Online Annexes of the October 2023 *Fiscal Monitor*: Chapter 1

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Online Annex 1.1. Mitigation Targets for Paris Agreement, Policies, and Sector Targets for G20 Economies

Online Annex Table 1.1.1. Mitigation Targets for Paris Agreement, Policies, and Sector Targets for G20 Economies

	Last Mitigation Pledge for Paris Agreement [1/]	Year for Net Zero Target	Instrument/Coverage (April 2022, 2030 prices, US $/ton)[3/]	Power: Generation Shares, %: Renewables: 2021	Power: Generation Shares, %: Renewables: Future Target (year) [4/]	Power: Generation Shares, %: Coal: 2021	Power: Generation Shares, %: Coal: Future Target (year)	Industry	Transport: CO2/km: 2021	Transport: CO2/km: Future Target (year)	Transport: Share of Electric Vehicle Sales: 2021	Transport: Share of Electric Vehicle Sales: Future Target (year)	Buildings
Argentina	Net emissions cap of 359 MtCO2e in 2030	2050 [2/]	Carbon tax for all emissions (5,5)	27	20 (2025) [4/]	1							
Australia	Reduce GHGs 43% below 2005 by 2030	2050 [2/]		20	68 (2030)	51		Reduce the energy intensity of industry 30 percent between 2015 and 2030.			1	30 (2030)	
Brazil	Reduce GHGs 43% below 2005 by 2030	2050		83	[4/]	5			125	119 (2022)	<1		
Canada	Reduce GHGs 30% below 2005 by 2030	2050	Carbon tax/ETS for power, industry, transport, buildings (40, 140)	68	90 (2030)	4	0 (2030)		123	100 (2026)	4	100 (2035)	All new buildings net zero emissions by 2030.
China	Reduce CO2/GDP 65% below 2005 by 2030	2060	ETS for electricity to be expanded to industry (9, 9); The ETS takes the form of tradable emission rate standard.	28	80 (2060)	56		Peak aluminium and steel CO_2 emissions by 2025, and reduce them 40 and 30 percent, respectively from that peak by 2040.	116	72 (2030)	6	100 (2035)	Green buildings to account for 50% of new urban buildings.
France	Reduce GHGs 55% below 1990 by 2030	2050 [2/]	EU ETS for power/industry (87,140), domestic tax for industry/buildings/transport (49, 60)	22	40 (2030) [4/]	1	0 (2022)	Reduce (all GHG) emissions from industry 37 percent by 2030 relative to 2019.	100	61 (2030)	11	100 (2030) [5/]	Reduce building sector emissions 44% below 2020 emisison by 2030; EU legislation requires all new buildings to be nearly zero energy.
Germany	Reduce GHGs 65% below 1990 by 2030	2045	EU ETS for power/industry (87,140), domestic ETS for buildings/transport (33,55)	41	80 (2030)	17	0 (2030)	Reduce CO_2 emissions 49–51 percent below 1990 levels by 2030	100	61 (2030)	14	100 (2030) [5/]	Reduce building sector emissions 43% below 2020 emisison by 2030; EU legislation requires all new buildings to be nearly zero energy.
India	Reduce GHG/GDP 33–35% below 2005 by 2030	2070		22	50 (2030)	64			114	112 (2022)	<1	30 (2030) [5/]	Reduce energy use for new commercial buildings 50% by 2030.
Indonesia	Reduce GHGs 29%(41%) below BAU in 2030	2060		17	48 (2030)	51	30 (2025)				<1	numeric (2025) [5/]	Reduce energy intensity ≥ 1% per year until 2025.*
Italy	Reduce GHGs 55% below 1990 by 2030	2050 [2/]	EU ETS for power/industry(87,140)	41	55 (2030)	5	0 (2025)		100	61 (2030)	4	100 (2030) [5/]	Reduce building sector emissions 25% below 2020 emisisons by 2030; EU legislation requires all new buildings to be nearly zero energy.
Japan	Reduce GHGs 46% below 2013 by 2030	2050	Carbon tax for all emissions (2,2), Subnational ETS schemes	20	36-38 (2030)	31	19 (2030)	Reduce CO_2 emissions 38% below 2013 levels by 2030	106	92 (2030)	<1	100(2035)	Reduce building sector CO_2 emissions 66% below 2013 levels by 2030. All new houses net zero emissions by 2030.
Mexico	Reduce GHGs 22% (36%) below BAU in 2030	2050 [2/]	Carbon tax for all emission (0.4-4,0.4-4); carbon price on additional carbon contents relative to natural gas. ETS for power/industry (4,4). Subnational carbon trading schemes.	18	35 (2024)	5			114	85 (2025)	<1	n/a [5/]	All new buildings net zero emissions by 2030.
Russia	Reduce GHGs to 70% of 1990 level by 2030	2060 [2/]		18	20 (2020)	9						production (2030) [5/]	Reduce energy consumption for all buildings 3.7% a year 2031–50.
Saudi Arabia	Reduce GHGs 278 MtCO2e below BAU by 2030	2060 [2/]		0	50(2030)	0						30 (2030)	
South Africa	Reduce GHGs to 350–420 MtCO2e in 2025 and 2030	2050 [2/]	Carbon tax for all emissions (10, 10)	6	41(2030)	87		Reduce energy consumption of manufacturing 16 percent below 2015 levels by 2030.	138	n/a	<1		All new buildings net zero emissions by 2030.
South Korea	Reduce GHGs 40% below 2017 by 2030	2050	ETS for power/industry/buildings (19, 19)	5	30 (2030)	30	0 (2050)		98	84 (2030)	3	numeric (2025) [5/]	All new buildings net zero emissions by 2030.
Türkiye	Reduce GHGs 20% (25%) below BAU by 2030	2053		44	60(2030) [4/]	19		Reduce energy intensity by at least 10 percent in each subsector by 2023 (2011 baseline)				numeric (2030) [5/]	
United Kingdom	Reduce GHGs 68% below 1990 by 2030	2050	ETS for power/industry (99,130), domestic tax for power (24,24)	39	100 (2035)	2	0 (2024)	Reduce CO_2 emisisons 67 percent below 2018 levels by 2035.	100	61 (2030)	11	100 (2030)	Reduce CO2 emisisons for all new buildings 75–80% by 2030.
United States	Reduce GHGs 50–52% below 2005 by 2025	2050	Subnational ETS schemes	19	28(2030) [4/]	12			123	100 (2026)	2	50 (2030)	All new buildings net zero emissions by 2030.

Sources: UN Framework Convention on Climate Change 2021; and IMF staff compilation.

Note: BAU = business as usual; CO_2 = carbon dioxide; ETS = emission trading system; GHGs = greenhouse gases; MtCO2e = Metric Tons of Carbon Dioxide Equivalent.

1 Targets conditional on international support are in brackets. Reduction target for France and Italy is based on EU-wide target.

2 Target has been announced but is not yet featured in policy documents. For France and Italy, they refer to the EU-wide target.

3 Where prices, or caps in ETSs, are not specified in legislation for 2030 they are based on 2022 prices or, as in Germany, the last available year where a price is specified. For the EU ETS, the 2030 price is an estimate based on the Climate Policy Assessment Tool.

4 Argentina's target excludes large hydro, which is included in its generation share; Brazil's latest nationally determined contributions no longer include a renewable target; the entry for France is set as the EU-wide target. Entries for Türkiye and the United States are inferred from other numeric targets.

5 The category refers to road transport. For France, Germany, and Italy, the targets are set as the EU-wide target levels. For India, target is for private cars. Target for commercial vehicles = 70%, buses = 40%, two and three-wheeler sales = 80%. For Indonesia, target is for 2 million electric vehicles in stock by 2025. For Japan, target includes EV, PHV (Plug-in Hybrid Vehicles), FCV (Fuel Cell Vehicles), and HEV (Fuel Cell Vehicles). For Mexico, no federal target but Jalisco, Mexico, committed to 100 (2030). For Russia, the annual electric vehicle production target of 220,000 units by 2030. South Korea has a target of 1.13 million electric vehicles in the passenger vehicle stock by 2025. Türkiye has a target of 1 million electric vehicles in the vehicle stock by 2030.

Online Annex 1.2. Macro-Fiscal Implications of Climate Policies[1]

This annex describes the details of the dynamic general equilibrium model used in the chapter to assess the debt impact of fiscal policy packages and presents additional scenarios and sensitivity analyses.

Model Framework

The analysis employs a New Keynesian dynamic general equilibrium closed-economy model with a rich set of fiscal policies based on Traum and Yang (2015) and additional climate components on energy inputs. The model has forward-looking agents, a key feature to consider investment decisions and behavioral responses to fiscal climate policies. The model is perfect foresight, and its transition dynamics are solved nonlinearly, which matters given the large magnitude of the changes in the energy sector. The following equations focus mainly on the additional climate and technology features.

Final goods are produced combining energy y_t^E and non-energy inputs y_t^F with a Constant Elasticity of Substitution function with elasticity η_f and energy share ς_f:

$$y_t = \left((1 - \varsigma)^{1/\eta_f}(y_t^F)^{(\eta_f - 1)/\eta_f} + \varsigma^{1/\eta_f}(y_t^E)^{(\eta_f - 1)/\eta_f}\right)^{\eta_f/(\eta_f - 1)}.$$

Energy itself is also produced with a Constant Elasticity of Substitution bundle of green and brown sources of energy, with elasticity η and brown energy share ω:

$$y_t^E = \left((1 - \omega)^{1/\eta}(y_t^G)^{(\eta - 1)/\eta} + \omega^{1/\eta}(y_t^B)^{(\eta - 1)/\eta}\right)^{\eta/(\eta - 1)}.$$

Carbon emissions are directly proportional to the brown energy output. Each energy source $i = \{G, B\}$ employs private capital k^i and labor h^i, with productivity A^i, as well as public capital k^{Gi} in the case of green energy (for example, electricity grids). The production function for green energy source G is thus:

$$y_t^G = A_t^G\left(\left((1 - w_G)^{1/\eta_G}(k_{t-1}^G)^{(\eta_G - 1)/\eta_G} + w_G^{1/\eta_G}(k_{t-1}^{GG})^{(\eta_G - 1)/\eta_G}\right)^{\eta_G/(\eta_G - 1)}\right)^{1 - \alpha_G}(h_t^G)^{\alpha_G},$$

where the share of public capital is set to zero for brown energy—a simplifying assumption that does not affect key results.

In addition, productivity in each energy source benefits from learning-by-doing externalities. It grows in proportion to the existing capital stock:

$$\log(A_t^i) = \alpha^i \log\left({k_{t-1}^i}/{k_{SS}^i}\right) + \epsilon_t^i,$$

where k_{SS}^i indicates the steady-state capital level and ϵ_t^i is an exogenous trend.

Private investment is subject to adjustment costs, capturing potential bottlenecks for green investment, such as scarcity or supply disruptions of critical minerals, including from rising geopolitical fragmentation, and/or bottlenecks in divesting stranded brown assets. Adjustment costs grow quadratically in proportion to the deviation of the investment ratio in each capital stock i_t^j / k_{t-1}^j from the depreciation rate, thus imposing a cost on both sharp capital accumulation and divestment. The capital accumulation function for each capital stock j (private green, private brown, public green, or generic) is:

$$k_t^j(1 + g)(1 + n) = (1 - \delta)k_{t-1}^j + i_t^j - \frac{\gamma_j}{2}\left(\frac{i_t^j}{k_{t-1}^j} - \delta\right)^2 k_{t-1}^j,$$

where g is the balanced-growth-path in output per capita, n is the population growth, δ is the depreciation rate, and γ_i is the adjustment cost parameter.

