); Bundesbank Online Panel—Firms; CFO Survey (Duke University, Federal Reserve Bank of Richmond, and Federal Reserve Bank of Atlanta); and IMF staff estimates.
Note: The stacked bars reflect the proportions of sampled firms that responded to surveys on whether they will adjust investment in emission reductions based on incentives of the Inflation Reduction Act (firms in the *United States*) and Green Deal industrial policies (firms in *Germany*). The vertical bars show the share of firms that report cost as one of the top three constraints on investment in emission reduction. NA = not applicable or no change.

been, on average, remarkably resilient to the 2022 energy price shock, with no large cuts in firms' output, employment, or profitability (Box 1.3).[20] Firms have been able to pass the shocks to downstream firms or final consumers. Firms in *Germany*, which faced a larger spike in energy prices, responded to the price hike by both increasing or planning to increase investment in energy efficiency and reducing energy consumption.

Policymakers can also provide firms with fiscal incentives to enhance their green investment, although the effectiveness of these incentives depends on their design and implementation. Results from the same surveys show that some firms in *Germany* and the *United States* responded to the fiscal incentives announced in recent policy packages, such as the US Inflation Reduction Act of 2022 and the EU Green Deal Industrial Plan. Firms taking advantage of these fiscal incentives were often already investing in emission reductions, especially if they considered cost a major hurdle for investment (Figures 1.17 and 1.18). However, the majority of firms in *Germany* reported that they were uncertain about the impact of policies on their climate-related investment plans.

This firm-level empirical analysis provides evidence that firms respond to regulations and fiscal incentives, which can accelerate the green transition, in particular when firms can calculate the impact of fiscal policies on their profitability from investing in the green transition. These findings offer several lessons for policy design and implementation:

- *Regulatory measures can facilitate the green transition, with varying effects.* Evidence suggests that firms adapt to stricter climate regulations by increasing investment. Policies that require firms to monitor their climate targets could reinforce higher carbon prices and are often associated with higher investment in low-carbon technologies by firms, particularly those in energy-intensive sectors.
- *Firms have been resilient on average and adapted to higher carbon prices.* Firms were broadly resilient to the 2022 energy price spikes and likely could adapt to higher energy prices by reducing energy consumption, investing in energy efficiency, and passing higher costs on to consumers or downstream

[20]The surveys were conducted in collaboration with the Federal Reserve Bank of Atlanta's Business Inflation Expectations Survey; Duke University, Federal Reserve Bank of Richmond, and Federal Reserve Bank of Atlanta CFO Survey; and Bundesbank Online Panel in *Germany*.

firms. Concerns that firms have difficulty adjusting to higher energy prices appear less relevant at the aggregate level, which strengthens the case for carbon pricing policies. Nonetheless, more adverse impacts to certain sectors or localities could occur if shocks are stronger and more persistent, suggesting the need for using a mix of instruments to accelerate the green transition.

- *Both policy design and implementation matter.* Fiscal incentives, in addition to higher carbon pricing, can encourage firms to invest. Policies need to be well communicated, including their horizon, their coverage, and the eligibility criteria for incentives, to provide certainty to firms in regard to the intended policies; otherwise, policy uncertainty could hamper investment (Berestycki and others 2022). Targeting can help minimize fiscal costs because some energy-intensive firms would have engaged in the same level of investment in green technologies even without fiscal incentives.

Conclusion

Climate action is an urgent global imperative, presenting policymakers with a fundamental trilemma between achieving climate goals, fiscal sustainability, and political feasibility. Prolonging the business-as-usual path and taking only moderate action will not contain global warming, leaving the world vulnerable to potential catastrophic consequences. The time to act is now, with a strong, clear, and concerted mix of policy efforts on the part of governments. Relying mostly on spending-based policies to achieve the net-zero-emissions goal will lead to fast-rising debt beyond the currently projected rising path, exacerbating risks to fiscal sustainability. Relying solely on carbon pricing to reach net zero, on the other hand, is likely to be politically unpalatable.

This chapter offers new insights to navigate this trilemma, recognizing that policymakers will need to strike a balance when crafting an optimal policy package. Achieving these joint goals will require a carefully calibrated mix of revenue- and spending-based mitigation instruments that involves carbon pricing—necessary but not sufficient to reach the net-zero-emission goals—and other complementary measures, such as transfers, green subsidies and investment, and regulatory measures. The optimal mix varies across countries. Evidence presented on firms' investment responses and resilience to recent energy price shocks also strengthens the case for using a mix of policies to facilitate decarbonization.

Climate policies to decarbonize economies will likely entail a net fiscal cost, which varies considerably across countries depending on size of investment needs, revenues from carbon pricing, and borrowing costs. Advanced economies with sufficient fiscal space could likely accommodate a small increase in debt if needed. Yet many emerging market and developing economies with high debt will find it more challenging to accommodate rising debt, especially as many face pressing priorities for climate adaptation and other development goals. This calls for action to enhance domestic revenue mobilization and improve spending efficiency, combined with efforts to catalyze private financing and undertake structural reforms to accelerate growth.

Addressing climate change involves a collective responsibility to ensure a sustainable, thriving, and resilient world. No single country can tackle it alone. Policymakers must coordinate their efforts by setting minimum carbon prices, removing trade barriers, avoiding costly subsidy races, and developing an international architecture to crowd-in private financing. Facilitating access to established low-carbon technologies and developing strong institutions in emerging market and developing economies can accelerate adoption and narrow technology gaps. Financial support for low-income countries will be crucial to meet their sizable development needs and enable them to cope with climate change. The IMF's Resilience and Sustainability Trust provides long-term financing that can help emerging market and developing economies achieve these goals.

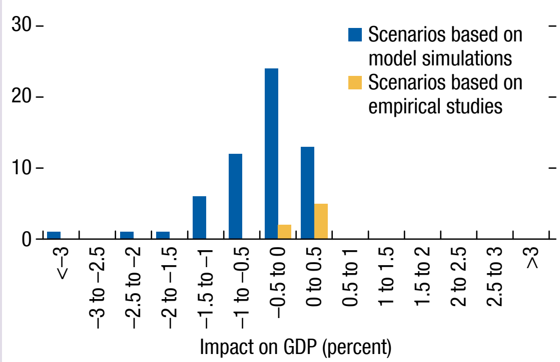
Box 1.1. GDP Impact of Climate Mitigation Policies

The impact of climate mitigation policies on the overall economy is important for policymakers. Analysis on the effects of climate mitigation policies on GDP and other macroeconomic variables has a long history. Can such policies raise GDP while also reducing emissions (a so-called double dividend) (Bovenberg 1999)? For instance, it has been argued that while carbon pricing increases the cost of energy, which could dampen output in the near term, using carbon revenues to reduce other distortionary taxes on labor or capital could raise output. Such a positive effect could be more likely in countries with large informal sectors, high levels of local air pollution, or low energy efficiency (Heine and Black 2019).

Studies have historically centered on model simulations, from which no consensus has emerged (Patuelli, Nijkamp, and Pels 2005; Freire-González 2018; Köppl and Schratzenstaller 2022). More recently, as an increasing number of countries have implemented climate mitigation policies, empirical evidence has been able to test the effect of carbon pricing on GDP. Figure 1.1.1 shows the estimated impacts on GDP of climate mitigation policies based on a new meta-analysis of both ex ante (simulation-based results prior to policy implementation) and ex post (empirical post-implementation) studies. Estimates vary across these studies owing to differences in revenue-recycling strategies, reform strength (such as tax rates and emission reductions achieved), country and sectoral coverage, and whether they consider broader endogenous behavioral responses on the part of households and firms. The simulation-based studies show large variation in effects on GDP, which are somewhat skewed toward negative (although small) impacts. By contrast, the small but growing number of empirical studies show a different pattern of mostly positive impacts (Yamazaki 2017; Bernard and Kichian 2021; Metcalf and Stock 2023).

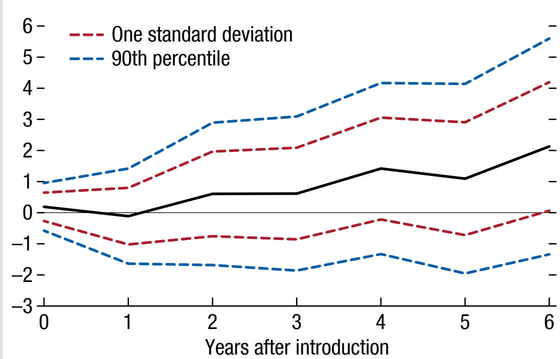
Figure 1.1.2 provides further support for this idea, showing the estimated cumulative impact on GDP from a $40 carbon price covering 30 percent of national emissions in EU countries during 1990–2019 (see also Metcalf and Stock 2023). The estimates implicitly capture the impact from revenue recycling (Online Annex 1.10). While the confidence intervals are wide, the point estimates suggest that the impact on GDP could be positive during the six years following the reform.

Figure 1.1.1. Meta-analysis: GDP Impact after Five Years
(Number of scenarios)



Source: IMF staff compilations.
Note: "Scenarios based on model simulations" includes all studies based on such simulations, especially those employing competitive general equilibrium models. The figure excludes scenarios that do not include recycling of revenues. Endpoints on horizontal axis are included on the left side of each range.

Figure 1.1.2. Impact of Carbon Prices at $40 a Ton on Real GDP for EU Countries, 1990–2019
(Percentage points)



Source: IMF staff estimates based on Metcalf and Stock 2023.
Note: The carbon tax covers 30 percent of emissions.

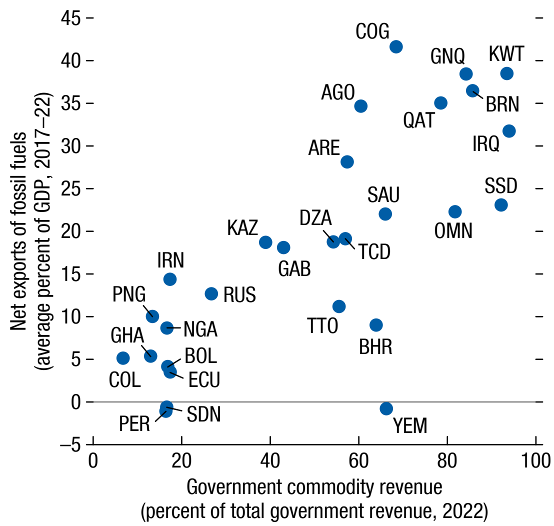
Box 1.2. The Energy Transition of Fossil Fuel-Exporting Countries

Fossil fuel-exporting countries face additional challenges during the global energy transition. First, the scope they will have for using extractive revenues to finance economic development will be highly sensitive to the pace of global decarbonization efforts. Second, fossil fuel-exporting countries will need to continue to supply adequate volumes of hydrocarbon products as the world tries to lower demand for fossil fuels while safeguarding energy security. Third, they will need to reduce domestic greenhouse gas emissions, including those in extractive industries, to meet their climate targets consistent with the 2015 Paris Agreement (Mesa Puyo and others 2023).