Heterogeneity among households, with a fraction Ω of hand-to-mouth households, allows one to analyze the distributional effects of climate policies. Fiscal policies include instruments to tackle climate change such as carbon pricing, green subsidies, public investment, and conventional fiscal tools such as targeted transfers, as well as standard taxes on consumption, labor, and capital income. Sovereign interest rates are increasing in the debt-to-GDP ratio to

[1] Prepared by Daniel Garcia-Macia and Anh Nguyen.

capture the downward-sloping demand for safe assets, which is particularly relevant for countries with less fiscal space. Specifically, the functional form follows Mian, Straub, and Sufi (2022), with the convenience yield of holding government debt equal to:

$$\widehat{CY}_t = -\varphi \frac{b_t - \bar{b}}{\bar{b}}.$$

where $\widehat{CY}_t$ is the convenience yield in deviation from the steady state, φ is the debt elasticity, and b_t is the level of debt ($\bar{b}$ in the steady state). Higher government debt increases interest rates as liquidity and safety premiums on government debt diminish (Krishnamurthy and Vissing-Jorgensen 2012).

Data and Calibration

The simulations in the chapter compare a business-as-usual baseline based on current policies with policy scenarios that reduce emissions by 80 percent by 2050 in advanced economies and by 2060 in emerging market economies. The baseline paths for output, population, and government debt are based on IMF World Economic Outlook database projections, long-term projections by the Organisation for Economic Co-operation and Development, and the UN population projection, while the emissions path and initial carbon prices are consistent with analyses using the Climate Policy Assessment Tool and initial energy shares from the US Energy Information Administration and International Energy Agency. The model is calibrated to a representative advanced economy based on the *Group of Seven* and a representative emerging market is an average of countries including *Argentina, Brazil, China, India, Indonesia, Mexico, South Africa,* and *Türkiye*.

Online Annex Table 1.2.1. Calibration of Model Parameters

Parameters	Symbol	Value	Sources
Energy-related Parameters			
Elasticity of energy in final goods production	η_f	0.21	Labandeira, Labeaga, and López-Otero (2017)
Elasticity between green and brown energy	η	3.5	Acemoglu and others (2012)
Elasticity between private green capital and public green capital	η_G	0.9	See text for discussion
Share of energy in final goods production	ς_f	0.07	Känzig (2023)
Share of brown source in energy production	ω	0.8 (AE)/0.9 (EM)	IEA's World Energy Balances, also see text for discussion
Share of public green capital in the green capital	w_G	0.16	Based on Traum and Yang (2015)
Macroeconomic Parameters			
Discount factor	β	0.99	Standard value
Intertemporal elasticity of substitution	σ	1	Standard value
Depreciation rate	δ	0.025	Standard value
Inverse Frisch elasticity		2	Standard value
Share of labor in green, brown, and non-energy production	α_i	0.68	Standard value
Debt elasticity	φ	0 (AE)/0.003 (EM)	See text for discussion
Price elasticity	ϵ_p	10	Standard value
Capital adjustment cost	γ_i	4	Standard value, also see text for further discussion
Price adjustment cost	κ	52.9	Match the average frequency of price changes (every three quarters)
Consumption tax rate	τ^c	12 percent	Standard value
Labor income tax rate	τ^w	20 percent	Standard value
Capital income tax rate	τ^k	20 percent	Standard value
Lump-sum tax: Response to debt-to-GDP ratio	ϕ_B	0.01	Gomes, Jacquinot, and Pisani (2012), see text for discussion
Taylor rule: smoothing	ρ	0.5	Standard value
Taylor rule: response to inflation	γ_π	2	Standard value
Taylor rule: response to output gap	γ_y	0.125	Standard value
Inflation target	$\bar{\pi}$	2 percent (AE)/4 percent (EM)	Standard value

Source: Authors' compilations.
Note: Standard values are based on Smets and Wouters (2007), Christiano, Eichenbaum, and Evans (2005), Gomes, Jacquinot, and Pisani (2012), and Traum and Yang (2015). AE = advanced economies; EM = emerging market economies; IEA = International Energy Agency.

Key parameters of the model are in line with the literature (Online Annex Table 1.2.1). The share of public capital (w_G) in green capital is set to 0.16, matching generic public capital in Traum and Yang (2015). The elasticity between private green capital and public green capital is set to 0.9, close to but slightly smaller than the unit elasticity used in the case of generic public investment, reflecting the specific need of public investment in green production. The share of liquidity constraints households is 30 percent in advanced economies (Kaplan, Violante, and Weidner 2014; Kumhof and others 2010; Gomes, Jacquinot, and Pisani 2010) and 50 percent in emerging market economies (Kumhof and others 2010).

The capital adjustment cost is set to the standard value of 4. At the steady state, the adjustment cost is always zero regardless of the adjustment cost parameter. In the preferred net zero emission package of advanced economies, the ex post annual cost on output is very small, about 0.03 percent of GDP to 2050 on average (or 0.8 percent in total between 2023–50). The effect of inflation is captured in the real interest rate contribution to debt. The policy package has a moderate inflationary impact during the transition, as higher carbon pricing tends to increase production costs, while the expansion of green energy production lower the price of green energy (see October 2022 World Economic Outlook for a discussion on near-term inflationary effects of climate policies). In the scenario with investment bottlenecks, the adjustment cost parameter is increased to 100. This implies that under the same set of climate policies as in the preferred package, the annual adjustment cost would rise to 0.25 percent of GDP on average, and the green capital stock would only grow by half as much by 2050. Hence, stronger policy action would be needed to achieve the net zero target.

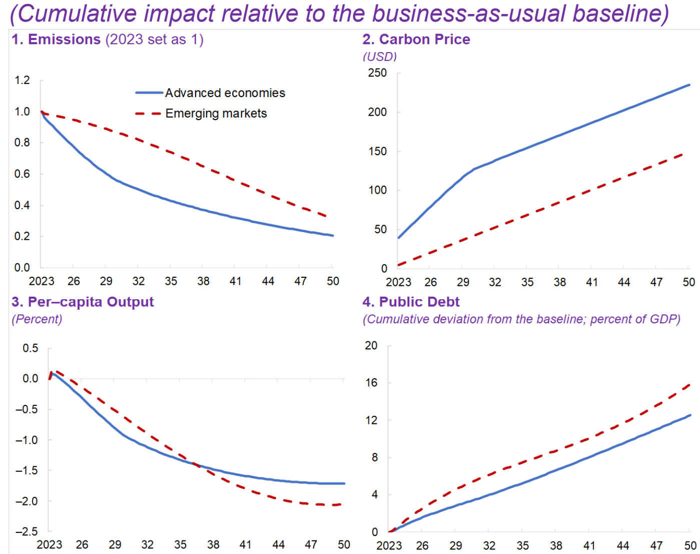
The debt elasticity of the convenience yield (φ) is set to zero for the advanced economies, while representative emerging market economies are calibrated so that the equilibrium interest rate increases by 20 basis points when government debt increases by 10 percent (Mian, Straub, and Sufi 2022).[2]

Combination of Well-Sequenced Policy Instruments

The well-sequenced package consists of four policy instruments: carbon pricing, green public investment, subsidies for green production, and targeted transfers to liquidity constrained households. In a representative *advanced economy*, annual green public investment is assumed to increase permanently by 0.4 percent of GDP compared to the business-as-usual baseline. This assumption aligns with the estimates from the International Energy Agency (IEA 2021), the assumption of the *United Kingdom*'s Office for Budget Responsibility (2021), and European Commission (2020). For example, the European Commission (2020) estimates an annual total investment need of 1.6–2.3 percent of GDP. Given the share of public investment is around 20–25 percent of the total, the public investment needs are about 0.4 percent of GDP. The annual green subsidy is 0.2 percent of GDP higher relative to the baseline scenario until 2030, and then gradually

Online Annex Figure 1.2.1. Policy Package Combining Different Fiscal Instruments

(Cumulative impact relative to the business-as-usual baseline)



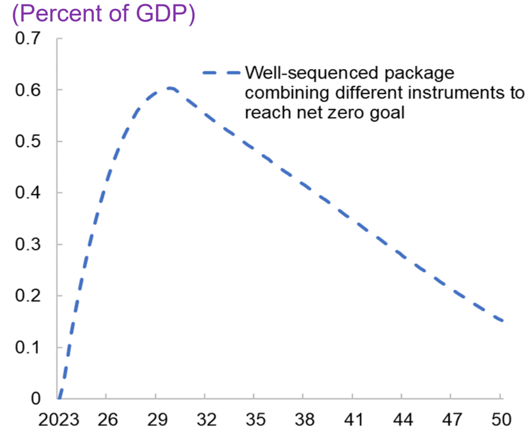
Source: IMF staff simulations.
Note: The policy package is designed to achieve net zero emissions by 2050 in advanced economies (blue line) and by 2060 in emerging market economies (red line). Parameters and fiscal instruments are calibrated to a representative advanced economy (average of Group of Seven) and a representative emerging market economy, assumed to be the weighted average of large emerging market economies (Argentina, Brazil, China, India, Indonesia, Mexico, South Africa, Türkiye).

[2] In addition, to focus on the impact of climate policy on debt, the debt stabilization channel is suspended in the model until 2050 (for advanced economies) and 2060 (for emerging market economies), and henceforth a lump-sum tax is set to gradually increase in response to debt to GDP to ensure the government's intertemporal budget constraint is met.

fades away. This calibration falls within the range of the estimate in the Inflation Reduction Act of the *United States* (a total of $270 billion of tax credit, or 1 percent of GDP in total, until 2031). The initial carbon price is set to $40. The emission trajectory aims to achieve a decline of 40–50 percent by 2030 and 80 percent by 2050 relative to 2023 (IMF 2021; Black and others 2022).

This policy package would require an ambitious increase in carbon pricing from the current levels—reaching $130 per metric ton by 2030 and $235 per metric ton by 2050, respectively in line with the net zero emission scenario in IEA (2021) estimates—but smaller than the $280 per metric ton by 2050 needed if carbon pricing was the only instrument (Online Annex Figure 1.2.1). Revenues from higher carbon prices are projected to peak around 2030 because the gradual decarbonization of the economy would reduce the tax base of carbon and other fuel taxes, unless taxes are shifted to other bases (such as vehicle mileage, instead of fossil fuel use) (Online Annex Figure 1.2.2). The policy package incentivizes private sector investment in green energy production, doubling the green private capital stock relative to the business as usual scenario. This is partly owing to the crowd-in effects from the complementary role of public capital. The endogenous green investment by the private sector accounts for the majority of total green investment in the decarbonization efforts.

Online Annex Figure 1.2.2. Carbon Revenue on the Path to Net Zero
(Percent of GDP)



Source: IMF staff simulations.
Note: Calibrated to a representative large advanced economy (average of Group of Seven) achieving net zero emissions in 2050.

In a representative *emerging market*, annual public green investment is set to increase permanently by 0.8 percent of GDP relative to the business-as-usual baseline, in line with (IEA 2021).[3] The increase in the green subsidy in emerging market economies is half the value in advanced economies, due to limited innovation capacity. The initial carbon price is set to $5 per ton and will rise to $45 per ton in 2030 and $150 per ton by 2050. As shown in Online Annex Figure 1.2.1, emission reduction efforts in emerging markets are backloaded, achieving net zero emissions by 2060, to reflect their need to prioritize development. As in the advanced economies, the policy package encourages private green investment, tripling the green private capital stock by 2050.

The simulations for both scenarios assume no earmarking of carbon revenues to specific spending, to distinguish the macro-fiscal effects of climate policies from other fiscal policies, except for a transfer targeted to hand-to-mouth households. In particular, 30 percent of carbon revenue is transferred to vulnerable households.

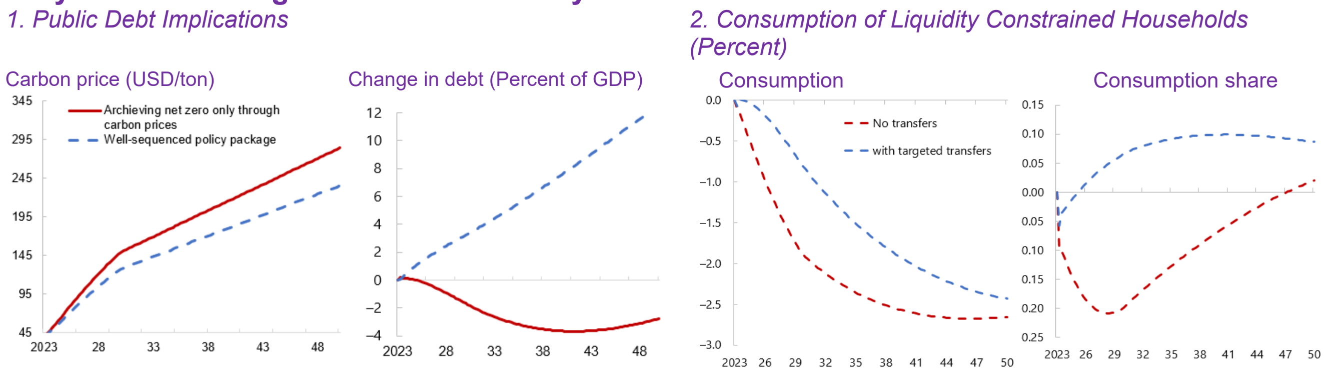
Additional Scenarios and Sensitivity Analysis

Reliance Primarily on Carbon Pricing

To benchmark the model against the literature, a scenario achieving net zero emissions with carbon pricing as the only climate policy is presented for the advanced economy (Online Annex Figure 1.2.3). The scenario shows that this would require raising carbon prices to $150 per ton by 2030 and $280 per ton by 2050 (panel 1). The increase in carbon pricing would generate revenue and reduce deficits, which reduces the real interest rate and the debt ratio, but at a slight expense of lower output. Carbon pricing is an effective tool to achieve net zero, but it could lead to uneven transition costs among households (panel 2), with some facing a disproportionate decline in consumption, calling for targeted transfers to mitigate the adverse impact.

[3] According to the IEA, the annual total investment need for emerging market and developing economies is US$2.2 trillion. Public investment is assumed to account for between 20–25 percent of the total.

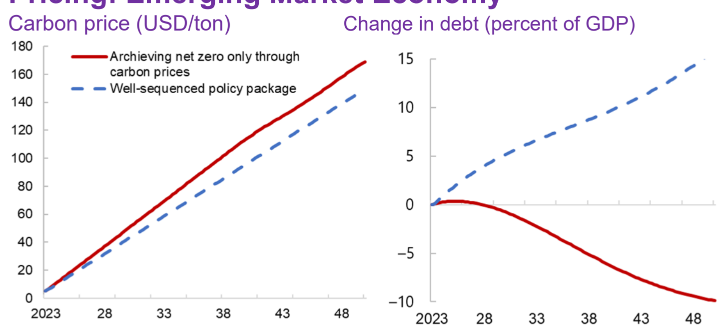
Online Annex Figure 1.2.3. Illustrative Debt Impact when Climate Policy Packages Involve Only Carbon Pricing: Advanced Economy



Source: IMF staff simulations.
Note: Simulations based on a representative large advanced economy with carbon pricing as the only climate instrument to reach net zero target.

For a representative large emerging market economy, a similar scenario is conducted to use primarily carbon pricing to achieve net zero emissions. The scenario assumes no green subsidies and modest public investment for mitigation at ¼ percent of GDP. In this case, carbon prices would need to raise to $165 per ton by 2050 (Online Annex Figure 1.2.4). The increase in carbon pricing would generate revenue and lead to a small primary surplus of 0.4 percent of GDP, which reduces the real interest rate and debt ratio, but at an expense of smaller output and an uneven decline in consumption across households, calling for targeted transfers to mitigate the adverse impact.

Online Figure 1.2.4. Illustrative Debt Impact when Climate Policy Packages Involve Primarily Carbon Pricing: Emerging Market Economy



Source: IMF staff simulations.
Note: Simulation based on a representative large emerging market economy with primarily carbon pricing as the only climate instrument to reach net zero target.

Delays in Carbon Pricing

Scenarios where carbon pricing action is postponed by three years relative to the preferred policy package are considered next, with private investment and subsidies boosted to achieve the same emission reduction path (Online Annex Figure 1.2.5). Two separate scenarios are considered. In the first scenario, after the initial three-year delay, carbon prices are raised quickly to catch up with the path in the preferred package by 2030 (dashed blue line). In the second scenario, carbon prices do not fully catch up with the baseline price path until 2050 (dashed red line). Both scenarios show that debt would increase in advanced economies, by 3 percentage points of GDP by 2050 in the former and almost 6 percentage points in the latter. In emerging market economies, debt worsens substantially if the carbon price fails to catch up promptly after the delay, and by slightly less than in advanced economies otherwise.

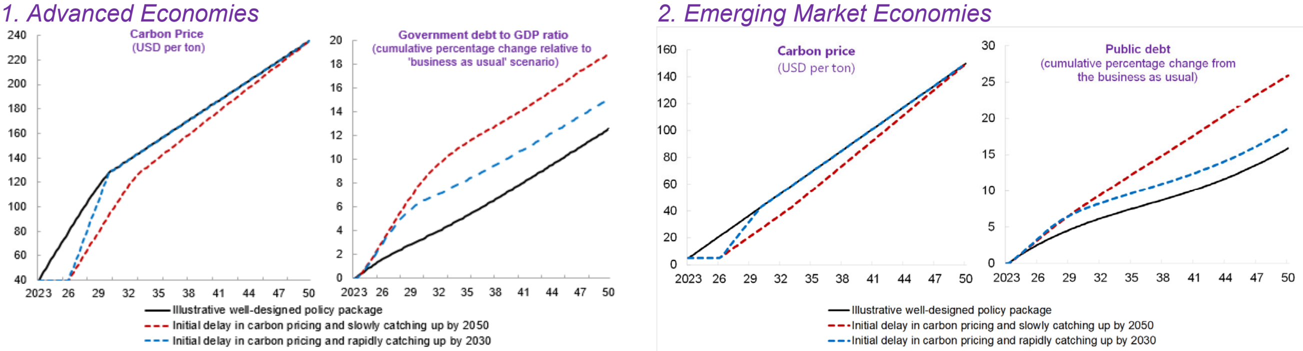
Uncertainty and Heterogeneity in Investment Needs and Transfers across Emerging Market Economies

Public investment needs in emerging market is subject to large uncertainty and varies across countries. For example, estimates in IEA (2022) suggest additional mitigation investment needs by 2030 would be greater for South Asia than other regions. Countries may also reduce fossil fuel investment while scaling up green investment, leading to a lower net public investment on mitigation, particularly for those fossil-fuel-producing countries. Similarly, the extent of transfers to compensate on households depends on the financial constraints, informality of the economy, and strength of the social safety nets, which vary considerably across emerging markets. These suggest public investment needs and transfers may be greater or smaller than the one assumed in the baseline. Sensitivity analyses suggest that the simulated rise in debt for emerging markets is in the range of 8-25 percent of GDP by 2050 for transfers at 30-50 percent of carbon revenues and public investment about ½ and ¾ percent of GDP (Online Annex Figure 1.2.6).

Online Annex Figure 1.2.5. Debt Implications of Delaying Climate Action on Carbon Prices

(Relative to the business-as-usual scenario)

1. Advanced Economies *2. Emerging Market Economies*



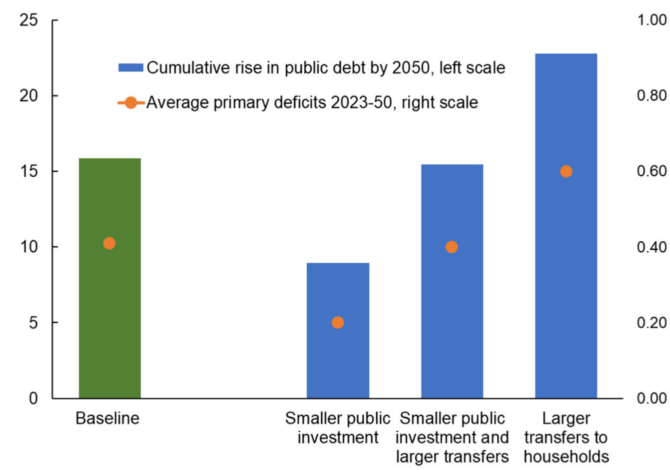
Source: IMF staff simulations.
Note: Delay refers to a postponement of carbon pricing by three years (from 2023 to 2026) relative to the preferred policy package.

Technology Spillovers in Emerging Market Economies

The emerging market calibration is extended to cover two sources of technological developments. First, technology spillovers from advanced to emerging market economies are considered. Each 1 percentage point of total factor productivity increase in the advanced economy's energy sector is assumed to spill over to a 0.1 percentage point increase in the same sector in emerging market economies (Adler and others 2017). This would lead to a positive spillover in green production and a negative one in brown production. Second, unlike in the main scenario, a small amount of learning-by-doing takes place in energy sectors, with a 2 percent elasticity of total factor productivity to capital accumulation (lower than the 10 percent assumed for advanced economies given weaker innovation capacity in developing countries (Awate and others 2012). Technological spillovers can help emerging markets to achieve net zero with a smaller increase in carbon price, mitigating the output loss and decline in consumption.

Online Annex Figure 1.2.6. Sensitivity of Public Debt to Public Investment and Transfers for Emerging Market Economies

(Percent of GDP relative to the business-as-usual scenario)



Source: IMF staff compilation.
Policy packages are set to reach net zero emissions by 2060. Parameters and fiscal instruments are calibrated to a representative emerging market, assumed to be the weighted average of large emerging market economies (*Argentina, Brazil, China, India, Indonesia, Mexico, South Africa, and Türkiye*). The baseline is the well-sequenced policy package discussed in the chapter, which consists of transfers at 30 percent of carbon revenues and public investment at about ¾ percent of GDP. Alternative scenarios explore sensitivity on the size of transfers (higher at 50 percent of carbon revenues) and public investment (lower at ½ percent of GDP per year).

Sensitivity to Parameter Changes

Simulation results are subject to many sources of uncertainty, including model parameters that are difficult to estimate precisely, nonlinear effects of more forceful climate policies, and the impact of emission reduction targets on global temperatures. Debt dynamics vary with alternative assumptions on the elasticity of substitution between energy sources and fiscal outlays on green investment and subsidies (Online Annex Table 1.2.2). A lower elasticity of substitution between green and brown energy is found to require a much higher carbon price (US$660 compared with

US$235 in the main scenario). Higher carbon prices would lead to more revenue and less debt accumulation. If the increase of carbon price is capped, for instance, at US$350, then green investment and subsidies need to be higher, resulting in greater debt accumulation. Higher investment and subsidies also raise debt, but the required carbon price is smaller and therefore the output cost too. Meanwhile, higher transfers (50 percent of carbon revenues) would slightly increase debt compared to the main scenario.

Online Annex Table 1.2.2. Sensitivity of Debt Dynamics to Parameters and Scenarios

Scenario	**Carbon Price in 2050** (USD per ton)	**Change in Debt Ratio** Relative to "Business-as-Usual" Baseline by 2050 (percent of GDP)
Policy Package to Reach Net Zero Emission Goal (benchmark)	$235 (advanced economy)	12.5 (advanced economy)
· Lower elasticity of substitution between green and brown energy $\eta = 2$	$660	−1.6
· Lower elasticity of substitution between green and brown energy $\eta = 2$ limiting carbon pricing at $350, but scaling up investment and subsidies	$350	29
· Higher green investment (0.6 percent of GDP, or 0.2 percentage point higher than benchmark)	$215	24
· Higher green subsidies (0.4 percent of GDP, or 0.2 percentage point higher than benchmark)	$215	19
· Advanced economy simulation: Higher transfers (50 percent of carbon revenues; relative to 30 percent in the benchmark)	$235	15

Source: Authors' simulation results.
Note: Values for a representative advanced economy (average of Group of Seven countries).