In more than half of fossil fuel-exporting countries, receipts from commodities make up more than half of total fiscal revenues. At the same time, a quarter of these countries have fossil fuel exports greater than 25 percent of GDP (Figure 1.2.1). The fossil fuel-dependent countries are highly concentrated in Africa, the Middle East and Central Asia, and the Western Hemisphere. While some of the largest hydrocarbon producers, such as *Canada*, *China*, and the *United States*, have more diversified economies and revenue bases, reduced demand for fossil fuels will still affect subnational regions in these countries unevenly, given the way fossil fuel resources are concentrated.

The scope for using revenues from fossil fuel extraction to finance development or economic diversification will be highly sensitive to the global energy transition path (Figure 1.2.2). The model framework in Baunsgaard and Vernon (2023) provides a first approximation of the impact on fossil fuel revenue under various scenarios for the global energy transition outlined in International Energy Agency (2022b): a *stated-policies scenario*, an *announced-pledges scenario*, and a *net zero scenario*.[1] Analyses show that a number of countries are highly exposed to energy transition risks—for example, 10 countries currently earn more than half of their revenues from fossil fuels and could face at least an 80 percent drop in such revenues by 2040 under the net zero scenario (for example, *Equatorial Guinea*, *Iraq*, and *Oman*)—and nearly all countries face large declines in revenue by 2030 under the net zero scenario as a result of falling prices of, and demand for, fossil fuels. A slower global energy transition could permit certain fossil fuel producers to increase their market shares on account of relatively lower extraction costs or other comparative advantages (for example, *Iran*, *Kuwait*, and *Qatar*). While revenue declines in most regions under the announced-pledges scenario, revenues among members of the Organization of the Petroleum Exporting Countries are more resilient, as their collective market share rises over the medium term owing to lower extraction costs, although some face a decline in fossil fuel revenues by 2040. Fiscal policy

Figure 1.2.1. High Dependence on Commodity Revenues and Exports for Fossil Fuel-Exporting Countries



Sources: IMF, World Economic Outlook database; UN Conference on Trade and Development; and IMF staff calculations.
Note: Commodity revenue includes all exploitable resources and fossil fuel revenue predominant among surveyed countries. Exports include other related primary products but exclude petrochemicals. Data labels in the figure use International Organization for Standardization (ISO) country codes.

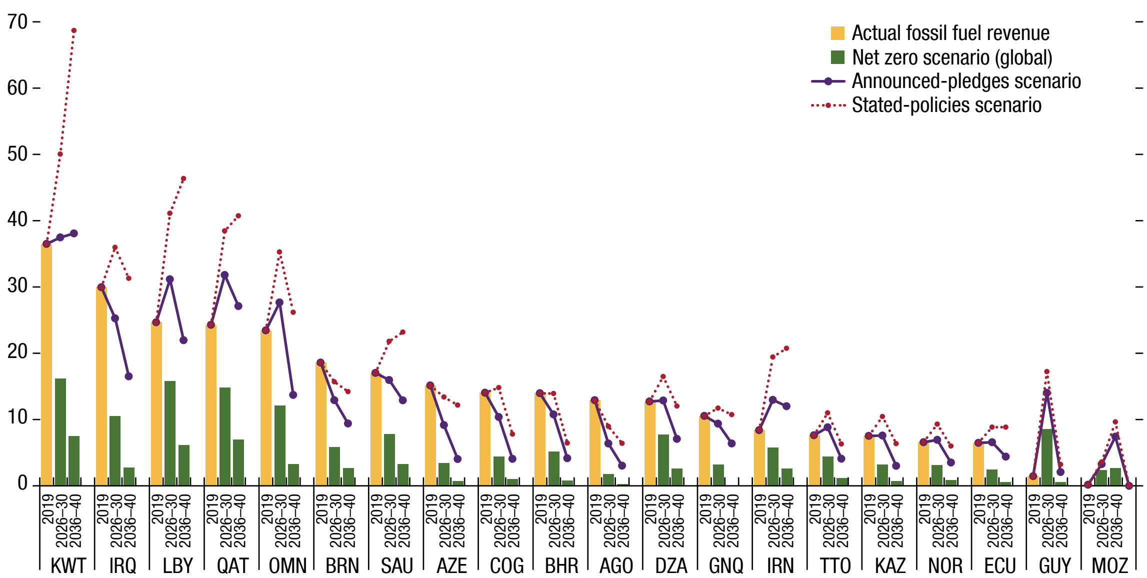
[1]In the stated-policies scenario, only current policies and those under development are implemented; oil prices are projected to rise, and demand peaks in 2035. In the announced-pledges scenario, governments achieve their mitigation targets; oil prices are projected to be stable, and demand peaks in 2024. In the net zero scenario, global warming is limited to 1.5 degrees Celsius, and there is no new development in the area of fossil fuels. As a simplifying assumption, GDP is held constant across scenarios. Results are sensitive to the assumptions regarding future prices of and demand for fossil fuels, as well as country-level production (see Baunsgaard and Vernon 2023).