Online Annex 1.3. Charging per Vehicle Kilometer Traveled[4]

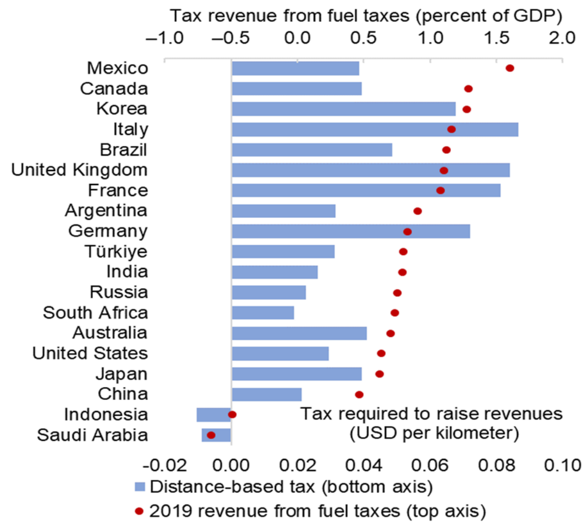
This annex estimates the potential transportation tax revenues based on the distance traveled by vehicles.

To offset revenue loss of existing fuel taxes from decarbonization, countries may consider alternative revenue policies. One option is to transition to taxes that are based on charging all motorists per vehicle kilometer traveled. This could provide a robust alternative revenue base during the transition away from internal combustion engine vehicles to electric vehicles because the latter is not affected by emission rates. Charges on vehicle kilometer traveled could be fine-tuned to manage efficiently road traffic congestion by time and location.

Technologies on electric metering has increasingly addressed implementation challenges and abuse of information collected on an individual's driving habit at a relatively low cost. For example, driving behavior of motorists is monitored under a global positioning system and households receive the associated bills. Privacy concerns are addressed through strict legal requirements on agencies that collect the information or through debiting prepaid smart cards without recording vehicle license numbers. Charging the distance traveled by vehicles is sometimes promoted through subsidizing (taxing) new vehicles with (without) monitoring capacity, which could later turn mandatory.

Online Annex Figure 1.3.1. Transportation Tax Revenue

(Percent of GDP; US dollars per kilometer)



Source: IMF staff using the Climate Policy Assessment Tool.
Note: Revenue excludes value-added tax collected on fuels.

Estimates show that charges on vehicle distance traveled—if applied nationwide at a uniform rate on all vehicles—of around 4 to 8 cents per kilometer is needed across countries to raise the same revenue as the current road fuel taxes (Online Annex Figure 1.3.1).

[4] Prepared by Ian Parry and Nate Vernon.

Online Annex 1.4. Applications of Feebates[5]

This annex illustrates applications of feebates beyond vehicle tax systems.

Feebates are increasingly integrated into vehicle tax systems, but the mechanism can also be applied to other sectors (Online Annex Table 1.4.1).

Transportation. Under a pure feebate, new vehicles are subject to a fee equal to a carbon price multiplied by the difference between their carbon emission rate per kilometer and a pivot point emission rate, scaled by lifetime vehicle kilometers driven. In practice, when linked to carbon emissions rates, vehicle tax systems are often staggered, and rates increase by more than proportion to carbon emissions (Sallee and Slemrod 2012). Administration for vehicle feebates is minimal as they just require a recalibration of existing vehicle taxes and emission rates for different vehicle models and vintages. Subsidies for electric vehicles generally decline over time as the average fleet emission rate declines, reflecting the cost differential between electronic and gasoline/diesel vehicles falls over time.

Industry. Feebates could incentivize cleaner production in carbon-intensive industries such as aluminum, steel, cement, and chemicals. The feebate would apply to emissions from fuel combustion and process emissions (for example, carbon released during the transformation of clinker into cement), which avoids a first-order burden on the average producer. A separate scheme is needed for each industry but the emissions prices across different schemes are harmonized to promote cost-effectiveness. Administration is simpler than for emission trading systems because the government monitors emissions rates of firms but not the trading market.

Power. Power generators would be subject to a fee. A feebate promotes shifting from coal to gas generation and from these fuels to nuclear, renewables, and fossil fuel generation with carbon capture and storage. In contrast, renewable policies promote only shifting to renewables and without differentiating the carbon intensity of the fuel. Administration for a feebate includes monitoring of carbon emission rates for power generators and applying relevant fees/rebates.

Buildings. In countries with energy performance ratings for buildings, feebates could be integrated into the annual property tax systems (for example, to promote insulation upgrades) with fees (subsidies) applying where buildings have relatively low (high) ratings. Feebate schemes can promote adoption of energy efficient appliances and can apply taxes to gas- and oil-based heating systems and a subsidy toward electric heat pumps.

Forestry. A national forestry feebate program could promote increasing carbon storage, including afforestation, reduced deforestation, and enhanced management practices (for example, planting larger trees, lengthening rotations, fertilizing, or tree thinning). Landowners at the agricultural/forestry border that reduce carbon storage on their land more than a baseline year are subject to fees, while landowners that increase carbon storage over time receive subsidies. Property rights at the border need to be well defined and carbon inventories measured (by satellites, aerial photography, and on-the-ground tree sampling), for example, under the Reducing Emissions from Deforestation and Forest Degradation program. Feebates involve rental payments on an annual basis rather than large one-off payments for tree planting, given carbon storage may not be permanent (for example, due to subsequent harvesting or loss through fires, pests, or windstorms). Fees and rebates could build off registries of landowners used for business tax collection or farm support programs (Mendelsohn, Sedjo, and Sohngen 2012; Parry 2021) and applied sequentially.

Extractives. Methane is a potent greenhouse gas, and the bulk of its mitigation can be done at low cost in the extractives sector.[6] Methane emissions could be subject to taxes integrated into existing fiscal regimes for extractive industries. Given commodities are often exported, a revenue-neutral tax could partially replace other broader taxes. A feebate approach provides similar incentives with simpler administration. While firm-level emissions are not directly monitored in most cases, requirements to monitor emissions (*Norway*) or an application of proxy emissions fees (based on characteristics of technologies and default emissions factors linked to these characteristics) can be used.

[5] Prepared by Ian Parry.

[6] For example, capturing methane at the mine mouth or wellhead and using it for onsite power generation, compressing or liquifying the gas for sale, flaring methane (which releases less potent carbon), and improving infrastructure maintenance for gas processing and distribution. See UN Environment Programme and Climate and Clean Air Coalition (2021).

International maritime. The International Maritime Organization has pledged to reduce carbon emissions from international maritime transport (currently 2 percent of global emissions) by 50 percent below 2008 levels by 2050. Achieving it will require development and deployment of zero emission vessels such as hydrogen ships. A carbon levy with a price of US$75 per ton in 2030 is needed to promote the deployment of such vessels, which generates revenues for research and investment to develop those vessels. Such high tax burden may not be feasible (Parry and others 2022) but an alternative is to use a variant of feebates, which impose a smaller burden on the industry. For example, ship operators would be taxed on the difference between their emissions per ton-kilometer of freight and a pivot point emission rate per ton-kilometer, multiplied by their total ton-kilometer. Separate feebates for different emission intensities may be needed.

Online Annex Table 1.4.1. Potential Feebate Mechanisms and Capacity Requirements across Sectors

Sector	Feebate Mechanism	Capacity Requirements
Transport	Vehicle sales subject to fee = CO2 price × (CO2/km of the vehicle - pivot point CO2/km) × average lifetime km driven. Separate feebates (with harmoized prices) could apply to cars and heavy trucks	Can be integrated into existing capacity for collecting vehicle registration taxes
Industry	Firms subject to fee = CO2 price × (emission rate - pivot point rate for the industry) × production. Separate feebates (with harmonized prices) could apply to different industries	Monitoring of firm emission rates.
Power	Generators subject to fee = CO2 price × (average CO2/kWh across their plants - pivot point CO2/kWh) × production	Monitoring of firm emission rates.
Forestry	Landowners at agricultural/forestry border subject to a periodic fee = (rental) CO2 price × (carbon storage on their land in a baseline period - carbon storage in the current period)	Requires property rights defined at the agricultural/forestry border and periodic monitoing of forest carbon inventories (e.g., through REDD+). Could be introduced sequentially starting with payments for land set asides
Extractives	Firms subject to fee = CO2 price × (methane emission rate in CO2 equivalent - pivot point emission rate) × production.	Administration can build off existing business tax regimes. Firms may be subject to emissions reporting requirements or feebate could be based on observed technologies and default emissions factors
International maritime	Ship operators subject to fee = CO2 price × (CO2 emissions per tonne km - pivot point CO2 emissions per tonne km for ship classification) × tonne km. Separate feebates (with harmonized prices) could apply to container and bulk ships.	Collected from operators under supervision of International Maritime Organization (IMO). Operators could remit fees on an individual route or annual basis using fuel data reported to IMO. Port access could be denied to operators unable to verify payments.

Source: IMF staff compilation.
Note: CO2 = carbon dioxide.

Online Annex 1.5. The Solar Photovoltaic Experience[7]

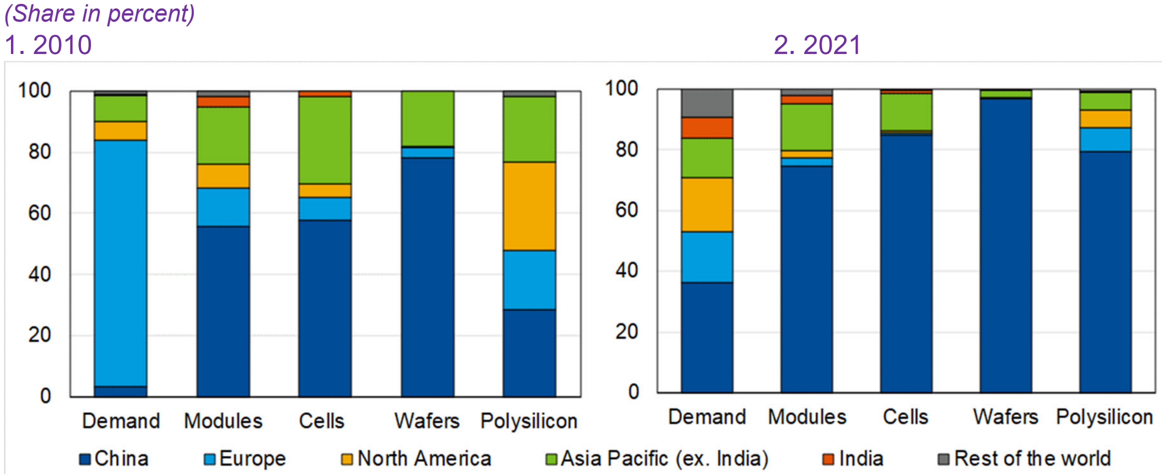
The annex presents some stylized facts on the global share of solar photovoltaic (PV) equipment.

Innovation and deployment of solar PV technology have experienced exponential growth since the 2000s. Green subsidies, feed-in tariffs, tax credits, loan guarantees, grants, and favorable regulations have promoted the growth of the solar panel industry, notably in *China*, *Germany*, *Japan*, and the *United States*. As a result, manufacturing costs reduced dramatically, allowing for a 35-fold increase in new solar power capacity in 2015 relative to 2006 (International Energy Agency 2016; Gerarden 2023). Solar PV has become the most affordable electricity renewable generation technology in history (International Energy Agency 2022), making it cheaper than fossil fuels in most countries.

Global solar PV manufacturing started in Europe, *Japan*, and the *United States*, partly supported by government subsidies in the early stage. In the 1990s, *Germany* implemented a feed-in tariff policy that offered guaranteed prices, which supported the growth of solar industry. In the early 2000s in *Japan* and the late 2000s in the *United States*, implemented policies to promote the growth of solar industries and the adoption of solar energy with some success, such as tax credits, loan guarantees, and grants to promote the growth of solar industries and the adoption of solar energy with some success (Online Annex Figure 1.5.1, panel 1).

Online Annex Figure 1.5.1. Solar Photovoltaic Manufacturing Capacity

(Share in percent)



Source: International Energy Agency 2022.
Note: The first column shows the composition of global demand for solar photovoltaic by regions in 2010 and 2021. The rest of the columns show key stages of manufacturing production for solar, including modules, cells, wafers, and polysilicon.

China is now the world's largest producer of solar panels. In the mid-2000s, *China* began to support domestic solar industry via subsidies (for example, a multitiered feed-in tariff system across different regions), tax incentives, favorable land use policies, and low-interest loans. This enabled the economies of scale, supporting continuous innovation and shaping the global supply chain, demand, and the price of solar PV production. Since 2011, China has invested 10 times more than Europe (US$50 billion) in new PV supply capacity, and currently accounts for more than 80 percent of global manufacturing capacity (Online Annex Figure 1.5.1). The cost has declined by more than 80 percent since 2010 and makes China a key supplier. High concentration of production may create risks. China's green subsidies and predominant role could pose supply-demand imbalances in the solar PV equipment, while its share of global key manufacturing stages (polysilicon, ingot, and wafer) will soon reach close to 95 percent, with a single province in *China* (*Xinjiang*) accounting for more than 40 percent of global polysilicon. This geographical concentration in the global supply chain could create vulnerabilities for the energy transition.

[7] Prepared by Simon Black and Pedro Juarros.

Online Annex 1.6. Intergenerational Impact of Climate Policies[8]

This annex illustrates the effects of climate policies on debt will bring uneven impact across age groups during the green transition to net zero climate goals, suggesting the demographic structure plays a role in the green transition.

An Overlapping Generation Model

The model is based on Kotlikoff and others (2021) that has different fiscal climate instruments, like carbon tax and green public investment, to reach the net zero goal by 2050. The model has two types of firms: energy firms and a firm producing final goods—the latter has the Cobb-Douglas technology:

$$Y_t = A_t K_{y,t}^{\alpha} L_{y,t}^{\beta} E_t^{1-\alpha-\beta},$$

where is Y_t the final output with price normalized to 1; and A_t, $K_{y,t}$, $L_{y,t}$, and E_t refer to total factor productivity and factor inputs of capital, labor, and energy, respectively. The firm maximizes its profit taking the factor prices as given:

Capital: $\alpha A_t K_{y,t}^{\alpha-1} L_{y,t}^{\beta} E_t^{1-\alpha-\beta} = r_t + \delta$; labor $\beta A_t K_{y,t}^{\alpha} L_{y,t}^{\beta-1} E_t^{1-\alpha-\beta} = w_t$; energy:$(1-\alpha-\beta) A_t K_{y,t}^{\alpha} L_{y,t}^{\beta} E_t^{-\alpha-\beta} = p_t^e$

For the energy sector, there four perfectly substitutable energy sources: clean energy (S_t), oil (Oil_t), gas (Gas_t), and coal ($Coal_t$). The total energy output E_t satisfies:

$$E_t = S_t + \kappa_O\, Oil_t + \kappa_G\, Gas_t + \kappa_C\, Coal_t.$$

Each type of brown energy (oil, gas, coal) is measured in units of carbon emission. The parameters κ_O, κ_G, and κ_C are energy efficiency coefficients, calibrated to capture the energy composition (Boden and others 2017). Production of clean energy follows:

$$S_t = B_t\, K_{G,t}^{\alpha_G}\, K_{s,t}^{\theta} L_{s,t}^{\varphi}\, H_{s,t}^{1-\theta-\varphi}$$

where B_t, $K_{G,t}$, $K_{s,t}$, and $H_{s,t}$ refer to the productivity level, public green capital, private demands for capital, labor, and land of the clean energy sector, respectively. Parameters θ and φ are capital and labor share. The productivity S_t may benefit from public investment. Land is fixed at $\overline{H}$ with n_t as the rental price of land. The clean energy producer maximizes the profit given factor prices:

$$p_t^e\, \theta\, B_t\, K_{G,t}^{\alpha_G}\, K_{s,t}^{\theta-1} L_{s,t}^{\varphi}\, H_{s,t}^{1-\theta-\varphi} = r_t + \delta$$

$$p_t^e\, \varphi\, B_t\, K_{G,t}^{\alpha_G}\, K_{s,t}^{\theta} L_{s,t}^{\varphi-1}\, H_{s,t}^{1-\theta-\varphi} = w_t$$

$$p_t^e\, (1-\theta-\varphi) B_t\, K_{G,t}^{\alpha_G}\, K_{s,t}^{\theta} L_{s,t}^{\varphi}\, H_{s,t}^{-\theta-\varphi} = n_t$$

Brown energy producers, indexed by $M \in \{Oil, Gas, Coal\}$, have a finite energy reserves, R_t^M. The costs of extracting these reserves are increasing in the cumulative amount extracted. The following functional form is used for the extraction cost of dirt energy of type M per unit of brown energy extracted. The last term ensures that extraction costs approach infinity when reserves approach zero:

$$c_t^M(R_t^M) = \xi_1^M + \xi_2^M(R_0^M - R_t^M) + \xi_3^M(R_0^M - R_t^M)^2 + \xi_4^M(R_0^M - R_t^M)^3 + \frac{1}{R_t^M}$$

Brown energy-producing firms maximize market value, V_t^M, given by

$$V_t^M = \sum_{j=0}^{\infty} \left(p_{t+j}^M - c_{t+j}^M\left(R_{t+j}^M\right) - \tau_{t+j}\right) M_{t+j} \left(\prod_{i=0}^{j} \frac{1}{1+r_{t+i}}\right)$$

subject to $R_t^M = R_{t-1}^M - M_t$; $-R_t^M \le 0$; and $-M_t \le 0$,

where p_t^M is the per-unit price of brown energy M, and τ_t is the tax per unit of carbon levied at time t.

[8] Prepared by Yongquan Cao.

Each period in the model corresponds to one calendar year and each household is active in markets for 55 periods. Households born at time t maximize utility:

$$U\_t = \sum_{j=1}^{55} \frac{1}{(1+\rho)^j} \frac{C_{t+j-1,j}^{1-\sigma} - 1}{1-\sigma}$$

Subject to their own budget constraint $a_{t+1,j+1} = (1 + r_t)a_{t,j} + w_t\, l_j + T_{t,j} - C_{t,j}$, where $C_{t,j}$, $T_{t,j}$, $a_{t,j}$, and l_j correspond to consumption, government transfers, assets, and labor supply of generation j at time t, ρ is the time preference and σ is the coefficient of relative risk aversion. Household assets comprise physical capital, the value of brown energy firms, the value of land, and government debt. The supply of capital and labor is equal to the sum of their sectoral demands ($K_t = K_{y,t} + K_{s,t}$) and $\sum_{j=1}^{55} P_{t,j}\, l_{t,j} = L_{y,t} + L_{s,t}$.

Government needs to spend on green public investment and transfers, collect carbon tax, and issue debts to finance any deficits. The green public capital evolves as $K_{G,t+1} = (1 - \delta_G)K_{G,t} + I_{G,t}$. Government debt evolves according to the following equation:

$$D_{t+1} = (1 + r_t)D_t + \sum_{j=1}^{55} P_{t,j}\, T_{t,j} - \tau_t \sum_{M \in \{Oil,Gas,Coal\}} M_t + I_{G,t}.$$

The market-clearing condition for assets is given in the following, where $P_{t,j}$ is the population of generation j at time t and D_t is government debt.

$$\sum_{j=1}^{55} P_{t,j}\, a_{t,j} = K_t + V_t^O + V_t^G + V_t^C + Q_t + D_t.$$

The potential adverse impact from global warming is captured through a damage function, following the functional form in Nordhaus (1994, 2008, 2010) and Nordhaus and Yang (1996):

$$Damage_t = 1 - \frac{1}{1 + \pi_1\, T_t^A + \pi_2\,(T_t^A)^2}.$$

The term T_t^A refers to the change, since 1900, in global mean surface temperature. The damage function alters total factor productivity according to $A_t = (1 - Damage_t)Z_t$, where Z_t is an exogenous path of total factor productivity absent climate change. The analysis adopts Nordhaus' three-reservoir (the atmosphere, the upper ocean, and the lower ocean) temperature model to capture the link between temperature and carbon emission.

Scenarios

Three scenarios are used to illustrate the impact of climate policies on debt and how it then affects different age groups. First, a baseline of the business-as-usual scenario assumes no additional climate policies (*baseline*). The second scenario assumes that the government would adopt a carbon tax starting at $45 per ton, which would increase along with energy prices, as well as an extra 0.2 percent of GDP per year on public green investment until 2050. The associated fiscal surplus would therefore reduce debt-to-GDP ratio (*debt reduction scenario*). In the third scenario, in addition to the carbon prices and green public investment mentioned earlier, the government raises transfers to mitigate the costs of the green transition for certain cohorts and allows the government debt to rise over the medium term.

Simulation Results

The model is calibrated similar to Kotlikoff and others (2021) for the global economy. Key results are the comparison of welfare difference (measured by equivalent consumption) across age groups. The consumption equivalence measures the portion of remaining lifetime consumption an agent is willing to give up at each period to participate in another economy in which climate policies, such as carbon taxes and green investment, are active. Three main channels influence the lifetime consumption of households:

1. *Asset holding channel:* Climate policies during transition to net zero raise the valuation of green firms and reduce that for brown energy firms. In the model, households accumulate assets at a young age and sell the assets when turning old to smooth their lifetime consumption. This implies that existing established cohorts with more asset

holdings at present are more sensitive to changes in climate policies. The magnitude will depend on the relative household's holdings of brown and green firms and how valuations change over time.

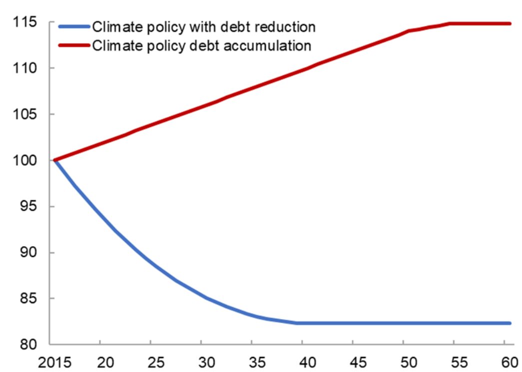
2. *Wage channel:* Climate policies affect relative prices of production factors and thus change the wages over time in the equilibrium. For instance, carbon tax alone initially slows down slightly on activity and reduces wages but the reduced global warming in the long term would lift wages and output relative to the baseline. At the household level, given the labor supply follows a hump shape over lifetime, the current working-age and future cohorts are more sensitive to changes in wage dynamics.
3. *Government redistribution channel:* In light of transition cost from climate policies, governments may mitigate such cost through redistributive transfers, partly financed through debt. Climate policies that affect debt dynamics have different impacts across age group dynamics over time.

Climate policies on their own bring uneven impact on household consumption across cohorts (Online Annex Figure 1.6.1). In general, future cohorts benefit from more forceful action to tackle climate change today, as expected. Current established cohorts face a trade-off between increased asset values (as valuation of green firms and land more than offsets the decline in valuation of brown firms) and slightly lower wages for the remainder of working years. Current young cohorts are the most adversely affected owing to fewer asset holdings and unfavorable wage dynamics during their working years.