Box 1.2 *(continued)*

can help address fiscal and economic challenges fossil fuel producers face during the energy transition:

- Fossil fuel producers should withdraw explicit fossil fuel subsidies—which are currently estimated at 5.1 percent of GDP, on average—and gradually phase in emission pricing policies (Black and others 2023a). Methane fees can efficiently reduce emissions in the extractive sector (Parry and others 2022). Carbon pricing provides incentives to switch to lower carbon sources of energy, freeing up hydrocarbons for export markets, which can improve health and generate fiscal revenue.
- Upstream fiscal regimes can be adjusted to shift risks associated with energy transition from investors to government if countries want to attract private investment to extend the life of fossil fuel reserves. Fiscal regimes reliant on profit-based instruments are progressive, as they allocate more risks and upside to the government at the cost of forgoing earlier and more stable revenues from production-based fiscal instruments (royalties). Given existing fiscal regime conditions and revenue objectives, governments should assess the appropriate mix of production and profit-based instruments to strike a balance between capturing a fair share of rents and securing a reasonable minimum share of revenue from extractive projects.
- National oil companies are key to advancing national policies for the energy transition. As those companies diversify into other businesses, it is important that they manage their balance sheets and associated fiscal risks carefully and that commercial basis drives their investment decisions.
- Fossil fuel producers need to build larger fiscal buffers and strengthen their fiscal frameworks to better manage resource wealth, as they face greater uncertainty during the energy transition. Increased savings of fossil fuel revenue in the near term could be managed under sovereign wealth funds (savings or stabilization funds) to ensure a just transition, promote intergenerational equity, and reduce procyclicality of fiscal policy (IMF 2012; Basdevant, Hooley, and Imamoglu 2021).

Figure 1.2.2. Fiscal Revenues for Select Fossil Fuel Producers under Various Energy Transition Scenarios
(Percent of GDP)



Source: IMF staff calculations.
Note: The figure shows selected fossil fuel-producing countries where fossil fuel revenues make the highest contribution to total revenue as well as large new producers such as *Guyana* and *Mozambique*. The outlook in regard to energy markets is based on International Energy Agency (2022b), which considers scenarios involving "stated policies," "announced pledges," and net zero emissions. The green bar for the net-zero-policy scenario shows the revenue decline for most countries relative to actual fossil fuel revenues in 2019. The purple and red lines show the revenues generated in the announced-pledges and the stated-policies scenarios. Data labels in the figure use International Organization for Standardization (ISO) country codes.

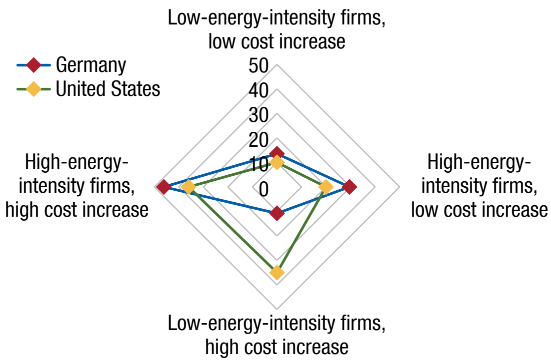
Box 1.3. How Have Firms Responded to Recent Energy Price Shocks?

The speed of the energy transition necessary to achieve the Paris Agreement climate goals has raised concerns that firms could face difficulties in adjusting to higher energy prices. The energy price spikes in 2022, partly driven by *Russia*'s invasion of *Ukraine*, provide a natural experiment for assessing whether firms are resilient when energy prices surge and how they adjust to such surges.

Two surveys, one among firms in *Germany* and the other among firms in the *United States*, show that more than three-quarters of firms in each country experienced a rise in their energy costs in 2022, with a higher share of firms in energy-intensive industries reporting an energy price shock (Figure 1.3.1). The increase was much larger in *Germany*, where nearly 20 percent of surveyed firms (four times higher than the share of firms in the *United States*) reported their energy costs as rising by more than 50 percent during 2022. In response, more than 40 percent of the firms surveyed in *Germany* passed on a quarter or more of the cost increase to downstream firms or customers, compared with 36 percent of surveyed firms in the *United States* (Online Annex 1.9).

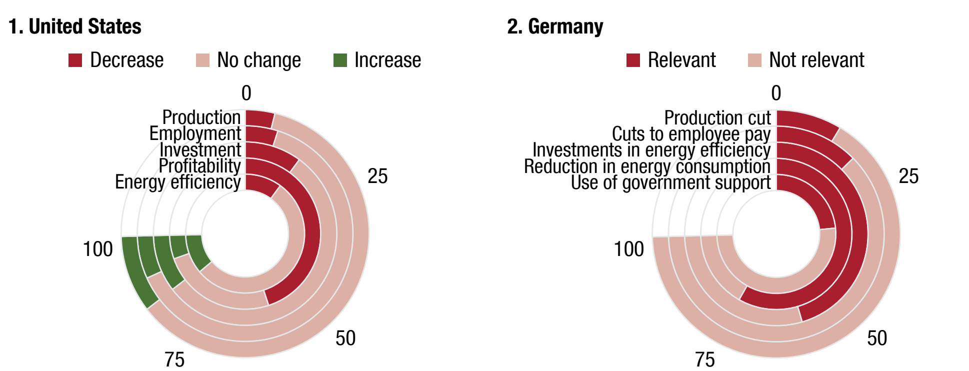
Less than 10 percent of surveyed firms in the *United States*, where the energy price shock was less acute, reported a cut in production or employment, but an even larger share reported an increase in either or both. The share of surveyed firms reporting a reduction in investment was somewhat higher, but so was the share of firms reporting an increase, with the majority reporting no change (Figure 1.3.2). Although 60 percent of the US firms surveyed reported a reduction in profitability, only 6 percent indicated that profitability had declined significantly. Overall, balance sheets of US firms surveyed seemed to have remained

Figure 1.3.1. Firms Experiencing Energy Price Shocks, 2022
(Percent of surveyed firms)



Sources: Business Inflation Expectations Survey (Federal Reserve Bank of Atlanta); Bundesbank Online Panel; CFO Survey (Duke University, Federal Reserve Bank of Atlanta, Federal Reserve Bank of Richmond); and IMF staff estimates.
Note: A large (small) increase in energy costs is defined as an increase of greater (less) than 50 percent in 2022. Firms are classified as high (low) energy intensity if their energy costs are greater (less) than 3 percent of their operational costs.

Figure 1.3.2. Impact of Rise in Energy Cost on Firms' Performance and Investment
(Percent of surveyed firms)



Sources: Business Inflation Expectations Survey (Federal Reserve Bank of Atlanta); Bundesbank Online Panel; CFO Survey (Duke University, Federal Reserve Bank of Atlanta, and Federal Reserve Bank of Richmond); and IMF staff estimates.
Note: The figure shows the proportion of firms experiencing a rise in energy costs that indicated a change in output, employment, investment, profitability, energy consumption, energy efficiency, or the use of government support measures (See Online Annex 1.9).

Box 1.3 *(continued)*

resilient to the energy price shock. Most firms that responded to the survey did not respond to higher energy prices by improving their energy efficiency.

This is in sharp contrast to what surveyed firms in *Germany* reported. In the face of a larger energy price shock (almost a doubling of nonresidential electricity prices relative to 2021 levels), 60 percent of surveyed firms in *Germany* reported investing or planning to invest in energy efficiency; and more than three-quarters reducing or planning to reduce their energy consumption. Somewhat surprisingly, only 12 percent of the responding firms reported an output loss. Hence, most surveyed firms in *Germany* were resilient by improving energy efficiency and reducing energy consumption. Differences between *Germany* and the *United States* may be attributable to the size and the perceived persistence of the shock or the level of government support received. For example, firms in *Germany* may have considered the energy price shock to be longer lasting and hence warranting investment in energy efficiency. Potential disruptions to firms could be larger if the shocks were more persistent.

References

Aghion, Philippe, and Peter Howitt. 2005. "Growth with Quality-Improving Innovations: An Integrated Framework." In *Handbook of Economic Growth*, Volume 1, part A, edited by Philippe Aghion and Steven N. Durlauf. Amsterdam: Elsevier.

Akanbi, Olusegun, William Gbohoui, and W. Raphael Lam. 2023. "Calibrating Fiscal Rules: A Consideration of Natural Disaster Risks." IMF Technical Notes and Manuals 2023/02, International Monetary Fund, Washington, DC.

Aligishiev, Zamid, Matthieu Bellon, and Emanuele Massetti. 2022. "Macro-Fiscal Implications of Adaptation to Climate Change." IMF Staff Climate Note 2022/002, International Monetary Fund, Washington, DC.

Bartolini, David, Valerie Cerra, Yujin Kim, and Johanna Tiedemann. 2023. "A Macroeconomic Model for Climate and Sustainable Development: The C-SDG Model." Unpublished, International Monetary Fund, Washington, DC.

Basdevant, Olivier, John Hooley, and Eslem Imamoglu. 2021. "How to Design a Fiscal Strategy in a Resource-Rich Country." How-To Note 21/01, International Monetary Fund, Washington, DC.

Battersby, Bryn, Raphael Espinoza, Jason Harris, GeeHee Hong, Sandra Lizarazo, Paolo Mauro, and Amanda Sayegh. 2022. "The State as Financier of Last Resort", IMF Staff Discussion Note 2022/003, International Monetary Fund, Washington, DC.

Baunsgaard, Thomas, and Nate Vernon. 2023. "Climate Change Mitigation and Extractive Industries: Scenario Analysis of Revenue Implications." Unpublished, International Monetary Fund, Washington, DC.

Benitez, Juan Carlos, Mario Mansour, Miguel Pecho, and Charles Vellutini. 2023. "Building Tax Capacity in Developing Countries." Unpublished, International Monetary Fund, Washington, DC.

Berestycki, Clara, Stefano Carattini, Antione Dechezleprêtre, and Tobias Kruse. 2022. "Measuring and Assessing the Effects of Climate Policy Uncertainty." OECD Economics Department Working Paper 1724, Organisation for Economic Co-operation and Development, Paris.

Bernard, Jean-Thomas, and Maral Kichian. 2021. "The Impact of a Revenue-Neutral Carbon Tax on GDP Dynamics: The Case of British Columbia." *The Energy Journal* 42 (3): 205–24.

Bistline, John, Neil Mehrotra, and Catherine Wolfram. 2023. "Economic Implications of the Climate Provisions for the Inflation Reduction Act." NBER Working Paper 31267, National Bureau of Economic Research, Cambridge, MA.

Black, Simon, Jean Chateau, Florence Jaumotte, Ian Parry, Gregor Schwerhoff, Sneha Thube, and Karlygash Zhunussova. 2022a. "Getting on Track to Net Zero: Accelerating a Global Just Transition in This Decade." IMF Staff Climate Note 2022/010, International Monetary Fund, Washington, DC.