Simulation results also suggest that climate policies affect debt dynamics, which will bring different impact across age groups. Debt will rise if the government scales up green public investment and raises the transfers to mitigate the uneven cost of green transition largely through debt financing (Online Annex Figure 1.6.2). In contrast, if carbon revenue is retained rather than redistributed, debt could gradually decline by about 15 percentage points of GDP by mid-2050s in the *debt reduction scenario*. If the government decides to mitigate the adverse impact for current cohorts through debt-financed transfers, the rise in debt service will need to be met by higher taxes on future cohorts. Hence, different debt levels will affect unevenly across cohorts, suggesting demographic structure plays a role in the green transition.

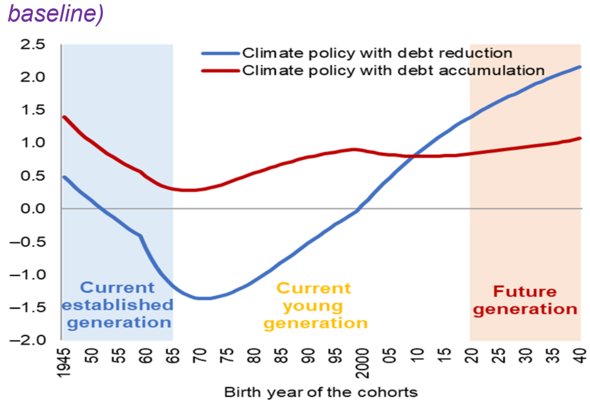
Online Annex Figure 1.6.1. Changes in the Debt-to-GDP Ratio

(Percentage points; baseline = 100)



Online Annex Figure 1.6.2. Lifetime Consumption across Cohorts

(Percentage difference relative to the "business-as-usual" baseline)



Sources: IMF staff estimates.
Note: The consumption-equivalent welfare difference is measured by the fraction of remaining lifetime consumption an agent is willing to give up at each period to join the economy in which carbon tax and transfers are active.

Online Annex 1.7. Public Financial Management[9]

The annex presents selected country examples of how governments apply green public financial management (PFM) practices and highlights the gaps in management of climate public investment.

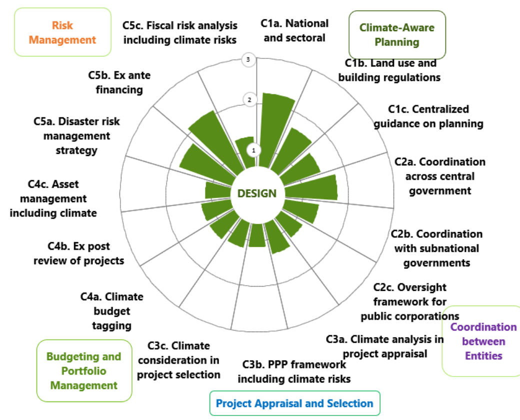
Green public financial management integrates climate considerations into existing budget management. It helps prioritize and direct scarce public resources to policies that are responsive to climate concerns and align with the country's strategic objectives. Green PFM practices aim to promote transparency and accountability for climate impact of fiscal policies, and signal a willingness to address climate challenges in a holistic manner. For emerging market and developing economies, green PFM also serves as a framework for managing climate finance funds.

Countries can achieve greening of PFM by adapting existing frameworks, systems, and practices, without a full-scale reengineering. Several countries have introduced practices tailored to their policy objectives and institutional capacity:

- *Strategic planning and fiscal frameworks:* The Scottish authorities in the *United Kingdom*, for example, quantify in the budget submission greenhouse gas emissions related to government procurement. It builds awareness among stakeholders of the climate impact of policy choices and facilitates an informed debate. *Rwanda's* FY23/24 fiscal risk statement includes discrete risks from climate change and a fiscal sustainability analysis under different climate scenarios. *Burkina Faso* included climate components in its 2023 fiscal risk statement, which analyzed the macro-fiscal effects of natural disasters.
- *Budget preparation:* The 2021 Green Budget in *France* tracked spending, including tax expenditures, against climate change objectives and other environmental objectives based on the European Union Taxonomy of Sustainable Environmental Outcomes. The tagging system also tracks expenditures that are detrimental to the achievement of environmental goals. *Turks and Caicos Islands* required ministries to present climate impact of fiscal programs in the 2023–24 budget circular and made climate assessment an integral part of new spending requests.

  Budget execution, accounting, and reporting: Dominican Republic includes environmental criteria in bid evaluations to promote green procurement. Expenditure tracking across themes and programs in *Bangladesh* helps monitor the financial execution of the government's climate plan, which facilitates reporting to Parliament and enhances transparency. Legal backing to green PFM practices can put them on a firmer footing and support their adoption.
- *Control and audit:* In *Canada*, the Commissioner of Environment and Sustainable Development provides independent audits and recommendations on the federal government's climate strategy.

Online Annex Figure 1.7.1. Average Scores for IMF C-PIMAs



Sources: National C-PIMAs; and IMF staff estimates.
Note: The IMF's Climate Public Investment Management Assessment (C-PIMA) framework provides countries a tool to assess the readiness of their public investment management practices to climate considerations and develop appropriate reform measures. PPP = Public private partnership.

Public investment in climate transition: Cross-country experience from the 29 IMF Climate-Public Investment Management Assessment (C-PIMAs) suggests that countries have stronger planning and relatively well-developed disaster risk management, but fall short on project appraisal and selection, which could negate the gains achieved elsewhere (Online Annex Figure 1.7.1).[10]; Interagency coordination—central to investment planning and execution across different tiers of governments—is needed to improve expenditure efficiency. C-PIMAs also highlight the need for mainstreaming climate considerations into ex post reviews and assets management.

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[9] Prepared by Christophe Hemous and Sandeep Saxena.
[10] The IMF's Climate-Public Investment Management Assessment (C-PIMA) assesses the readiness of a country's public investment management practices to climate considerations and helps in developing appropriate reform measures (IMF 2021).

Online Annex 1.8. Government Policies Shape Firm Investment in Climate[11]

This annex presents the details on the data and empirical methodology on firm investment response to regulations, energy costs changes, and policy incentives.

Firm Investment in Climate Mitigation and Adaptation

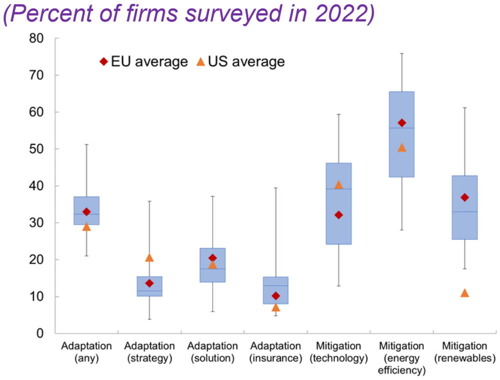
Data are based on the 2022 wave of the European Investment Bank Group Survey on Investment and Investment Finance (EIBIS).[12] The survey covers all 27 *EU* economies, the *United Kingdom* (until 2021), and the *United States* (since 2019), comprising about 13,000 firms annually. The survey is designed to be representative at EU level, country level, as well as sector and firm size class levels for most countries. It contains firm characteristics, past investment activities and plans, and how firms perceive their investment needs, financing, and constraints. Firms provide a binary response along different categories of investment in climate mitigation and adaptation. The analysis focuses on firms' decision to invest in new, less polluting business areas and technologies, energy efficiency, or renewable energy generation.

The number of firms that report investing in mitigation activities is high, with 57 percent of firms investing in energy efficiency and slightly more than a third of firms investing in new, emission-reducing technologies or renewable energy generation (Online Annex Figure 1.8.1). A third of firms invest in some adaptation, though less than 20 percent report investing in each individual category (strategies, solution, or insurance). Disparities are notable across countries. While the *United States* shows more firms investing in green technologies than in Europe, fewer US firms invested in less on renewable energy.

The analysis uses a simple linear regression model, with binary outcome variables, and including country fixed effects and robust standard errors. Explanatory variables include firm characteristics (age, size, and whether a firm engages in innovative activity), sector characteristics (energy-intensive or hard-to-abate[13]), firms' reported constraints on investment (access to finance, energy costs, and uncertainty), and their perceptions on climate (physical risks, regulations as posing a risk for operation, or an opportunity).

Online Annex Figure 1.8.1. Firms' Investment in Adaptation and Mitigation

(Percent of firms surveyed in 2022)



Sources: European Investment Bank Group Survey on Investment and Investment Finance 2022; and IMF staff estimates.
Note: The graph shows the distribution of the country-level share of firms investing in the corresponding climate measure across the European Union. The box and whiskers represent the interquartile range and lowest/highest share in the European Union, while red and orange dots represent the EU and US averages, respectively. EU = European Union; US = United States.

Results show that the likelihood of investing in new, less-polluting technologies is higher among firms in energy-intensive or hard-to-abate sectors, and those report energy costs as a major constraint. Firms that were affected by extreme weather events or perceive the green transition as an opportunity are more likely to invest in new technologies (Online Annex Figure 1.8.2). Similar patterns are observed in the likelihood of firms to invest in energy efficiency and in renewable energy, with the exception that firms in sectors with high abatement cost are less likely to invest in either of these mitigation measures (Online Annex Table 1.8.1).

Across all types of climate investment categories, firms that set and monitor emissions targets are the most likely to invest. This corroborates existing literature that firm-level climate targets are positively correlated with investment in

[11] Prepared by Salma Khalid and Alexandra Solovyeva, with inputs from Fotios Kalantzis and Marcin Wolski of the European Investment Bank.

[12] For technical details of the EIBIS surveys, including sampling and weighting, questionnaire development and translation, the fieldwork, and quality control and data processing, please see Brutscher and others 2020).

[13] Energy-intensive sectors are defined as belonging to NACE sector classifications 10–12, 17–20, 23–24, 35; hard-to-abate sectors are defined as belong to NACE sectors 50–51, 20, 23–24, and 4941.

renewable energy (Wang and Sueyoshi 2018) and emissions reduction (Ioannou, Li, and Serafeim 2016; Dahlmann, Branicki, and Brammer 2019; Hsueh 2022; Berestycki and others 2022). While one cannot distinguish whether firms' climate targets are voluntary or a result of mandatory regulation, our results show that the likelihood of firms setting or monitoring climate targets is stronger for firms in energy-intensive or hard-to-abate sectors, which are more likely to be regulated or mandatorily required to monitor emission (Online Annex Figure 1.8.2; Online Annex Table 1.8.1). Existing literature also shows that regulation can enhance voluntary climate action (Hsueh 2019), and that regulation reduces the risks of "greenwashing," wherein firms communicate positively on environmental messages but have poor environmental records (Mateo-Marquez, González-González, and Zamora-Ramírez 2022). Many countries, including *France*, *Japan*, and the *United States*, have regulations mandating the disclosures of climate risks by firms (Carattini and others 2022). Taken together, these results suggest that regulations to monitor emissions can enhance climate investment by firms.

Online Annex Figure 1.8.2. Key Determinants of Climate Investment by Firms
(Coefficient estimates)

Sources: European Investment Bank Group Survey on Investment and Investment Finance 2022; and IMF staff estimates.
Note: The figure represents the coefficient estimates (whiskers indicating 95 percent confidence interval) from a linear probability model including country fixed effects and robust standard errors. Results are consistent with European Investment Bank (2023). Results are based on responses to the questions: (1) Panel 1: Is your firm investing in new, less polluting business areas and technologies to reduce greenhouse gas emissions? (2) Panel 2: Is your firm investing in energy efficiency to reduce greenhouse gas emissions? (3) Panel 3: Has your firm developed or invested in adaptation strategies, solutions, or insurance to build resilience to the physical risks to your company caused by climate change? (4) Panel 4: Does your firm set and monitor targets for its own emissions?