Black, Simon, Danielle Minnett, Ian Parry, James Roaf, and Karlygash Zhunussova. 2022b. "A Framework for Comparing Climate Mitigation Policies across Countries." IMF Working Paper 22/254, International Monetary Fund, Washington, DC.

Black, Simon, Antung A. Liu, Ian Parry, and Nate Vernon. 2023a. "IMF Fossil Fuel Subsidies Data: 2023 Update." Unpublished, International Monetary Fund, Washington, DC.

Black, Simon, Ian Parry, Victor Mylonas, Nate Vernon, and Karlygash Zhunussova. 2023b. "The IMF-World Bank Climate Policy Assessment Tool (CPAT): A Model to Help Countries Mitigate Climate Change." IMF Working Paper 23/128, International Monetary Fund, Washington, DC.

Black, Simon, Ian Parry, and Karlygash Zhunussova. 2023. "Getting on Track to Net Zero: An IMF Staff Update for the COP28 Global Stock Take." Unpublished, International Monetary Fund, Washington, DC.

Bovenberg, A. Lans. 1999. "Green Tax Reforms and the Double Dividend: An Updated Reader's Guide." *International Tax and Public Finance* 6 (3): 421–43.

Brutscher, Philipp-Bastian, Andrea Coali, Julie Delanote, and Peter Harasztosi. 2020. "EIB Group Survey on Investment and Investment Finance: A Technical Note on Data Quality." EIB Working Paper 2020/08, European Investment Bank, Luxembourg.

Budina, Nina, Christian Ebeke, Florence Jaumotte, Andrea Medici, Augustus Panton, Marina Tavares, and Bella Yao. 2023. "Structural Reforms to Accelerate Green Growth and Ease Policy Trade-Offs in EMDEs." Unpublished, International Monetary Fund, Washington, DC.

Capelle, Damien, Nicola Pierri, and German Villegas Bauer. 2023. "Mitigating Climate Change at the Firm Level: Mind the Laggards." Unpublished, International Monetary Fund, Washington, DC.

Carattini, Stefano, Edgar Hertwich, Givi Melkadze, and Jeffrey G. Shrader. 2022. "Mandatory Disclosure Is Key to Address Climate Risks: Financial Regulations Would Help Signal Risks to Investors." *Science* 378 (6618): 352–54.

Chang, Yongsung, João Gomes, and Frank Schorfheide. 2002. "Learning-by-doing as a Propagation Mechanism." *American Economic Review* 92 (5): 1498–520.

Cherif, Reda, Fuad Hasanov, Nikola Spatafora, Rahul Giri, Dimitre Milkov, Saad Quayyum, Gonzalo Salinas, and others. 2022. "Industrial Policy for Growth and Diversification: A Conceptual Framework." IMF Departmental Paper 2022/017, International Monetary Fund, Washington, DC.

Coady, David, Ian W. H. Parry, and Baoping Shang. 2018. "Energy Price Reform: Lessons for Policymakers." *Review of Environmental Economics and Policy* 12 (2): 197–219.

Colmer, Jonathan, Ralf Martin, Mirabelle Muûls, and Ulrich J. Wagner. 2022. "Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme." CEPR Discussion Paper DP16982, Centre for Economic Policy Research, London.

Dabla-Norris, Era, Thomas Helbling, Kenichiro Kashiwase, Giacomo Magistretti, and Mouhamadou Sy. 2023a. "Asia's Perspectives on Climate Change: Policies, Perceptions, and Gaps." Unpublished, International Monetary Fund, Washington, DC.

Dabla-Norris, Era, Thomas Helbling, Salma Khalid, Hibah Khan, Giacomo Magistretti, Alexandre Sollaci, and Krishna Srinivasan. 2023b. "Public Perceptions of Climate Mitigation Policies: Evidence from Cross-Country Surveys." IMF Staff Discussion Note 2023/002, International Monetary Fund, Washington, DC.

Dabla-Norris, Era, Salma Khalid, Giacomo Magistretti, and Aleandre Sollaci. Forthcoming. "Public Support for Climate Change Mitigation Policies: A Cross-Country Survey." IMF Working Paper, International Monetary Fund, Washington, DC.

Dahlmann, Frederik, Layla Branicki, and Stephen Brammer. 2019. "Managing Carbon Aspirations: The Influence of Corporate Climate Change Targets on Environmental Performance." *Journal of Business Ethics* 158 (1): 1–24.

de Mooij, Ruud, Simon Black, Vitor Gaspar, Ian Parry, and Karlygash Zhunussova. 2023. "How Does Decarbonization Change the Fiscal Equation?" Presentation at Peterson Institute of International Economics, Washington, DC, June 5.

Dechezleprêtre, Antoine, Daniel Nachtigall, and Frank Venmans. 2018. "The Joint Impact of the European Union Emissions Trading System on Carbon Emissions and Economic Performance." OECD Economics Department Working Paper 1515, Organisation for Economic Co-operation and Development, Paris.

Deutsche Bundesbank. 2023. "Germany as a Location of Business: Selected Aspects of Current Dependencies and Medium-Term Challenges." Monthly Report, September 2023, Frankfurt.

Dietz, Simon, and Nicolas Stern. 2015. "Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions." *The Economic Journal* 125 (583): 574–620.

Ditlevsen, Peter, and Susanne Ditlevsen. 2023. "Warning of a Forthcoming Collapse of the Atlantic Meridional Overturning Circulation." *Nature Communications* 14 (1): 4254.

Douenne, Thomas, and Adrien Fabre. 2002. "Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion." *American Economic Journal: Economic Policy* 14 (1): 81–110.

Freire-González, Jaume. 2018. "Environmental Taxation and the Double Dividend Hypothesis in CGE Modelling Literature: A Critical Review." *Journal of Policy Modeling* 40 (1): 194–223.

Georgieva, Kristalina. 2022. "Getting Back on Track to Net Zero: Three Critical Priorities for COP27." *IMF Blog*, November 4. https://www.imf.org/en/Blogs/Articles/2022/11/04/getting-back-on-track-to-net-zero-three-critical-priorities-for-cop27

Gourinchas, Pierre-Olivier, Gregor Schwerhoff, and Antonio Spilimbergo. 2023. "New Challenges to Climate Policies." Unpublished, International Monetary Fund, Washington, DC.

Harris, Jason, Tjeerd Tim, and Jyoti Rahman. 2023. "Macro-Fiscal Risks of Climate Change: User Guide for the Quantitative Climate Change Risk Assessment Fiscal Tool (Q-CRAFT)." Unpublished, International Monetary Fund, Washington, DC.

Harris, Jason, Tjeerd Tim, John Zohrab, Viera Karolova, and Jyoti Rahman. 2022. "Georgia: Technical Assistance Report—Updating the Balance Sheet and Quantifying Fiscal Risks from Climate Change." IMF Country Report 22/150, Washington, DC.

Heine, Dirk, and Simon Black. 2019. "Benefits beyond Climate: Environmental Tax Reform in Developing Countries." In *Fiscal Policies for Development and Climate Action*, edited by Miria A. Pigato. Washington, DC: World Bank.

Intergovernmental Panel on Climate Change (IPCC). 2021. "Technical Summary." In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Valérie Masson-Delmotte, Panmao Zhai, Anna Pirani, Sarah L. Connors, Clotilde Péan, Sophie Berger, Nada Caud, and others. Cambridge, UK: Cambridge University Press.

International Energy Agency (IEA). 2020. *Energy Technology Perspectives 2020*. Paris.

International Energy Agency (IEA). 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris.

International Energy Agency (IEA). 2022a. *Technology and Innovation Pathways for Zero-Carbon-Ready Buildings by 2030: A Strategic Vision from the IEA Technology Collaboration Programmes*. Paris.

International Energy Agency (IEA). 2022b. *World Energy Outlook 2022*. Paris.

International Monetary Fund (IMF). 2012. "Macroeconomic Policy Frameworks for Resource-Rich Development Countries." IMF Policy Paper, Washington, DC.

International Monetary Fund (IMF). 2021. "Reaching Net Zero Emissions." G20 Background Note, Washington, DC.

International Monetary Fund (IMF). 2023a. "Kenya: Fifth Reviews Under the Extended Fund Facility and Extended Credit Facility Arrangements and Request for a 20-month Arrangement under the Resilience and Sustainability Facility, Requests for Extension, Rephasing, and Augmentation of Access, Modification of a Performance Criterion, and Monetary Policy Consultation Clause—Press Release; Staff

Report; and Statement by the Executive Director for Kenya." IMF Country Report 23/266, Washington, DC.

International Monetary Fund (IMF). 2023b. *Data for a Greener World: A Guide for Practitioners and Policymakers*, edited by Serkan Arslanalp, Kristina Kostial, and Gabriel Quiros-Romero, Washington, DC.

International Monetary Fund (IMF). Forthcoming. "How to Cover Industrial Policy Issues in Country Work." Washington, DC.

International Renewable Energy Agency (IRENA). 2022. *Renewable Power Generation Costs in 2021*. Abu Dhabi.

Ioannou, Ioannis, Shelley Xin Li, and George Serafeim. 2016. "The Effect of Target Difficulty on Target Completion: The Case of Reducing Carbon Emissions." *Accounting Review* 91 (5): 1467–92.

Kalantzis, Fotios, Salma Khalid, W. Raphael Lam, Alexandra Solovyeva, and Marcin Wolski. Forthcoming. "The Impact of Stringent Climate Policies on Firms Regulated under the EU Emissions Trading Scheme." IMF Working Paper, International Monetary Fund, Washington, DC.

Kammer, Alfred. 2023. "Europe, and the World, Should Use Green Subsidies Cooperatively." *IMF Blog*, May 11. https://www.imf.org/en/Blogs/Articles/2023/05/11/europe-and-the-world-should-use-green-subsidies-cooperatively

Känzig, Diego R. 2023. "The Unequal Economic Consequences of Carbon Pricing." NBER Working Paper 31221, National Bureau of Economic Research, Cambridge, MA.

Keen, Michael, Ian Parry, and James Roaf. 2021. "Border Carbon Adjustments: Rationale, Design, and Impact." IMF Working Paper 21/239, International Monetary Fund, Washington, DC.

Kiessling, Johan. 2007. "Institutions and ICT Technology Adoption." Unpublished, Department of Economics, Stockholm University, Stockholm.

Klenert, David, Linus Mattauch, Emmanuel Combet, Ottmar Edenhofer, Cameron Hepburn, Ryan Rafaty, and Nicholas Stern. 2018. "Making Carbon Pricing Work for Citizens." *Nature Climate Change* 8 (8): 669–77.