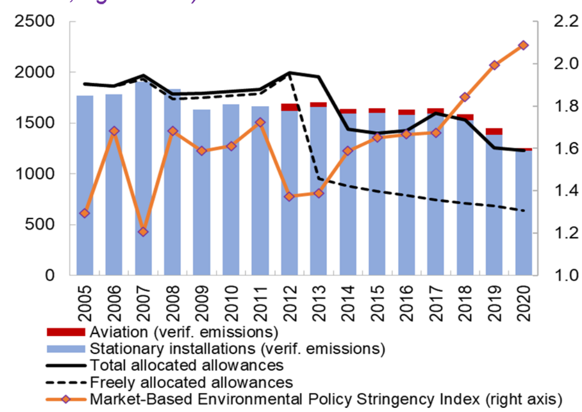
Climate Policy Stringency and Firms Regulated under the EU Emissions Trading System

To shed light on the effects of tightening of climate regulations on firms, the analysis focuses on the EU Emissions Trading System (ETS). The EU ETS is a cap-and-trade scheme that imposes a market-based regulatory pressure on installations (13,000 installations such as power stations and large industrial plants, and airlines operating) and covers 45 percent of the EU greenhouse gas emissions. ETS-regulated firms need to have a European Emission Allowance for emissions in each year. The overall emissions by all

ETS-regulated firms are limited by a cap, while emission allowances are auctioned off, allocated for free to firms, and then traded in the carbon market. During the initial phases from 2005 to 2012, emission allowances were largely free, and the total allowances exceeded actual emissions. Since 2012, the EU ETS was extended to cover more gases and sectors, and free allowances were significantly reduced (to be phased out by 2030) with the EU-wide emission cap set to decrease every year. The tightening of ETS has raised carbon prices to €25 per ton in early 2020 and contributed to more stringent market-based policies in the EU (Online Annex Figure 1.8.3). The stringency of market-based climate policies is measured by the OECD market-based Environmental Policy Stringency index, which is based on policy stringency that puts a price on pollution such as permit prices from CO_2 trading schemes, taxes on CO_2, NO_x, SO_x, and fuel.

Online Annex Figure 1.8.3. Europe: ETS Emissions and Climate Policy Stringency

(Metric tons of carbon dioxide equivalent, left scale; index, right scale)



Sources: European Union Transaction Log; Organisation for Economic Co-operation and Development; and IMF staff calculations.
Note: The figure shows a simple average of market-based Environmental Policy Stringency indices of 21 European countries with available data. ETS = emission trading system.

To quantify the impact of tighter environmental policies on European firms, the analysis matches EU ETS data with the Bureau van Dijk's Orbis firm database and identifies 7,200 ETS-regulated firms (or two-thirds of ETS installations). Data cleaning steps follow Diez, Fan, and Villegas-Sánchez (2021). Only nonfinancial firms with at least 10 consecutive years of sales data are included. The sample consists of nearly 1 million firms (including 1,870 ETS-regulated firms) from 12 European countries over 1995–2020.[14] The general form of the baseline panel regression specification is as follows:

$$\Delta y_{i,t} = \alpha_i + \Theta^{MB} X_{i,t,c} \Delta EPS^{MB}_{c,t-1} + \Theta^{NMB} X_{i,t,c} \Delta EPS^{NMB}_{c,t-1} + \Upsilon Z_{c,t-1} + \Omega W_{i,t-1} + D_{t,c,s} + \varepsilon_{i,t},$$

where $\Delta y_{i,t} = y_{i,t} - y_{i,t-1}$, and $y_{i,t}$ is log of turnover, input costs (material costs), profits (earnings before interest, taxes, depreciation and amortization), and fixed assets (total non-current assets after depreciation) of firm *i* in year *t*. $\Delta EPS^{MB}_{c,t}$ ($\Delta EPS^{NMB}_{c,t}$) denote changes in the market-based (non-market based) Environmental Policy Stringency (EPS) in country *c* between years *t* – 1 and *t*. $X_{i,t,c} = \left[1, ETS^0_i, ETS^P_{i,t}, ETS^P_{i,t} \times P^{CO2}_t\right]$ is a vector of variables, where the dummy variable ETS^0_i indicates if a firm has at least one installation subject to the ETS; $ETS^P_{i,t}$ indicates whether the ETS-regulated firm had positive payable emissions in year *t* (emission exceeding the free allowance levels); and P^{CO2}_t indicates if carbon prices are above the 75th percentile during 2008–20 (excluding the first phase of ETS during 2005–07 because at that time allowances were largely free at national level). $\Theta^{MB} = [\beta^{MB}_0, \beta^{MB}_1, \beta^{MB}_2, \beta^{MB}_3]$ and $\Theta^{NMB} = [\beta^{NMB}_0, \beta^{NMB}_1, \beta^{NMB}_2, \beta^{NMB}_3]$ are vectors of corresponding regression coefficients. Finally, α_i denotes firm *i* fixed effect; $W_{i,t}$ and $Z_{c,t}$ are vectors of firm-level and country-level control variables, respectively. The regression also includes country-sector and sector-year fixed effects ($D_{t,c,s}$).

Results suggest that more stringent market-based climate policies have had no significant impact on firms' performance on average (Online Annex Table 1.8.2), consistent with the findings of limited aggregate impact on output from higher carbon prices (Colmer and others 2022). For example, an increase in the market-based EPS index by one unit is associated with limited declines in input costs and turnover (less than 1 percentage point) and a small

[14] The sample includes *Belgium*, *Czech Republic*, *Denmark*, *Estonia*, *Finland*, *France*, *Germany*, *Greece*, *Italy*, *Portugal*, *Spain*, and the *United Kingdom*. The sample period coverage varies by country. Sectors are defined at the 2-digit NACE level. All variables on flows are converted into real terms using the 2-digit NACE level deflators. For the fixed assets, we use World Bank WDI investment deflators at the country level.

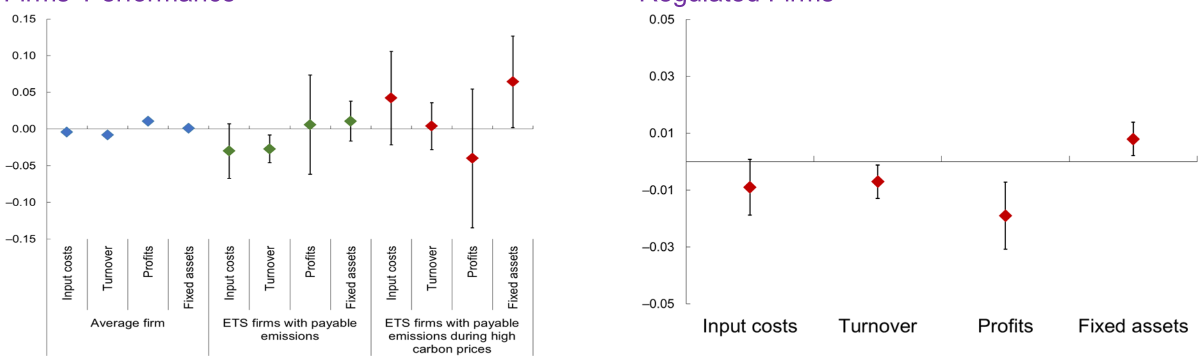
increase in profits, with no significant change in fixed assets.[15] ETS-regulated firms have not been adversely affected (Online Annex Figure 1.8.4, panel 1). Despite a decrease in turnover (2.7 percentage points), profits are flat on average (though there are large differences across firms). While a tightening of policies does not raise investment—proxied by a change in fixed assets—for an average ETS-regulated firm that emits more than free allowance levels, the impact turns positive and significant when carbon prices are high. Specifically, a tightening of market-based regulations by one unit is associated with a rise in investment by about 6½ percentage points but no significant impact on input costs, turnover, or profits (Online Annex Table 1.8.2). An alternative shock for the stringency of climate policy at the installation level points to a moderate increase in the level of fixed assets among ETS-regulated firms during periods when they face rising emission costs (Online Annex Figure 1.8.4, panel 2). The effects on turnover and profits are more limited.

Online Annex Figure 1.8.4. Estimated Impact of Policies on Firms' Performance

(Coefficient estimates)

1. European Environmental Policy Stringency and Firms' Performance

2. Emission Cost Shock and Performance of ETS-Regulated Firms



Sources: EU Emission Trading System; IMF, World Economic Outlook database; Kalantzis and others (forthcoming); ORBIS; and Organisation for Economic Co-operation and Development.

Panel 1 shows estimated coefficients from a panel regression of 12 European countries over 1995–2020. Panel 2 shows estimated coefficients from a panel regression model based on ETS and Bureau van Dijk ORBIS data. Both panels include firm, country-sector, and year-sector fixed effects and robust standard errors clustered at the firm level. The dependent variables are changes in input costs (material costs), turnover, profits (earnings before interest, taxes, depreciation and amortization), and fixed assets (in logarithms). Each coefficient estimate represents the impact from a change in Organisation for Economic Co-operation and Development market-based Environmental Policy Stringency index on the corresponding dependent variable. ETS-regulated firms are those with ETS-registered installations. Payable carbon emissions are calculated as the difference between verified emissions and free allowances. "High carbon price" is a dummy variable that takes on a value of 1 in years with the carbon prices exceeding the 75th percentile. The whiskers indicate the 95 percent confidence interval of the estimated coefficients. ETS = emission trading system.

Taken together, empirical results indicate that more stringent market-based regulations will bring an impact on ETS-regulated firms only when carbon prices are high. Moreover, those ETS-regulated firms have had adjustment margins to respond and limit the adverse impact on profitability, including enhancing investment. These corroborate other studies that find no evidence of tighter regulations weakening firms' performance (Dechezleprêtre, Nachtigall, and Venmans 2018; Dechezleprêtre and Kruse 2022) and the EU ETS, at its early stages, contributed to higher investment for regulated firms in some countries (Jaraitė and Di Maria 2016; Dechezleprêtre, Nachtigall, and Venmans 2018).

[15] An average increase in the market-based EPS index for 12 countries in our sample over the 2012–20 period is about 0.9. Hence, a unit increase in the index can be interpreted as tightening of climate policies over the medium term. Regressions for turnover, profits and fixed assets are estimated with a sample that includes firms with missing data on input costs. Results are robust to excluding those firms.

Online Annex Table 1.8.1. Estimates of Likelihood of Investing in Climate Areas

Variables	New Technology	Energy Efficiency	Renewables	Any Adaptation	Climate Target
Age of firm > 20 years	0.025***	0.075***	0.057***	0.019**	0.045***
Small/medium firm	–0.053***	–0.126***	–0.072***	–0.072***	–0.278***
Firm with innovative products/processes	0.103***	0.099***	0.063***	0.085***	0.055***
Energy-intensive sector	0.048***	0.095***	0.118***	0.023	0.122***
Sector with high emission abatement cost	0.042***	–0.053***	–0.098***	–0.016	0.058***
Energy cost is a major obstacle to investment	0.032***	0.076***	0.039***	0.028***	0.051***
Access to finance is a major obstacle to investment	–0.007	–0.029**	–0.021*	0.006	0.012
Uncertainty is a major obstacle to investment	–0.002	–0.015	0.000	–0.015*	–0.026***
Physical risks from climate change will have major impact on firm	0.072***	0.078***	0.072***	0.171***	0.048***
Transition to stricter climate standards represents a risk for firm	0.045***	0.045***	0.015	0.051***	0.058***
Transition to stricter climate standards represents an opportunity for firm	0.136***	0.101***	0.103***	0.111***	0.131***
Firm sets and monitors climate targets	0.213***	0.206***	0.160***	0.180***	
Constant	0.130***	0.312***	0.166***	0.109***	0.360***
Observations	11,331	11,331	11,331	11,286	11,356
R-squared	0.171	0.174	0.165	0.14	0.149
Country fixed effects	Yes	Yes	Yes	Yes	Yes

Sources: European Investment Bank 2023; and IMF and European Investment Bank staff calculations.
Note: The table represents the coefficient estimates from a linear regression model including country fixed effects and robust standard errors. Results are consistent with European Investment Bank (2023). The first column reports whether firms invest in new, less polluting technologies to reduce emissions. The second column reports whether firms invest in energy efficiency. The third column reports whether firms invest in onsite/offsite renewable energy generation. The fourth column reports whether firms develop or build resilience to physical risks from climate change, including adaptation strategies, adaptation solutions, or insurance products. The last column reports whether firms set or monitor targets for emissions. Standard errors are not reported here but are available from authors. ***, **, and * denote statistical significance at 1 percent, 5 percent, and 10 percent levels, respectively.