Köppl, Angela, and Margit Schratzenstaller. 2022. "Carbon Taxation: A Review of the Empirical Literature." *Journal of Economic Surveys* 37 (4): 1353–88.

Kotlikoff, Laurence J., Felix Kubler, Andrey Polbin, and Simon Scheidegger. 2021. "Can Today's and Tomorrow's World Uniformly Gain from Carbon Taxation?" NBER Working Paper 29224, National Bureau of Economic Research, Cambridge, MA.

Manca, Fabio. 2009. "Technology Catching-Up and the Role of Institutions." Research Institute of Applied Economics Working Paper 2009/12, University of Barcelona, Barcelona.

McKay, David, Jesse Abrams, Ricarda Winkelmann, Boris Sakschewski, Sina Loriani, Ingo Fetzer, Sarah Cornell, and others. 2022. "Exceeding 1.5°C Global Warming Could Trigger Multiple Climate Tipping Points." *Science* 377 (6611).

Mercure, Jean-Francois, Hector Pollitt, Jorge E. Viñuales, Neil Edwards, Phil Holden, Unnada Chewpreecha, Pablo Salas, and others. 2018. "Macroeconomic Impact of Stranded Fossil Fuel Assets." *Nature Climate Change* 8 (7): 588–93.

Mesa Puyo, Diego, Augustus Panton, Tarun Sridhar, Martin Stuermer, Christoph Ungerer, and Alice Tianbo Zhang. 2023. "Fossil Fuel Exporters and the Energy Transition." Unpublished, International Monetary Fund, Washington, DC.

Metcalf, Gilbert. 2023. "Five Myths about Carbon Pricing." NBER Working Paper 31104, National Bureau of Economic Research, Cambridge, MA.

Metcalf, Gilbert E., and James H. Stock. 2023. "The Macroeconomic Impact of Europe's Carbon Taxes." *American Economic Journal: Macroeconomics* 15 (3): 265–86.

Nordhaus, William. 2021. *The Spirt of Green: The Economics of Collisions and Contagions in a Crowded World*. Princeton, NJ: Princeton University Press.

Parry, Ian, Peter Dohlman, Cory Hillier, Martin Kaufman, Kyung Kwak, Florian Misch, James Roaf, and others. 2021. "Carbon Pricing: What Role for Border Carbon Adjustments?" IMF Staff Climate Note 2021/004, International Monetary Fund, Washington, DC.

Parry, Ian, Simon Black, Danielle Minnett, Victor Mylonas, and Nate Vernon. 2022. "How to Cut Methane Emissions." IMF Staff Climate Note 2022/008, International Monetary Fund, Washington, DC.

Parry, Ian, Simon Black, Danielle Minnett, and Karlygash Zhunussova. 2023. "Policies to Decarbonize Industry While Addressing Competitiveness and Carbon Leakage." Unpublished, International Monetary Fund, Washington, DC.

Parry, Ian, Simon Black, and Karlygash Zhunussova. 2022. "Carbon Taxes or Emissions Trading Systems?: Instrument Choice and Design." IMF Staff Climate Note 2022/006, International Monetary Fund, Washington, DC.

Patuelli, Roberto, Peter Nijkamp, and Eric Pels. 2005. "Environmental Tax Reform and the Double Dividend: A Meta-analytical Performance Assessment." *Ecological Economics* 55 (4): 564–83.

Pisani-Ferry, Jean, and Selma Mahfouz. 2023. "The Economic Implications of Climate Action." Unpublished.

Stern, Nicholas, and Anna Valero. 2021. "Innovation, Growth and the Transition to Net-Zero Emissions." *Research Policy* 50 (9): 104293.

Traum, Nora, and Shu-Chun S. Yang. 2015. "When Does Government Debt Crowd Out Investment?" *Journal of Applied Econometrics* 30 (1): 24–45.

United Kingdom Office of Budget Responsibility. 2021. "Climate Change" (Chapter 3). In *Fiscal Risks Report 2021*. London.

United Nations Conference on Trade and Development (UNCTAD). 2022a. "Tackling Debt and Climate Challenges in Tandem: A Policy Agenda." UNCTAD Policy Brief 104, Geneva.

United Nations Conference on Trade and Development (UNCTAD). 2022b. *Technology and Innovation Report 2023: Opening Green Windows; Technological Opportunities for a Low-Carbon World.* Geneva.

Wang, Derek D., and Toshiyuki Sueyoshi. 2018. "Climate Change Mitigation Targets Set by Global Firms: Overview and Implications for Renewable Energy." *Renewable and Sustainable Energy Reviews* 94 (October): 386–98.

Way, Rupert, Matthew C. Ives, Penny Mealy, and J. Doyne Farmer. 2022. "Empirically Grounded Technology Forecasts and the Energy Transition." *Joule* 6 (9): 2057–82.

Yamazaki, Akio. 2017. "Jobs and Climate Policy: Evidence from British Columbia's Revenue-Neutral Carbon Tax." *Journal of Environmental Economics and Management* 83: 197–216.

Ziegler, Micah S., and Jessika E. Trancik. 2021a. "Data Series for Lithium-Ion Battery Technologies." Harvard Dataverse, V1. https://doi.org/10.7910/DVN/9FEJ7C

Ziegler, Micah S., and Jessika E. Trancik. 2021b. "Re-examining Rates of Lithium-Ion Battery Technology Improvement and Cost Decline." *Energy & Environmental Science* 14 (4): 1635–51.