Online Annex Table 1.8.2. Estimates of Tightening of Market-Based Policy Stringency

	Δ Log Input Costs	Δ Log Turnover	Δ Log Profits	Δ Log Fixed Assets
Lag ΔEPS Market	–0.004***	–0.008***	0.010***	0.001
Lag ΔEPS Non-Market	0.011***	0.002***	–0.000401	–0.003***
Lag ΔEPS Market × ETS firm	–0.048***	–0.025***	0.000	–0.016**
Lag ΔEPS Non-Market × ETS firm	0.002	–0.001	0.002	0.004
Lag ΔEPS Market × ETS firm with payable emissions	0.022	0.006	–0.00462	0.026*
Lag ΔEPS Non-Market × ETS firm with payable emissions	–0.043*	–0.005	0.086*	0.023
Lag ΔEPS Market × ETS firm with payable emissions × High carbon price	0.072**	0.031*	–0.0461	0.054
Lag Log Employment	–0.054***	–0.054***	0.001	0.018***
Lag Log Total Assets	–0.130***	–0.109***	–0.247***	–0.189***
Lag Real GDP growth	0.015***	0.012***	0.016***	0.008***
Lag Output gap	–0.009***	–0.006***	–0.011***	–0.001***
Constant	1.890***	1.626***	3.389***	2.599***
Observations	7,326,460	8,753,704	8,753,704	8,753,704
R-squared	0.126	0.184	0.086	0.128
Firm Fixed Effect	Yes	Yes	Yes	Yes
Sector	Non-Fin	Non-Fin	Non-Fin	Non-Fin
Country-Sector Fixed Effect	Yes	Yes	Yes	Yes
Year-Sector Fixed Effect	Yes	Yes	Yes	Yes

Sources: EU Emission Trading System; European Investment Bank; IMF, World Economic Outlook database, Kalantzis and others (forthcoming); ORBIS; and Organisation for Economic Co-operation and Development.
Note: The table presents the estimated coefficients from a panel regression model based on Bureau van Dijk ORBIS database. The sample consists of 12 European countries covering 1995–2020 and data cleaning follows Diez, Fan, and Villegas-Sánchez (2021). The dependent variables are changes in input costs (material costs), turnover, profits (earnings before interest, tax, depreciation, and amortization), and fixed assets (in logarithms). ΔEPS Market and ΔEPS Non-Market correspond to changes in Organisation for Economic Co-operation and Development market-based and non-market-based Environmental Policy Stringency indices, respectively. ETS firms correspond to firms with ETS-registered installations. Payable emissions are calculated as a difference between verified emissions and free allowances. “High carbon price” takes on a value of 1 in years with the EU carbon price above the 75th percentile. Standard errors are not reported here but are available from authors. ***, **, and * denote statistical significance at 1 percent, 5 percent, and 10 percent levels, respectively. ETS = emission trading system.

Online Annex 1.9. Surveys on Firms' Responses to Energy Price Spikes and Recent Climate Policy Packages[16]

The annex provides background on firm-level surveys conducted in Germany *and the* United States *in spring 2023.*

Context and Background

Soaring global energy prices in 2022, partly driven by Russia's invasion of Ukraine, had raised concerns that firms would be unable to adjust to higher energy prices, prompting government support to avoid supply disruptions and widespread bankruptcy (Amaglobeli and others 2023). The resulting push for energy security and green transition also contributed to the announcement of large policy packages, including the US Inflation Reduction Act and EU Green Deal for Industrial Policies in late 2022. This annex outlines the design and results of two novel surveys on firms in *Germany* (May 2023) and the *United States* (March 2023), with an aim to assess two questions: (1) how firms responded to the recent energy crisis in their operations or balance sheets; and (2) what main obstacles firms face when investing in low-carbon technology and to what extent firms have used incentives in recent policy packages.

Survey Design

The firm-level survey in the *United States* was conducted in partnership with researchers at the Federal Reserve Banks of Atlanta and Richmond. Thematic modules were designed to integrate into existing surveys, including the Atlanta Federal Reserve Bank's survey of Business Inflation Expectations (BIE) and the chief financial officer (CFO) survey by Duke University, Richmond Federal Reserve Bank, and Atlanta Federal Reserve Bank. The BIE survey measures one-year-ahead inflation sentiments in a nationally representative sample of businesses in the US states of Alabama, Florida, Georgia, Louisiana, Mississippi, and Tennessee, and typically features 300 respondents a month. The CFO survey is a nationally representative survey of financial decision makers with the US-wide coverage of firms ranging from small firms to Fortune 500 companies and features around 300 to 350 respondents a quarter. The survey was conducted in March 2023.

The German survey was conducted in May 2023, in collaboration with researchers in Bundesbank in *Germany*. Similarly, thematic modules was integrated into the Bundesbank's Online Panel—Firms (BOP-F) survey, which included both recurring questions on the economic situation of companies and their expectations and thematic special set of questions. The BOP-F survey covers all regions in *Germany* and, since July 2021, has been conducted on a quarterly basis with a sample of around 3,000 firms per month.

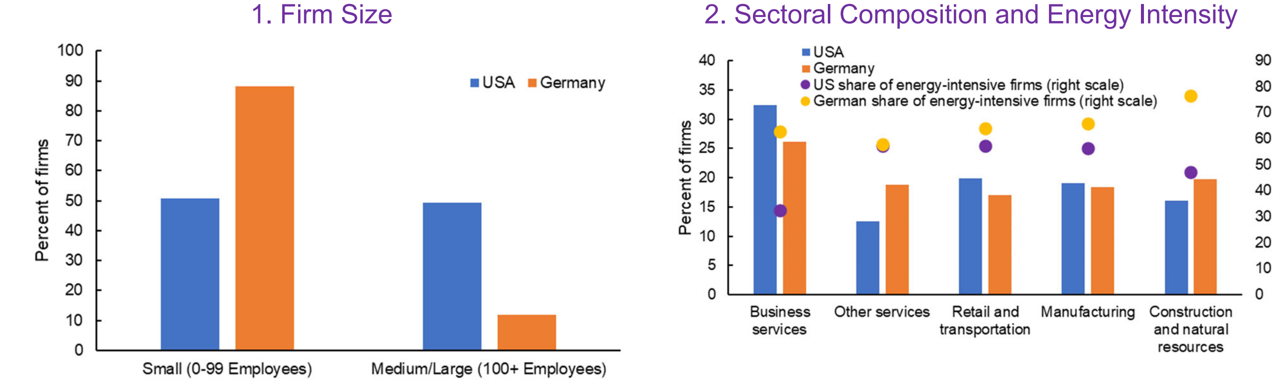
Where possible, survey questions were kept identical in both surveys on the firms in the *United States* and *Germany* to maximize comparability; where this was not possible, questions are set to be as similar as possible. Detailed survey questions are available upon request. The maximum number of respondents across all questions in the modules was 470 firms for the BIE and CFO surveys and 2,718 firms for the BOP-F survey, though response rates vary by question. The attrition rate is on par with typical surveys, and the resulting set of firms are a representative sample.

There are some structural differences in the US and German sample of firms in the surveys. In the sample of firms in Germany, most are small firms with fewer than 100 employees, while the US sample of firms are more evenly split between large firms and small- and medium-sized enterprises (Online Annex Figure 1.9.1, panel 1). The share of high-energy-intensity firms—defined as energy costs greater than 3 percent of total costs—are similar between the German and US samples of firms (Online Annex Figure 1.9.1, panel 2). In terms of sectors, a higher share of firms in *Germany* is in the "other services," which includes education, finance, health, information, and leisure, at 6 percentage points higher than the US firms in the surveys. Other sectors, such as energy-intensive construction and natural resources sectors, also show notable difference of around 4 percentage points than the US sample. Relative to the US sample,

[16] Prepared by Samir Jahan, with inputs from David Amaglobeli, Salma Khalid, W. Raphael Lam (International Monetary Fund); Brent Meyer, Sonya Waddell, and Daniel Weitz (Federal Reserve Banks of Richmond and Atlanta), Xuguang Simon Sheng (American University), and Pawel Smietanka (Bundesbank).

the share of high-energy-intensity small firms in *Germany* is far higher (91 percent of high energy intensity firms in *Germany* versus 48 percent in the *United States*).

Online Annex Figure 1.9.1. Characteristics of Firms in Germany and the United States



Sources: Deutsche Bundesbank; Duke University, Federal Reserve Banks of Atlanta and Richmond; and IMF staff calculations.

Online Annex 1.10. GDP Impacts from Carbon Pricing[17]

This annex updates the results in Metcalf and Stock (2020, 2023) using data from March 2023 World Bank Carbon Pricing Dashboard database.

The dynamic effects of carbon taxes on the level of real GDP are estimated using Jordà's (2005) local projection method with panel data for 31 EU countries over 1985–2019, exploiting cross-country and time variation in carbon tax adoption. The identification challenge is the potential simultaneity endogeneity, where strong economic growth incentivizes governments to plan, or increase, the carbon tax as they can afford it. The identification assumption is that carbon tax changes that are not predicted by historical countries' GDP growth and global shocks are exogenous (conditional exogeneity). These changes include, for example, responses to international climate policy pressure, changes in political preferences, or dealing with an inherited budget deficit or tax policy changes aimed at increasing potential growth.

Specifically, the cumulative effects of carbon taxes on the level of GDP is estimated:

$$100\,(\ln(GDP_{i,t+h}) - \ln(GDP_{i,t-1})) = \alpha_i + \alpha_t + \theta_h \tau_{i,t} + \beta(L)\,\tau_{i,t-1} + \gamma(L)\,\Delta\ln(GDP_{i,t-1}) + \mu_{i,t},$$

where $\tau_{i,t}$ is the coverage-weighted carbon tax (purchasing power parity 2017 US dollars per ton of carbon dioxide) in country *i* and year *t*. The data for real GDP, real carbon taxes, and the share of greenhouse gas emissions covered by the tax in 2018 is from the World Bank (2023a, 2023b). The adjusted gross national income is used to eliminate distortions from intellectual property inflows in *Ireland* and onshore GDP (excluding oil revenues) in *Norway*. Data for carbon tax and coverage of emissions use the March 2023 Carbon Pricing Dashboard (for details, see Metcalf and Stock 2023).

Any effect of the tax on the economy is assumed to be proportional to coverage of emissions times the tax rate. The regression controls for country-fixed effects to deal with the potential selection on the adoption of carbon taxes by economies with higher average GDP growth. We estimated the "unrestricted" case (Metcalf and Stock 2023, Figure 5), which does not impose the restriction that the carbon tax does not permanently affect the long-term GDP growth path (results are similar if the restriction is imposed). The results are robust controlling for four lags in the log change of the GDP deflator and the change in unemployment.

The regression includes time-fixed effects to control for the common *European Union*'s political and economic trends. The parameter *L* is set to 4 and the dynamic effects are estimated at horizons *h* = 0,1,…,6. The policy shock is defined as a one-time permanent increase in carbon tax by US$40 that covers 30 percent of the country's emissions (close to the sample average). This implies computing the sequence of shocks necessary to get the specified counterfactual carbon tax increase (Metcalf and Stock 2023). Standard errors are heteroskedasticity-robust.

[17] Prepared by Pedro Juarros.

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